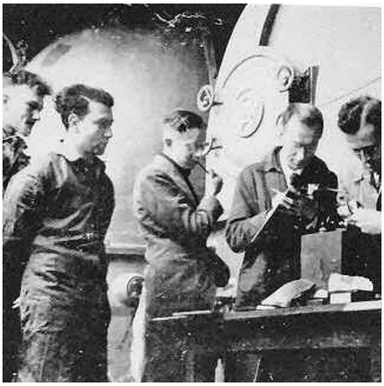
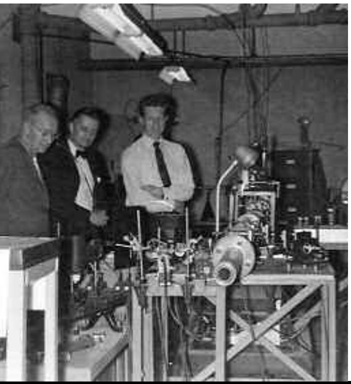
JMBC 15 years

1992





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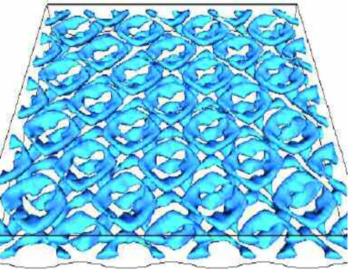

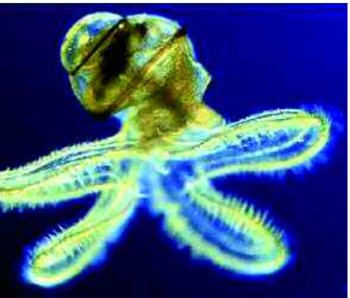

J.M. Burgerscentrum

Research School for Fluid Mechanics

TUD, TUE, UT, RUG, RUN, UL, WUR

JMBC 15 years

JM Burgers centre
Research School for Fluid Mechanics

TUD, TUE, UT, RUG, RUN, UL, WUR

G Ooms
CJ Hoogendoorn

Preface by the former and current scientific director of the JMBC

This year the JM Burgers Centre (JMBC) exists fifteen years as the Dutch research school on fluid mechanics accredited by the Royal Netherlands Academy of Sciences. The JMBC was accredited for the first time in 1992. Thereafter (in 1997 and 2002) re-accreditations were achieved. Recently we received information from the academy, that our research school was re-accredited again for a new period. The international peer panel that visited and evaluated the JMBC in September 2006 was extremely impressed with the quality and scope of fluid mechanics research in The Netherlands. It stated in its report:

"This research is clearly of an international stature, very visible through high-quality publications in high-quality journals, and yet of great relevance to the Dutch industry. The JMBC provides the Dutch industry and technological institutes with scientific personnel who are very qualified in fluid mechanics. The JMBC plays an instrumental role in sustaining this high level of research and education, by creating a critical mass and a coherent network of fluid mechanics research groups in The Netherlands. The Burgers professors have become an established and pivotal instrument for increased international visibility of Dutch fluid mechanics. The JMBC significantly enhances interaction between industry, technological institutes and academic institutions through the activities of the Industrial Advisory Board, the Programme Committee and the subject-based Contact Groups. The JMBC is important for creating networks among PhD students and between students, professors and industrial partners. This is achieved through the PhD courses, the annual Burgers Day, and the Contact Group meetings. All these activities have a very positive effect on fluid mechanics research and education in The Netherlands."

As former and current scientific directors of the JMBC we are proud about these achievements and highly value the large effort of the JMBC groups in this respect.

We hope that the reader will enjoy this book issued on the occasion of the fifteenth anniversary of the research school. It contains two autobiographical notes from Burgers; one about his early years in his parental home and the other about his study years at Leiden University. Moreover it contains many research highlights of JMBC groups from the last fifteen years. We are confident that the JMBC will continue to play its important role in stimulating fluid mechanics research in The Netherlands.

G Ooms
Scientific Director of the JMBC
from 1998

CJ Hoogendoorn
Former Scientific Director of the JMBC
from 1992 till 1998

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JF Dijksman
(also on behalf of AE Mynett)

On the 15th birthday of the JM Burgers Centre

A couple of weeks ago a colleague gave me two volumes of the Zeitschrift des Vereines Deutscher Ingenieure, one from 1892 and another from 1908. First of all, I was highly impressed by the extreme quality of the drawings and pictures, the almost modern level of explaining engineering mechanical issues and the devotion to machines and other mechanical contraptions. To mention a few examples from the 1892 volume: a lengthy description of the Schnelldampfer "Fürst Bismarck" powered by two triple expansion steam engines with a total peak power of almost 12000 indicator kWatt, a treatise by A Ritter on traveling waves, a contribution on the applications of electrical power by E Hartmann, an experimental study by C Bach about the strength of riveted connections, the railways of North America, a treatise on the stability of ships by Von Middendorf, the director of the Germanischen Lloyds in Berlin. From the 1908 volume, I would like to cite: a paper on the calculation of curved beams by A Baumann, a contribution on Euler stability of beams by H Lorentz, numerous papers on the fluid dynamics of turbines, the use of tidal energy, water power plants, boilers, steam engines, locomotives and so on. In addition, the first automobiles appear in the annals. Very clear is that in these years Fluid Dynamics and Engineering Mechanics were considered supportive disciplines.

Around the Second World War Applied Mechanics turned, next to its still supportive nature, into a discipline in its own with two main branches Engineering Mechanics and Fluid Dynamics. This has been land marked by the first issue of "Advances in Applied Mechanics" edited by R von Mises and Th Von Karman in 1948. This issue contains interesting contributions from both CB Biezeno and JM Burgers. Biezeno gave a survey of papers on elasticity published in The Netherlands from 1940-1946 and Burgers discussed a mathematical model illustrating the theory of turbulence. This work was a continuation of his fundamentally new approach in the theoretical study of turbulence.

The Fluid Dynamics scene in The Netherlands is in broad perspective divided over Delft University of Technology, Eindhoven University of Technology, Twente University, the State University of Groningen, Radboud University Nijmegen and the Universities of Utrecht and Leiden. To name a few areas of interest: aeronautics, ship hydrodynamics, rheology, multi-phase flows, transport phenomena, computational fluid dynamics, multi-scale physics, micro fluidics, bio fluidics, nano fluidics, combustion, etc. All participating groups are members of the Research School on Fluid Dynamics, the JM Burgers Centre, named after the founding father of Fluid Dynamics in The Netherlands.

Right from the start of the Research School in 1992 there was a strong collaboration with the GTIs (Large Technological Institutions) and Industry. The GTIs met in the so-called Program Committee, contacts with Industry were formalized in the Industrial Advisory Board. The first task of the Program Committee and Industrial Advisory Board was to participate in the selection of projects sponsored by the Ministry of Economic Affairs. During the years the number PhD students within the Burgers Centre grew to a number far above hundred.

As a next step in the merge of Engineering Mechanics and Fluid Mechanics into one discipline Applied Mechanics February 2006 professor Gijs Ooms announced that the Dutch Cabinet approved a proposal from the three universities of technology in The Netherlands - Delft, Eindhoven and Twente - to federate. A €50 million is being made available in five annual installments to combine their research at fives centers of excellence. Among these is Applied Mechanics (fluid- and solid mechanics). It is of great importance for the research schools on fluid dynamics and engineering mechanics that fluid and solid mechanics are considered as areas of excellence within the academic community in The Netherlands. The challenge for the future is to go for a European scale.

I consider as a main achievement of the Burgers Centre the mutual tuning of the research programs and the possibility to go for large investments on a national scale. Another achievement is that PhD students follow four PhD courses, most often in another university next to an international exposure through conference visits and traineeships. Informal contacts with the GTIs and Industry are organized via the members of the Program Committee and the Industrial Advisory Board, e.g. by company visits by groups of students or by individual visits.

From this place, I would like to acknowledge and congratulate professor Charles Hoogendoorn, the first scientific director for his massive effort to bring all the Dutch fluid dynamics groups in the Burgers centre. I also would like to acknowledge and congratulate the present scientific director professor Gijs Ooms. He guided successfully the Burgers centre through two accreditation procedures.

Finally, I would like to respectful recognize the work of the bureau of the JMBC, headed by Mrs. Ilse Hoekstein-Philips, for the professional and careful issuing of the official documents and organizing the events of the research school.

JF Dijksman
Chair of the JMBC
Industrial Advisory Board

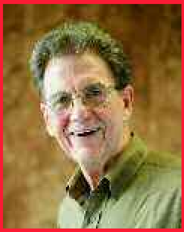
AE Mynett
Chair of the JMBC
Programme Committee

JM Wallace
J V Sengers

Burgers Program for Fluid Dynamics at the University of Maryland

After a long and distinguished scientific career at the Technical University Delft in The Netherlands, Johannes (Jan) Burgers moved to the United States in 1955 to begin a second career as a research professor at the University of Maryland's Institute of Fluid Dynamics and Applied Mathematics (IFDAM). At IFDAM he found a new stimulating environment with colleagues like Shih-I Pai and Elliott W Montroll and continued to be professionally active. The quarter century that Burgers spent at the University of Maryland was satisfying for him both scientifically and socially. At the University of Maryland he established a laboratory (see accompanying picture), began work on plasma dynamics and magnetohydrodynamics, continued his interest in philosophy and science, and further explored the implications of the non-linear equation named for him: the Burgers equation. This latter work eventually led to his monograph, "The Non-linear Diffusion Equation" in 1974; this monograph was reprinted by Kluwer in 2004 on the occasion of the inauguration of the Burgers Program for Fluid Dynamics to be discussed below. Burgers also became interested in high-speed gas dynamics (hypersonic flow and shock waves), a pursuit that resulted in an earlier monograph, "Flow Equations for Composite Gases" in 1969. A dinner was held in 1965 following a symposium organized in his honor on the occasion of his official retirement and his becoming a Professor Emeritus at age 70. After dinner Burgers, recalling his and his wife Annie's immigration to a new land, said "The way in which we were received at the University of Maryland surpassed anything which we could have imagined when we came to America with the hope of settling here. We felt at home immediately and a deep love for this country has grown in us. The friendship which one can find in the United States and in particular in its scientific circles is a source of everlasting joy, which pervades all phases of one's life and one's work." His passionate interest in many aspects of fluid dynamics and life around him continued undiminished until his death at age 86 on June 7, 1981.

At the European Turbulence Conference in the summer of 1994 in Sienna, Italy, Jim Wallace met Frans Nieuwstadt, and they discussed the legacy of Jan Burgers whose birth centenary would occur the following year. Frans had been one of the founding organizers of the JM Burgers Centrum in The Netherlands two years earlier, and was planning a week-long celebration of the legacy of Burgers. Jim Wallace agreed to come to Delft for the centenary celebration in January of 1995 to represent the University of Maryland, where Burgers had made his second scientific career. They also talked about a reciprocal visit of Frans to College Park for a centenary celebration at the University of Maryland, to be held in May of that year. At the one-day symposium at Maryland, Burgers' long-time colleagues at the Institute for Physical Science and Technology or IPST (which IFDAM had become in 1975 after its merger with the Institute for Molecular Physics), Bob Dorfman, Allan Faller and Shih-I Pai, remembered Jan Burgers' wonderfully gentle and unassuming manner and his many contributions to the intellectual life of the university. Ron Armstrong, Ugo Piomelli and Jim Wallace spoke about aspects of Burgers' legacy in solid mechanics and turbulence research. The day was culminated with a lecture of Frans Nieuwstadt on "The Legacy of JM Burgers."



JM Wallace
Burgers Program Maryland

JV Sengers
Burgers Program Maryland

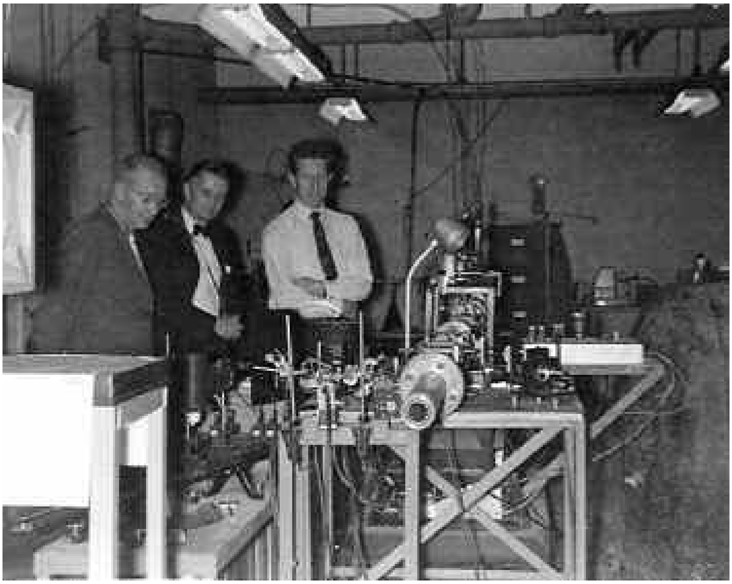
Katepalli Sreenivasan, then at Yale University, had been invited to the centenary symposium at Maryland. Although he could not attend, he wrote Jim Wallace to say that we at Maryland should continue to remember Jan Burgers and build on his legacy with an annual event. When Sreeni became Director of the Institute for Physical Science and Technology at the University of Maryland in 2002, he began raising funds to endow an annual Burgers Lectureship and together with Jan Sengers he put together a Burgers Board to organize this Lectureship. Frans Nieuwstadt spent several weeks at the University of Maryland in the Fall of 2003 and gave the first Burgers Lecture entitled “Resolving Reynolds’ Riddle.”

When Sreeni took a leave of absence from the University of Maryland to become Director of the International Center for Theoretical Physics in Trieste, Italy, Jan Sengers became Chair of the Burgers Board and brought great vigor to the task. He brought Jim Wallace onto the Burgers Board, and together they conceptualized a broad range of activities and participants constituting the Burgers Program in Fluid Dynamics. The Program describes itself as: “Inspired by the intellectual heritage of JM Burgers, the mission of the Burgers Program is to enhance the quality and international visibility of fluid dynamics research and educational programs at the University of Maryland with the help of an endowed Burgers Fund. Fluid dynamics in this context is viewed to include a broad range of dynamics, from nanoscales to geophysical scales, in simple and complex fluids.” More than 60 faculty members spread over 18 different academic and research units in the College of Computer, Mathematical and Physical Sciences and the A James Clark School of Engineering agreed to participate in the Burgers Program. It was agreed that the Program should invite a Burgers Visiting Professor each year. A website was created that can be seen at http://www.burgers.umd.edu .

The Burgers Program was inaugurated on November 18, 2004 with the first of its annual Burgers Symposia. Highlights of the day-long event were the remarks by Gijs Ooms, the Scientific Director of the JM Burgers Centrum (JMBC) in The Netherlands on “Life and work of JM Burgers in The Netherlands,” remarks by Jan Sengers on “The Legacy of JM Burgers at Maryland” and the Burgers Keynote Lecture on the “Dynamics of Turbulent Shear Flows” by Bruno Eckhardt of the Philipps Universität, Marburg. The President of the University of Maryland, Dan Mote, and the Deans of the College of Computer, Mathematical and Physical Sciences and of the School of Engineering, Stephen Halperin and Nariman Farvardin, welcomed the more than 75 participants. Each succeeding year the Symposium has been held as a half-day event. The 2005 Burgers Keynote Lecture: “On Dynamical Models of Turbulence” was given by Charles Meneveau of Johns Hopkins University. In 2006 Gijs Ooms gave the Burgers Keynote Lecture: “How Particles Interact and Form Bridges in Shear Flow Near a Wall at Low Reynolds Number.” In November of 2007 the Burgers Keynote Lecturer will be Detlef Lohse of the Twente University, as a representative of JMBC. In addition to several other invited talks, each year a poster session displaying current research of graduate students and post-docs is held, and two “best poster” certificates are awarded.

A program of visiting Burgers Faculty was initiated in 2004. Bruno Eckhardt was the first Burgers Visiting Professor during the 2004-2005 academic year. In the 2005-2006 academic year we enjoyed the visits of two Burgers Visiting Associate Professors: Saπa Kenjereπ of JMBC at the Technical University in Delft and Serge Simoëns of the Ecole Centrale de Lyon, France. They interacted with several of the Maryland faculty during their visits. From May - July, 2007 Jerry Westerweel, Director of the Laboratory for Aero and Hydrodynamics of JMBC at the Technical University in Delft was our Burgers Visiting Professor. While at the University of Maryland, he and Ken Kiger of our Mechanical Engineering Department offered a short course on PIV, and Jerry finished the draft of a book on this widely used experimental technique.

In April 2005 the Burgers Program began interacting with the Center for Applied and Environmental Fluid Mechanics of Johns Hopkins University in organizing an annual graduate student/post-doctoral fellow showcase symposium. The venue for the symposium alternates between the two universities each year. After a keynote address by a faculty member from the visiting institution, students and research associates give short presentations on their research. Members of the fluid dynamics community from around the region are invited to attend the symposium with the hope that the presentations will interest these attendees and create employment opportunities for the presenters.



Tob de Boer(right) and Jan Burgers (left) in the laboratory at the University of Maryland with Burgers' former student from Delft, Ir. Ruys. [courtesy of PC Tobias de Boer, currently Professor Emeritus of Mechanical and Aerospace Engineering at Cornell University].

In the fall of 2005 the Burgers Program for Fluid Dynamics was recognized by the Graduate School of the University of Maryland as an interdisciplinary Field Committee. We subsequently received grants from the Graduate School to enhance graduate education in fluid dynamics at the university. We are exploring the possibility of jointly offering graduate courses with the Center for Applied and Environmental Fluid Mechanics of Johns Hopkins University at a site convenient to the two campuses, which are located in College Park and Baltimore respectively, about thirty miles apart.

A seminar series called Fluid Dynamics Reviews, which has continued uninterrupted for over forty years at the University of Maryland, has been incorporated into the Burgers Program. It is supported by the Minta Martin research fund. The format allows for faculty and their students and post-docs from the Burgers Program as well as for visitors to give presentations five or six times each semester. The seminar series has sponsored the visits of a long list of very distinguished speakers over the many years it has been a part of the campus' intellectual life.

The partnership of our Burgers Program with the JMBC was celebrated with a one-day symposium at the Technical University Delft on January 12, 2006. This symposium attracted about 200 participants. Our Burgers 2004-2005 Visiting Professor, Bruno Eckhardt, was the keynote lecturer, and Jan Sengers and Ken Kiger from our Program also gave lectures, as did Saπa Kenjereπ, one of the two 2005-2006 Burgers Visiting Associate Professors.

The legacy of Johannes Burgers continues to live and grow at the University of Maryland. We are sure he would be pleased to know that his energetic pursuit of such a wide range of research avenues in the field of fluid dynamics after his arrival here in 1955 is being carried on, under the aegis of an interdisciplinary program bearing his name, in departments and research units across the campus of the University of Maryland.

1. James M Wallace is chair of the Burgers Board for Fluid Dynamics at the University of Maryland, College Park, MD, USA.
2. Jan V Sengers is a past chair and a current member of the Burgers Board for Fluid Dynamics at the University of Maryland, College Park, MD, USA.

JM Burgers on top of the windmill

JV Sengers
G Ooms

Introduction to the autobiographical notes of Burgers

Johannes (Jan) M Burgers was born in Arnhem in The Netherlands on January 13, 1895. His potential as an outstanding scholar was recognized early and he started to work as a Professor of "Aerodynamics, hydrodynamics and their applications" in the Department of Mechanical Engineering, Shipbuilding Engineering, and Electrical Engineering of the Technical University in Delft in 1918, two months before he received his PhD in the Physical and Mathematical Sciences from the University of Leiden under the supervision of Paul Ehrenfest. After an impressive career in fluid mechanics in The Netherlands, Jan Burgers moved in 1955 to the University of Maryland in College Park. MD, where, first as a Research Professor and subsequently as a Research Professor Emeritus, he remained professionally active till his death on June 7, 1981. A considerable amount of information about Jan Burgers and his work can be found in the well-known volume edited by FTM Nieuwstadt and JA Steketee [1]. This volume also contains biographical information.

When we went through the Archives at the University of Maryland and at the Delft University of Technology, we found 35 typewritten pages of biographical notes written by JM Burgers himself in 1962. These autobiographical notes cover two topics: a first chapter discussing his environment at home and a second chapter dealing with school and university education. In the manner that these autobiographical notes were written, it would seem that they were intended to be followed by additional chapters. However, checking the archives at the University of Maryland, at the Delft University of Technology, and at the Niels Bohr Library of the American Institute of Physics we have been unable to find any additional chapters. Hence, we have concluded that Burgers did not continue to compose a more complete autobiography. We did find a list of names of persons to whom these autobiographical notes were sent in 1962. The only other autobiographical information we are aware of are some memories of his early work in fluid mechanics at the Technical University in Delft that have appeared in the Annual Review of Fluid Mechanics in 1975 [2].

Because of their great historical interest we are using the occasion of the 15th anniversary of the JM Burgers Centre to make the autobiographical notes of Burgers available to the scientific community. The first chapter discusses extensively the influence of the parents on the young Jan Burgers. The second chapter deals with his primary and secondary school education and with his experience as a student and young scholar at the University of Leiden including the somewhat complex interactions with his PhD supervisor, Paul Ehrenfest. We are publishing these autobiographical notes verbatim except for some obvious spelling and grammar corrections.

Acknowledgment

The editors are indebted to Ilse Hoekstein-Philips for transcribing the autobiographical notes and bringing them in a form suitable for publication.

References

1. FTM Nieuwstadt and JA Steketee, eds., Selected Papers of JM Burgers (Kluwer, Dordrecht, 1995).
2. JM Burgers, Ann. Rev. Fluid Mech. 7 (1975), pp. 1-11.

JM Burgers
Autobiographical notes

Environment at Home

I have lived with my parents from my birth until my 19th year, when I left for the University of Leiden. Since the education which I have received at home has had a decisive influence on my development, I want to describe some features of the environment which have acted on my brother and me. To expand this into an actual biography of my parents, with observations on the circle of relatives and friends amidst whom they lived, would require an amount of work much larger than I can afford at this moment, although it would form an interesting story. Moreover, to my regret, there is no record of many valuable details, and often my memory gives only vague indications.

My father was born on October 23, 1862, in Arnhem, from relatively humble parents. My grandfather, whom I have not known, was a carpenter. He seems to have had a good sense of humor and the gift of acting, both matters which my father inherited from him (and my brother afterwards). Father had no more than a somewhat scanty primary school education; later he learned some French and German, and he certainly developed a good style for official letter writing, concise and to the point. From 1876 till 1886 father worked in the Arnhem office of a firm for the dispatch of parcels and goods, where an uncle of him was local director. For some years he lived with his mother in the village of Oosterbeek near Arnhem (walking to and from every day, a distance of about 4 km), and from 1884 to 1886 he also fulfilled the evening service at the post office in Oosterbeek, at the same time acting as telegraph operator. In 1886 he became "assistant" at the railway post office in Arnhem, where the parcel post from Germany was received and subjected to customs inspection. His work was heavy : from 8-12 a.m. and from 1-5 p.m. in the daytime, plus every other evening from 8-10.30 p.m., and every other Sunday morning and Sunday evening, There has even been a period of about l.5 years, when he had to work every Sunday morning, and evening. Free Saturday afternoons were utterly unknown at that time. Often there was work in (unpaid) overtime, when trains were late.

Father has developed himself extensively by reading. I do not know when this self-education began. It seems that in 1888 a friend once sold to him a small induction apparatus (operated with a galvanic pile, such as was used in the old days to produce nice electric shocks), and added to it some volumes of the "Ideeën" by the author E Douwes Dekker (1820-1887), who wrote under the pseudonym "Multatuli". Multatuli, in deeply felt, earnest and at the same time brilliant statements of his ideas, attacked many conventions which stifled society, and penetrated into everything, with an outlook far surpassing that of almost everybody at that time in our country.
These books have opened the eyes of many men and women in The Netherlands; they also did this to father and stirred him profoundly. They must have awakened into activity an already existing urge to understand. Father's genuine enthusiasm grew to such extent that he began to collect more books and also to make instruments for himself, or to buy some parts; he wanted to see what he had read with his own eyes and with his own apparatus. In this he found sympathy and support from some friends,

while also, from their marriage (September 8, 1893), my mother has fully supported all my father's inclinations for study. I do not know whether she came first in this respect, or whether these friends had come earlier, but my mother's wedding present to my father was a good microscope.

Although not being a scientist in the strict sense, my father had an excellent way of explaining to other people that what he had understood himself. He was very versatile in performing demonstration experiments with his instruments, and he started to give series of popular lectures on various subjects, a course in electricity being foremost. Again I regret not to have data about the way how it began. Apparently, father originally had been reading sections from Multatuli's works to members of a society of freethinkers "De Dageraad" (the Dawn); he had a good voice for reading aloud and for speaking in public; he always took his hearers in. I think that this was connected with his sense for acting, and also with a sense of fairness and of balanced criticism (he never became a hero worshipper).

I cannot reconstruct how father's lectures started as a more or less regular feature in the family life. They were of various kind: sometimes public lectures upon the invitation from an educational society, or a school, or from just a group of interested people, relatives, friends or other acquaintances, people from intellectual circles, or some old ladies of the aristocracy who took an interest in science. Lectures were also given in neighbouring cities, requiring a lot of preparation for the transportation of the instruments. From about 1908-1938 each winter in Arnhem father gave about half of the series of "Popular Lectures" arranged by the local Physical Society, lecturing on seven or eight consecutive Sundays from 7 - 8 p.m., before an audience of simple people, who were very devoted to father and felt the spell of his words and his experiments.

The main subjects of father's studies and lectures were elementary electricity, "static" and "galvanic", as it was then called; the microscope as an instrument, with its history; the microscopic living world; astronomy; geology. Every lecture was carefully prepared beforehand. For many lectures father also made extensive collections of slides (mainly reproductions from illustrations in books or periodicals; also from microphotographs which he had started to make, and photographs from specimens of his collections). This was done in the spare hours and the free Sundays which were left to him by his work at the post office, and my father often has said that doing this, notwithstanding the heavy work at the office, was the one thing which has kept his mind open and has protected him from becoming depressed.

It is true that the subjects mentioned looked more simple in those times than they do now. But it should also be kept in mind that many qualitative demonstration experiments can be extremely interesting to all kinds of people, if well explained. We enjoyed very much the whole “physique amusante”, which developed from experiments on static electricity. Father first had one Töpler-Voss electrical machine (acting on the induction principle), with glass disks, for producing sparks. This machine was transported in a wooden box to every place where lectures were given. It was operated by hand - how often was it my task to turn the handle for the demonstrations. Later on, a second one was acquired, and then two Wimshurst machines which were more powerful. One of these had four glass disks, and could be operated only during frosty winter days, when the room was heated and the air was dry. It gave sparks of 19 cm length, which we sent through large pieces of quartz or through crystals, in order to see the reflections illuminating the whole piece. With this machine we also could work an X-ray tube which father had received from a doctor, as it had become too hard for operation by the then existing induction coils (at that time we had no idea of the danger which may arise from radiation!).

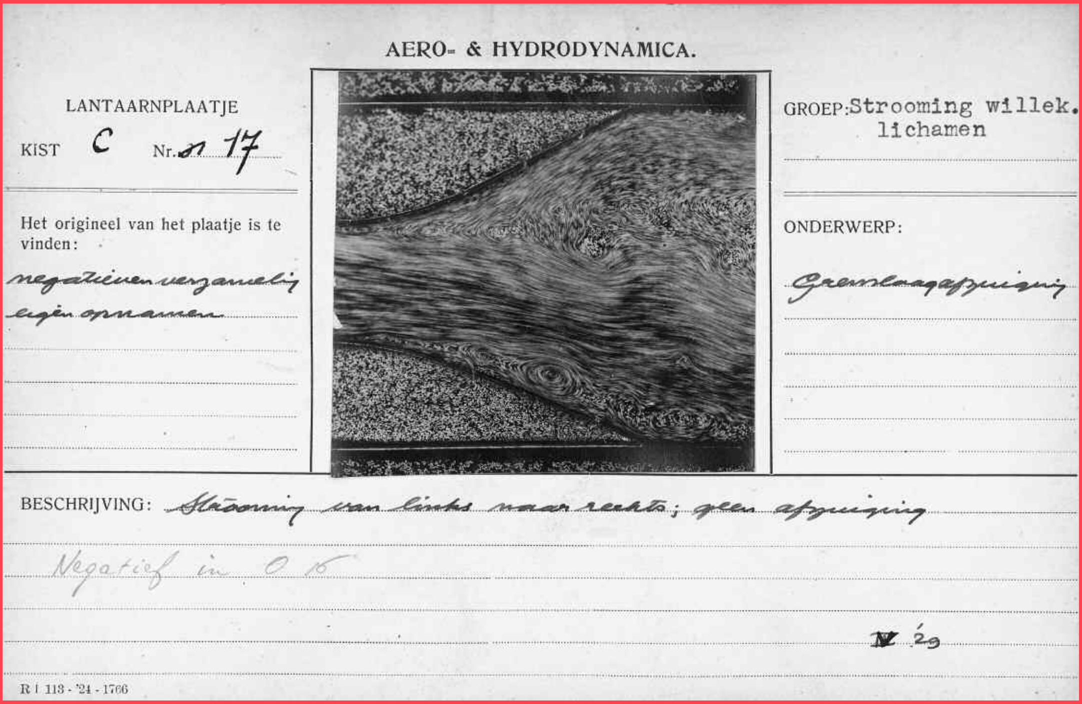
We had numerous Leyden jars, and also so-called “Franklin plates”, capacitors made from a piece of sheet glass, with tin foil on both sides. Often one side was cut up into numerous little pieces, so that one could see the small sparks between them during the period of charging, and then a very bright spark, beautifully ramified, at the moment of discharge.

There were also many Geissler tubes, for the discharge through rarefied air, with coloured glass bent in various shapes. We had galvanic batteries (father mostly used those which have a mixture of diluted sulfuric acid with potassium bichromate as electrolyte). Father made himself galvanometers with so-called “a-static” needle systems, which were suspended from a thread of unspun silk, obtained from silk worms which mother reared during one summer. Electroscopes were a specialty as well. The point of glory of the course was a demonstration of wireless telegraphy, with the Branly coherer as detector.

As far as I can remember, there have been many books at home, though often bought second hand. There was also a collection of minerals and later on there were shells; mother sometimes found an odd collection on the market place, left over from a sale of furniture. My father even gradually brought together a collection of historical microscopes, (again mother often was a great help in acquiring valuable items); after his death this collection has been presented by my brother and me to the Government Museum for the History of Science in Leiden.

As I mentioned, my father’s interests in these subjects were supported not only by my mother, but also through the presence in Arnhem of several friends with similar interests. They often worked together. Also father’s acquaintance with a very good instrumentmaker helped him greatly during many years. I still remember the building of a large Ruhmkorff inductor, on which one of father’s friends (still alive at this moment, February 1962, aged over 80 years) cooperated for many months, but it did not develop the power father had hoped it would give.

Usually there were many discussions between father and his friends, on a wide variety of subjects. Since these friends at the same time were good friends to my brother and me, they have performed a significant part in our education. For instance, they helped us with our playthings, with work in cardboard, wood, or other forms of handicraft, with drawing and sketching; and further with intelligent information and advice on many subjects.



AERO- & HYDRODYNAMICA.

LANTAARNPLAATJE

KIST C Nr. 17

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GROEP: Strooming willek. lichamen

ONDERWERP: Grenslaagafzuiging

BESCHRIJVING: Strooming van links naar rechts; geen afzuiging

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A so-called “Lantaarnplaatje” a former slide of the current dia-projector

Nearly always there was a microscope on my father's table. From our youth we heard about the strange world of life which is found in water. Once we had an aquarium and saw the making of a floating nest by the spinning water beetle, and the metamorphosis of a dragonfly. Father had various books on natural history, and amongst them there was Ernst Haeckel's "Kunstformen der Natur", with 100 large plates of beautiful representations of animals and plants, in particular the microscopic ones : Radiolaria, Foraminifera, Diatoms; various types of jellyfish and polyps; and many others.

During the summer we made many walks with father and mother in the surroundings of Arnhem, which have always been very beautiful, and which at that time were still much more free and unspoiled than they are now. We looked for interesting stones, and often found pebbles with fossils.

Father's mind was directed to clearness in thinking. At the same time it was, what I would call, "integrating", seeing things together and trying to understand their relations. Although attentive to details and to their meaning, his mind was not analytic in the sense that he felt interested in precise distinctions and divisions for their own sake. His interest moved easily from the wonders of the microscopic living world to the stars and their immense distances, or to demonstration experiments in electrostatics or galvanic electricity. At the same time he was a good talker, who liked a joke and who could take jokes, and he was a good actor. He could entertain, with often sparkling conversation, our many relatives and acquaintances, who came to our home for friendship and conviviality.

My father implanted in me reverence for the wonders of nature. I have inherited his desire to see things together, as well as his broadness of interest (I went even further than he did). I have always been an absorber of knowledge and one who likes to reproduce thoughts in a re-arranged form trying to bring out some general point of view, more than one who continually probes for new relations and tries to make discoveries. I have gone more "into the breadth" than "into the depth". But I can witness of the joy which results from understanding and from a wide area of interests. What knowledge I have, has always been for me something to live with - it is a part of myself.

On the whole, father's inclination was "descriptive". I may also characterize it as "constructive" or "educative", as opposed to breaking down a lot of ideas by continual criticism. His was a mind sustained by reverence for what could be known. In his work, both at his office, and at home, for instance when he was engaged in making some pieces of apparatus, or cleaning some instruments, he was methodic and precise, with the need to finish things well and never to leave loose ends. He did not like things lying around in disorder.

In political matters his attitude was liberal, and he felt attracted to socialistic ideas. Being a simple civil servant in a subordinate position, he did not like to go far. Also he was aware that usually there are many sides to each problem. He was not a member of a party, nor of a church. He did not feel the need for close association with others, nor the need for faith in a personal God. He stood on his own, like my brother and I learned to do. Father never used the notion of sin. The Bible was put away from us, as father and mother judged that it contained matters which are not fit for children's ears. We had no religious education in the customary sense, but we were imbibed with responsibility and mutual faith, by the atmosphere reigning at home. It was only much later, when I was a student in Leiden, that a chance remark by Ehrenfest, who once read to us Tolstoy's comment on Joseph's capitalistic activities in the service of Pharao, made me aware that one could look at the Bible from a point of view which had connections with current topics. My interest in it came later from the side of ancient history, when a modern translation of the Bible had made its contents much better accessible.

To come back to my father's attitude, he knew that we have to face the consequences of the deeds of other people as well as those of our own deeds, and that we must carry the burden together. Never would my father have said "why must this strike me?" He bravely accepted his share in troubles and disaster, and did not think himself as separate from his fellow men in this respect. He was never afraid of death and saw his end coming as a rest, for which he longed after the terrible experiences of the last year of the second world war (he was nearly 84 when he died on August 8, 1946). He did not ask for assistance from a minister, being true to his own ideas until the end. In all this my father was not dogmatic. Perhaps it was sometimes more a fancy than a reality that he believed always to be open for argument, but he certainly taught us to be open minded, and I know that the best teachers for young people must themselves have a strong belief in what they say. As to me, I am too often aware of all the complexities and alternatives which are present in any situation, to be a successful teacher of young people. I am apt to explain too much and leave the burden of the decision to others.

My father was always honest and scrupulous in his dealings with other people. That this formed a part of our education, will be understood. He taught us respect for the civil service, which is needed to run a country, as well as respect for our teachers. He had an aversion for anything that was showy or pompous, or even purely ceremonial, in which he could not see himself as a performer. Perhaps there was an element of shyness in this. Nevertheless, he took care not to hurt anybody, and he was not attracted to the role of a fighter. But he was carried on by a sincere idealism and respected all mankind as forming one great community. Our education was not directed towards patriotic feelings or towards some conventional loyalty, but towards a cosmopolitan outlook. We never were taught to consider a symbol as more important than humanity. The best of father's friends, those to whom we owed much in our education, shared these ideas. How great a shock came to all of us in August 1914, at the outbreak of the first world war, can perhaps be imagined.

I have kept from my youth an utter lack of feeling for ceremonial performances. In certain respects I am more reticent than my father was, who could be very convivial.

Sometimes I can understand (on theoretical grounds) that a form of ceremony will add to the meaning, say, of a reunion of people who have come through a struggle together, as was the case in The Netherlands just after the liberation in May 1945. On such an occasion I might even be able to express in words something of the thoughts which bind us but on the whole I find it difficult to see myself as a part of it. Also, for giving a speech, I am apt to be too concise, too brief;
I cannot elaborate on such matters.

We had music lessons, piano, and for my brother later the violin (father and mother used to make some music long ago, when we were small children). I have never learned to dance, and connected with this in some way is that I cannot give myself with ease to something in which emotional feelings would take the lead over thinking. I sometimes have the feeling that when I should become very angry with somebody,
I might loose my selfcontrol.

So far in these pages I have mentioned my mother only a few times, but it must be understood that there has been a deep reaching influence from our mother's side in the development of my brother and me, which, however, is harder to describe than the influence of my father. Mother was three years older than father, being born on October 5, 1859. She came from a family with some intellectual standing. It was a tradition in her family that in every generation there was one who studied theology and became a (protestant) minister. A cousin of her, whom I have known quite well, was doctor of medicine and had the position of inspector of public health in our province; he visited us from time to time and often talked with father about micro-organisms. A brother of my mother was surveyor. And mother herself, although her school education had not been much more than that of father, had a very intelligent mind and was clear in her thinking.

Mother made the home to be the place where it was safe for us to live, and where all our relatives were glad to make frequent visits. The fact that my father and mother lived in a way different from others, did not set them apart. And though amidst our relatives we were materially the poorer, I think most of them sensed that in our home there were things which were not so richly present elsewhere; interesting talk by my father, who was liked and even admired; things to be seen and heard; and hospitality and sympathy from my mother, who was a lady in every respect, who attracted everybody by her natural distinction and charm. She always had tea or coffee for everybody. She ensured that there was an atmosphere of comfort for those who visited us.

My mother was deeply devoted to father and to his ideals; she helped him fully and unconditionally, to such a degree that she sacrificed most of her own feminine desires and ambitions, wishing no more than to live with him and see through his eyes, so that father's program of life might be realized. She gave great care to our household; everything was attended to and all was neat and clean; she worked hard, and, as far as we could know as boys, everything ran smoothly. She was very apt at needlework and had been an assistant in a shop for needle work and the like, during several years before her marriage. The meagerness of my father's salary made it necessary that she sometimes undertook embroidery work for others (she embroidered the gold lettering on several banners for a corporation in Arnhem for scanty payment, as none of these corporations were rich). With all this she kept a definite refinement in our style of living, and always had a keen interest for everything that reached us. It is only much later that I have understood something of the sacrifice our mother has made. In the picture which settled in my mind, the image of my father, who certainly was an exceptional man, takes such a large place that it puts my mother somewhat in the shade, but she also was exceptional.

During many years my mother, who had a good handwriting, wrote a great deal of the notes which father used for his lectures, and she took part in the things on which he was working. This had been a constant great joy to her in those years. Later on, much and gradually all of this work fell upon me, and partly also upon my brother (we often made drawings for father's lectures or helped in the making of instruments). Mother then lost her place at father's table, opposite to him; that became my place and she remained more in the other room, the living and dining room.

To give some idea of my mother's influence, I would mention that father was not deep emotionally. He even had a certain intellectual limitation (perhaps a characteristic of the later part of the 19th century), which took for granted that reason would pervade the world. He was not aware of the possibility of far reaching mental strains, for which he had no understanding. Emotionally mother was a much deeper personality, though she forced herself to suppress much of this. I believe it is from her that I have inherited a desire to look for something beyond the evident outward appearance of things, in particular when I am moved by a landscape. I cannot find back where this originated, although I have some recollection of the enthusiasm mother could express when she saw a view which extended into a distance and suggested depths beyond human reach. Mother also loved flowers and could be very much impressed by the unexpected find of a wild flower. These strands of feelings have come to some fruition in myself only later, through influences of my first and of my second wife, but the roots certainly go back to my mother. I still am moved by a view through trees, a little violet in a forgotten corner, the call of a bird, the stars - these are the privileges which one can enjoy as a pedestrian who can look around and listen. My brother has been deeply impressed by mother's personality; I think that in his case it is her image which always comes first.

As a child my mother had received a religious education, but she abandoned all connections with a church through father's influence. She often told me that she had known the feeling of missing something, the singing in particular, which can be so helpful to give a certain outlet to one's feelings. She often told us about her youth - owing to the early death of her father, she had spent some years in an orphanage; she spoke about the boys she had known, and about the minister who gave religious instruction and for whom she always retained a great respect.

Most of our relatives were on mother's side, and there were many nice and convivial people among them. I must mention, however, that father had a sister, five years older than he, who was a widow from the times from which I have recollection. She lived in Arnhem, not far away from us, and my brother and I (and also the boys about whom I shall speak later) visited her often. She loved all of us and spoiled us sometimes a bit.

As I mentioned before, I have been educated without any church connection. It is only later in life that I developed interest in religious matters and obtained some understanding for their importance. I cannot believe in a personal God and I never feel an inclination to pray. What I possess as religious feeling probably comes from my mother, although there is in it a part derived from my father's idealism and, if I may say so, from his mental courage, reinterpreted in a way which grew up in my own mind. Here in this country (the United States) my wife and I have become members of the Unitarian Church in College Park.

When father had to retire from the post office in 1913 as a consequence of insufficient health (he had twice suffered from pneumonia, and was overworked by the heavy work at the post office and troubles with the customs people - father, belonging to the postal service, had to act in the interest of the addressees of the parcels, whereas the customs officers acted for the government), his pension was small.

Our household, however, was held up by the fact that several boys boarded with us, for a part boys whose parents lived in what were then The Netherlands East Indies, where secondary school education was scarce. The first one of these boys had come already in 1904. Father also received some money for his courses, but that was not a large sum, and would have been grossly insufficient for the household. Moreover, part of it served for buying instruments and appliances. About 1913, I myself and my brother were already earning some money by giving help and advice to other pupils of the secondary school, who could not keep up with school and home work.

Father was considered to have a good influence on the education of children and he gave much time towards taking care of their school work and their behavior.

Father loved children and could keep discipline, without becoming too exacting; he could be very playful and always had attraction for them. This now formed one part of his occupation, the other part being his own studies and his lectures. In retrospect I think that father's attitude with regard to child education was somewhat naive, and directed exclusively to the intellectual side and good behavior. Father certainly had a good influence upon children but he had no deep understanding for difficulties from which children may suffer. I must observe that in that period, now 50 years behind us, educational problems on the whole did not go as far as they reach now; life still was somewhat simpler and children were more inclined to accept discipline. What I must stress is that the burden upon mother was very great. She also gave her love to all the children, in particular to the first ones who came, and both father and mother did their utmost not to make any difference between us (my brother and me) and the other children.

But we had scanty domestic help and there was a lot to do in cooking and in taking care of the house, in mending clothing, etc. Domestic appliances were much less efficient than they are now, and always the amount of money that could be spent had to be calculated. Moreover, it was mother who always first felt the impact when we boys were quarreling or fighting. It also was mother who carried on the correspondence for the parents of the children (who lived in the East Indies) and who mostly talked with teachers or the principal, when there were difficulties with the progress of the children at school.

(I may mention that also when we were away from home at the university, and later when we were married, it was mother who always wrote letters to us; father's contribution usually was a loving greeting with the words "mother already has written everything").

As I mentioned, the first boy from the East Indies, AFE Jansen, came in 1904; his brother, JV Jansen, came about 1907. Their coming has had a very important effect for my brother and myself. Before this, the highest position on the social scale which was seen for us, was to become a schoolteacher (some of our female cousins, who were rather bright, went that way), or perhaps a surveyor or something like that. However, the father of these boys desired them to go to a secondary school, and as the first one did not differ much in age from me (he was 10 months older, but we were in the same grade), it then became possible that I should go with him, and that my brother should follow in due time. This was a first step ahead. It then happened that teachers and the director of the secondary school gave advice and help, and gradually it became understood that we might look forward to scientific studies.

The two boys Jansen whom I mentioned, have become very close friends to my brother and me. The older one has studied mechanical and electrotechnical engineering, and for many years has been conservator for metallography at the Technical University in Delft. He took an important part in the programming and arrangement of the new laboratory for metals which was opened in 1961, where my brother now works. The younger brother is now acting director of the Museum for Ethnography in Rotterdam and has an extensive knowledge of Western American Indian peoples, and of the peoples of Polynesia. Both of them have more than once expressed their indebtedness to our parental home. I am sure that also the other boys, and the two girls who later on have lived for some years in our parental home, still think back to those years with much pleasure and gratitude; in this home everybody got something which he could take along for his life. The last boys left my parent's home about 1926. For father and mother there have then been some quiet years, which they have both enjoyed. Also my mother found much pleasure in this period of freedom. I believe she still has taken care of a collection of butterflies which somebody had presented to my father. In the fall of 1929 an illness manifested itself, which became more and more serious, and which has clouded mother's last years. She died in October 1931.

Since then my father lived alone with a lady housekeeper, amidst his collections and his friends, and we regularly visited him. In 1940 came the disaster of the second world war and the occupation of The Netherlands. Father could manage, and we still came to him each year for many short periods - until the airborne American attack upon Arnhem in the fall of 1944. Then father and his housekeeper were evacuated. For three weeks they straggled around; finally they were picked up through the Red Cross and we could bring them to Delft where they stayed with us until August 1945, after the liberation. Father then returned to his house in Arnhem, with his housekeeper, but much had been destroyed and parts of his collections and instruments had been stolen (the collection of historical microscopes had been rescued through Government services). Much of the city was gone and several of our friends were no longer alive. Gradually father's forces diminished, from a kind of bodily and mental exhaustion until the end came in August 1946.

I will insert here three quotations from letters which my brother and I received after our father's death.

(From Dr. B Meylink, principal of the secondary school in 1948, and teacher of physics in the years that my brother and I were pupils there) :

"I never met anybody, not even amongst the very greatest, who had such a genuine enthusiasm for the natural sciences with respect to all new things which were discovered and to all new points of view which came to the foreground. He was so full of admiration for the grandeur of nature and the infiniteness of the universe, that it gave warmth every time you heard him speak about it."

(From Professor dr. AA Pulle, professor of botany at the University of Utrecht, who was born in Arnhem and had known my father when he - Pulle - was a boy) :

"During the last days I have thought rather much of the old times when your father and mother lived in the Gravenstraat, where the oldest of you was born on a winter evening. It was on the 13th of January; it must have been about 1895. A short time before I had made your father's acquaintance. At that time he had a primitive microscope (it must have been a good microscope, the one my mother had given to father, from the firm of Reichert in Vienna, Austria - JMB) and with great enthusiasm he looked for all kinds of micro-organisms. It was then that for the first time I saw diatoms (I am inclined to believe that this has been of influence on AA Pulle's later career; he also came from a modest family, were the mother, a widow, was teacher of needlecraft at one of the schools in Arnhem; she was a friend of my mother - JMB). Afterwards he has moved to a different quarter of the town, and then turned more to physics. The man was a wonder; what has he not attained with simple means and how great was his rare enthusiasm. My oldest boy, who came back from the East Indies a month ago, once stayed for a week in your father's home when he was a pupil at the secondary school, and even now he still could tell about all he has seen and experienced during that week."

JM Burgers at his farewell reception (1955)

(From Professor dr. JH Oort, professor of astronomy at the university of Leiden and a great friend of my brother and to me) :

"I have always felt a great admiration for your father. As I wrote already to your brother, I felt in him something of that which the apostles must have possessed, a an inner, simple, but unbreakable, strong faith, which radiated through the whole of his life so far as this was visible to me. There was no other such a man in Holland."

I will attempt to give an impression of my parents' home as it must have looked to a visitor. To my regret my memories no longer are precise. In August 1944 (now almost 18 years ago) I saw it for the last time in the state it had been for a long period. But during that period I had not looked at it with fully the keenness of interest it deserved. Since I had left home for the University (October 1914), there gradually developed differences in outlook between myself and father. This was a natural result of the expansion of my horizon and of interest in matters where I wanted to think independently. Also I married; my wife and I were very close in our thinking; we built our own life, and while father felt very strongly bent towards me, I had the need to be more detached from him. The same was the case in my second marriage, after the death of my first wife. When we came to Arnhem and stayed with father and mother, or, after mother's death, with father, it still was a very interesting environment, but I did no longer feel it as my environment, and even the collections of instruments, of minerals and shells, were no longer in the centre of our interests. We also knew that it would be impossible to find room for all these treasures either in our house, or in that of my brother and his wife. I have no recollections of the apartment where I have been born, but I remember much about the one to which father and mother moved in 1897. It was an apartment on a second floor (American reckoning), without a garden, but with an attic. Much of father's work was developed here, and I believe that here also began the cooperation with his friends. As long as I have known there were already many instruments for electricity, at least two microscopes, books, and some minerals (although at that time father did not know much about them). Much of father's photographic work started here. In 1906 we moved to a larger apartment, which had a basement, living rooms on the first floor, and bedrooms on part of the third floor and the attic. There was a small garden, although without much sunshine, but still so that mother, who loved gardening, could grow some flowers.

We lived there until 1913, and it was in these years that father's activity was at its greatest. In 1913, when father had already a leave of absence from duty as a result of insufficient health, father could buy a house with the help of some friends who lent money; this house again had a basement, a first floor with two large rooms and a smaller one; a second floor with two large rooms and two smaller ones; and a third floor with bedrooms and an attic. The kitchen, both in this house and in the previous one, was in the basement; when we had dinner in the living room, everything had to be carried up, while the dishes had to go down again (there was no kitchen elevator).

The 1913 house had a little garden which was better situated than the former one, and mother enjoyed very much that she could do more in it.

When a visitor would come in, in the 1906 house or in that of 1913, and was ushered into father's study (the front room on the first floor), he would see himself at once amidst cabinets with various instruments. Rooms in houses of this type in Holland had high ceilings and fairly large windows. In the middle of the room there was a large rectangular table; father had his chair on one side of it (opposite to the chimney; other chairs around the table were for us or for the visitors. Behind father's chair against the wall there was a large double set of bookshelves, with many books, and also sets of drawers with mineral specimens or shells, for which I had made the little cardboard trays and the labels. On the bottom shelf stood many boxes with father's slides (old standard size 3 / x 3 / inches; total number over 1000).

Against the other wall (to the left and the right of the chimney) there were two cabinets with instruments. I believe one had as its lower part a set of large shelves, where drawings and prints were stored. Between the two front windows (to the right from father's chair) stood a (Töpler-Voss) electrical machine, in a casing by itself. Father was accustomed to let it run from time to time with a hot-air motor, to produce little sparks "in order to have ozone in the room" which father believed to be refreshing. Somewhere around were pieces of quartz with crystals, and boxes with glass covers, containing minerals and fossils (other specimens were stored in a room in the basement. On the table there often was a jar with ditch water containing algae, the common polyp (Hydra viridis), daphnias and other microscopic living beings, and also a microscope. Sliding doors (to the left from father's chair) connected father's room with the living room, where mother usually sat. The sliding doors were closed when father gave a course, and a screen for projections could be unrolled before these doors. Sometimes the projection apparatus had a fixed place on the table ready for immediate use; later on, it usually was put aside and had to be brought out for the occasion. A large map of the Moon, in a frame behind glass, hung above the mantelpiece (opposite to father's chair), which map I had made for father. As it had been too much work to put in all the lunar craters, it contained only a selection; but it had all the maria, coloured in red, and at that time I was rather well versed in the geography of the Moon.

Suspended from the lamp (above the centre of the large table) was a magnetic needle which could swing in the vertical plane, indicating the inclination of the Earth's magnetic field. At times there stood on the table a little motor with clockwork for rotating cardboard disks on which we had painted all kinds of designs; these merged together for the unaided eye when the motor was speeded up, but presented a variety of interesting patterns when viewed in the darkened room by the intermittent light of a Geissler tube, connected to an induction apparatus with hammer interruptor. Somewhere a Crookes' radiometer was rotating, when the Sun shone upon it.

In mother's room, the living room, there was also a large table (for many years we had an oval table there), for all the boys who sat together at meal times, or were busy on their schoolwork. Along one wall there was a sideboard, and against the other wall, on both sides of the stove, some cabinets with mother's books and treasures (mother had a lovely little collection of exotic teapots), and the piano. The mantelpiece had a large mirror, and there were some pictures on the walls. From this room sliding doors led into a veranda or porch, closed in with glass, where mother had many flower pots, and a table at which she could sit in the summer. There was no room which mother had just for herself. From the veranda, steps led down into the garden.

The visitor, after having had tea from mother, then was taken upstairs (this refers only to the 1913 house), to be shown into the "museum room", which was above father's study. Here a lot of other instruments were on display in glass cabinets. There was the collection of historical microscopes, which included a hand microscope made by Musschenbroek in the 17th century, which father had rescued from a basket of rejected instruments from the old Physical Society in Arnhem (this Society had come into financial difficulties about 1902, and its collections were sold, mainly to the secondary school in Arnhem; but there were "left-overs"). There was also a large "solar microscope" and several instruments from famous 18th century and 19th century makers. In 1913, if I am not mistaken, father had bought, on a sale, a collection of acoustical instruments, with organ pipes, Cagniard Latour's siren, tuning forks of all sizes and pitches on large wooden resonant boxes, Helmholtz resonators, an apparatus to show Lissajous' figures with the aid of oscillating bars having various cross sections, etc. But we never have become at home in acoustics as much as we did in electricity, as this collection came when father, although still very active, was somewhat over the height of his desire to absorb new domains.

There were also various "curios" and in later years father often was presented interesting objects by acquaintances. There was, for instance, a tusk of a walrus with beautiful carvings, which had come from Eastern Siberia (Nizhny Kolymsk), and a collection of pieces of amber with insects (both of these are now in possession of my brother). There were many pieces of agate, cut and polished; a beautiful cameo shell, a set of ivory chess pieces, but much of this has been stolen during the period of evacuation of Arnhem. There were also interesting old books on shells (I once bought a whole set on a book sale in Leiden), and a copy of Rumphius "Ambonese Rariteitenkamer", a famous book on marine animals and shells of the East Indies, printed in 1705 (most of these books are with my brother now).

The room on the same floor above the living and dining room in the 1913 house, was the study room for the boys. On the third floor were the bedrooms, although father and mother had their bedroom on the second floor in one of the smaller rooms. Cold water came to the second floor (in the 1906 house it came at first only in the basement; later a tap was installed in the corridor on the first floor.

Water had to be carried up and down to the bed rooms on the higher floors. How much household work this meant, can be imagined. Mother had some help, and we, as well as the other boys took part in some chores, but this was not extensive. To come back to father's study, I do not remember where the big Wimshurst electrical machine stood with its four glass disks. It has been sold, like some other instruments, to a school in Eindhoven, already much before 1940. Little electrical motors of various sizes, steel magnets of various dimensions, electromagnets, galvanometers, induction coils of the Ruhmkorff type with hammer interruptor, Leiden jars, Geissler tubes, all such things were to be seen. During the years before 1931 the source of electric currents was galvanic piles, Leclanche for weak currents, and potassium bichromate plus hydrosulfuric acid when stronger currents were required. The mixture had to be prepared periodically, which always needed great care in mixing the acid with water. Some months after we had moved to the 1913 house, we got electric light (there was not yet a cable through the street, but it was put in, just for this occasion); we then could use lead accumulators, which were charged by inserting them into the circuit for the light. We also used a set of old fashioned carbon filament lamps, which admitted one Ampère each. It will be understood that father always had lots of auxiliary materials, tools, nails, screws, tin foil, copper wire of various thickness, ebonite, paraffin wax, wood, paper in various sizes, and all kinds of odds and ends. Father never could reject anything which still might turn out to be of some use.

After father's death, in 1946, my brother and I had to clear the house rather in a hurry, as it had to be sold so that it could be used by other families. There was much we had to throw away; in a sense this was a tragic end, but the more important objects which still were there, got appropriate destinations. Our own houses were not capacious enough to store all the objects (and sometimes the junk) which father had collected; moreover, both of us had already stored much in our houses. Some books and a few instruments were sold or given to father's last friends. The collections of minerals and shells went to our secondary school. The most important books were kept by us. The furniture was old fashioned; there was much which people nowadays did not like to use, or could not use, since modern houses do not have such large rooms with high ceilings. So the house came to an end - it still lives for a large part in our hearts.

There still is a point deriving from my father's influence upon me, which I could mention here. I have said that he was an excellent teacher. He had a healthy naturalness and soundness about himself, and he never sought to overawe anybody by a show of learnedness. He always genuinely tried to make others see what he had understood himself, and knowing the difficulties he had had to overcome in this he had understanding for those of others. The courses he gave, started in our home. It was his gift to explain phenomena, say of electricity or of light, to people who were not educated in physics. He did this from a desire to communicate to others the joy he had found himself in mastering any topic. For this purpose it was not necessary to go to far outlying fields : joy of understanding is possible with respect to the simple beginnings of a science. And the people around us liked to understand. They came to father for that purpose. My teacher of classical languages, for instance, liked to listen to explanations and to argue about them.

There were at that time a number of scholarly educated people in Arnhem and its neighbourhood. Many of them were members of the local Physical Society, or of the local branch of The Netherlands Society for Natural History. At the meetings of these societies we could often listen to very interesting speakers, for instance on radioactivity, or on the formation of the coal fields, and I still remember that once the reversal of the yellow sodium line was shown on the screen with a projecting spectroscope. There were also certain gentlemen who had extensive collections of butterflies. Others did biological experiments. The circle of people amidst whom my parents lived, including our relatives, would deserve a special description.

There was also available a good collection of serious popular and semi-popular books and journals on scientific subjects, some of them translated from the German, others original productions by enthusiastic writers and editors in Holland.

When I came to the secondary school, I gradually began to catch up in knowledge with father, and then got beyond him, as the secondary school brought algebra, geometry, trigonometry, etc, and a fuller course of physics (and chemistry) than my father had mastered. But father still was studying himself, and we were in the habit of talking about what we had read and arguing about it. A great event for us was the appearance of a very good translation of RK Duncan’s book “The New Knowledge” (1908), which opened our eyes to the phenomena exhibited by ions and electrons, and to those of radioactivity. It was a kind of revelation to us, bringing a lot of information and order concerning topics about which we had heard only in a vague way. We then learned how one progressed from Geissler tubes for electrical discharges to tubes exhibiting cathode rays, and father soon got a whole new series of demonstrations under way.

Later on, when I got ahead of father, I still sought to translate my further knowledge into terms which could be captured by him. This remained so, when I came to the university and learned about quantum mechanics, then in its first stage, with Bohr’s electron orbits around the nucleus. It came to my mind that a layman has no difficulty to accept that there exists only a set of discrete orbits. The notion of classical mechanics, according to which every orbit should be possible depending upon initial conditions, is rather an anomaly for a logical mind, looking for order and not having been subjected to training in differential equations.

The experience gained in this way has given me the conviction that every term, every notion and every equation used in theoretical physics, belongs to the set of ideas which are common possession of all intelligent and interested people.
Every physical notion is linked to other notions and these again to further concepts, and ultimately they have all arisen from the desire to give an interpretation of concrete observed facts. It is only the extreme length of the chains of reasoning, which cause the difficulty for a mind not trained to absorb such chains and not acquainted with the

$$u_t + u\,u_x = \upsilon\,u_{xx}$$

The famous Burgers' equation

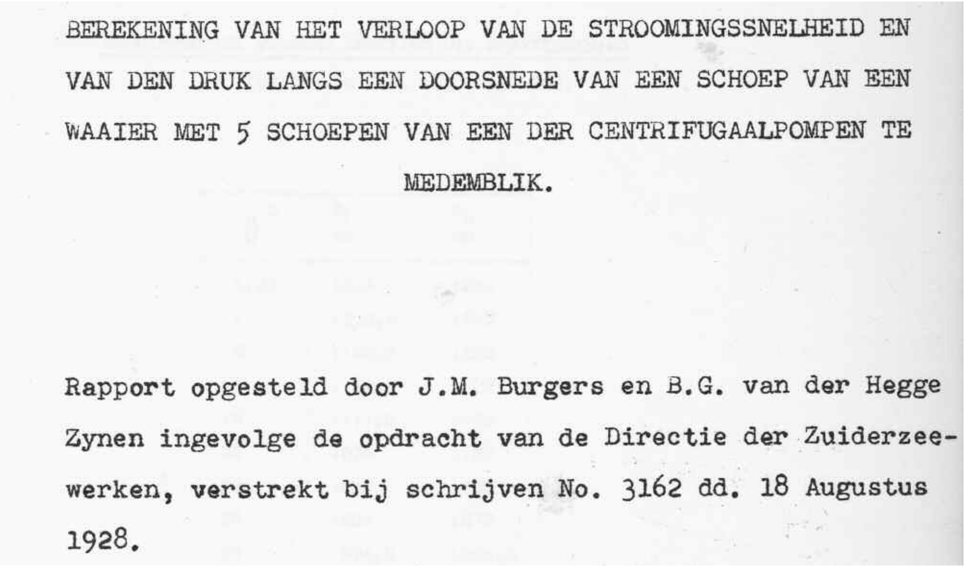
mathematical way of presenting chains in shorthand form. For a physicist working in the front lines it is often too cumbersome to look for a translation of newly conceived physical notions into common terms. Nevertheless, I believe it should be the task of every scientist to give some attention to the translation of his concepts into terms which make their meaning clear to non-specialists. The ultimate object of science is not its use for technical performances. Its ultimate purpose must be to expand the world picture shared by a large group of people, and to bring to them the joy of understanding. At the same time we should take care to point out the limitations involved in the scientific picture, resulting from its abstraction from values which sets it apart from much that is contained in life when viewed in its fulness.

Before closing this chapter and passing to school education, I would look back once more towards the atmosphere of clearness and of reasonableness, which we believed that existed before 1914. I mentioned that we made many walks around Arnhem; there was a connection between what we received at home and what we enjoyed in the open air. It laid the foundation for a deep love of the Earth and of the life its carries. It was a time when public transportation was measured to the needs of the excursionist and the pedestrian, when there was much less traffic and far less noise on the roads and when there was not yet the terrific expansion of the population, in numbers and in mobility, leading to the deterioration of the countryside by continuous building of new groups of houses, of roads for heavy traffic, or by “opening up" recreational areas.

Something of the atmosphere of this period is pictured in a novel by JB Priestley, "Bright Day" where also a group of old and young people is described who liked to walk. Much of this background of our life vanished with the first world war, although parts of it still could be recaptured in Holland for many years after 1918.

Both with my first wife and with my second wife I have often come back to Arnhem and again we made long walks. With my second wife, during the years "1942-1944", I even got a much better idea of this part of the country since we covered larger distances and had maps who explained the character of the landscape and its geology. Some parts of the country around Oosterbeek even now are still as beautiful as they were 50 years ago, as I saw on a trip with my brother in May 1961.

But it is a curious experience that I believe to have found in America, for instance in Maryland, some of the features and the moods which I absorbed in my boyhood. When coming to the new continent, I have kept open the "eyes of discovery", as an explorer who is elated by the landscapes and the new kinds of flowers amidst which he now can move around. This is a constant joy to me which makes me feel at home here.



BEREKENING VAN HET VERLOOP VAN DE STROOMINGSSNELHEID EN VAN DEN DRUK LANGS EEN DOORSNEDE VAN EEN SCHOEP VAN EEN WAAIER MET 5 SCHOEPEN VAN EEN DER CENTRIFUGAALPOMPEN TE MEDEMBLIK.

Rapport opgesteld door J.M. Burgers en B.G. van der Hegge Zynen ingevolge de opdracht van de Directie der Zuiderzee-werken, verstrekt bij schrijven No. 3162 dd. 18 Augustus 1928.

TABEL III.

LOGARITHMISCHE AFBEELDING VAN DE SCHOEP, OVERGEBRACHT IN DE COÖRDINATEN ξ, η.

θ°	BUITENZIJDE		BINNENZIJDE	
	ξ	η	ξ	η
0,22	+ 175,0	+ 0,8	+ 175,0	+ 0,8
1	+ 169,7	− 2,2	+ 168,2	+ 2,8
5	+ 138,0	− 3,1	+ 135,2	+ 4,9
10	+ 98,3	− 4,3	+ 94,1	+ 7,8
15	+ 58,7	− 5,9	+ 53,1	+ 10,3
20	+ 19,3	− 7,9	+ 12,4	+ 11,9
25	− 20,0	− 10,3	− 28,1	+ 13,1
30	− 59,1	− 13,3	− 68,5	+ 13,9
35	− 97,8	− 17,5	− 108,9	+ 14,5
40	− 136,7	− 20,8	− 149,2	+ 15,1
45	− 176,0	− 23,2	− 189,7	+ 16,4
50	− 215,8	− 24,1	− 230,2	+ 17,3
55	− 256,1	− 23,7	− 270,6	+ 18,0
60	− 297,8	− 19,0	− 310,3	+ 17,0
61	− 306,3	− 17,7	− 318,2	+ 16,5
62	− 315,0	− 15,9	− 326,0	+ 15,8
63	− 323,7	− 14,0	− 333,4	+ 14,0
64	− 332,4	− 11,7	− 340,4	+ 11,0
65	− 341,3	− 9,2	− 346,7	+ 6,3
65,63	− 348,5	− 0,8	− 348,5	+ 0,8

School and University Education

In this section I will speak briefly of influences emanating from school during the period I lived at home; then I shall pass on to the years at the University of Leiden, and the beginning of my career in Delft.

My brother and I had our primary and secondary school education in Arnhem in the city schools. Primary education was from the age of 6 to 12, secondary from one's 12th to the 17th year. The schools were very good. It is interesting to mention that we wrote on slates in the lower grades. I still remember the series of pictures of three quarters of an apple we made when we were engaged upon the multiplication of fractions. French started in the fourth year. We had much homework. I also think of the geography we had to learn, in particular from the European countries: series of mountain chains in France, the system of canals by which one could go from, say, Strasbourg to Paris, and the cities you met along important railroad connections from one country to another. History brought all the wars in which William III had been engaged. We also learned the grammar of our own language, and quite a lot of French grammar, with irregular verbs and the rules for the passé défini and the subjonctif.

In 1907 the older of the brothers Jansen and I passed the examination for admission to the secondary school, the "Hogere Burgerschool", with a five-year curriculum. My brother came two years behind us, owing to the difference of our ages. After we had passed the final examination of the secondary school in 1912, the older Jansen went to the Technical University in Delft, while I stayed at home during two years for an abbreviated course in Latin and Greek, which at that time was still necessary for admission to the other Universities, for which one had to pass a special examination. These languages I learned under the guidance of Dr. F Wolf, a teacher of classical languages at the "gymnasium" or classical school. He was a scholar with a wide interest in literature and he knew Sanscrit. He has never asked any payment for the time he gave me. During the same period (1912-1914) I daily went to the village of Velp to help a pupil of the secondary school with his home work, in order to earn some money; and I studied mathematical and physical topics.

We had excellent teachers at the secondary school. While in those years not directly preparing for university study (although it opened the road to the Technical University), the school furnished a good and extensive all-round education, including mathematics (without calculus), physics, chemistry, natural history, geography, history, literature, the three foreign languages (French, German, English) with summaries of their literary history, economics, an introduction into political science, drawing. We read Molière, Racine and other French authors; learned about Shakespeare, Milton, Dryden, Goldsmith (we read the "Vicar of Wakefield"); and learned about Schiller, Goethe, Lessing and other German authors. Dicken's novels I read at the time with my father in a Dutch translation.

For many years I have remained in close friendship with several teachers and with the principal (director), Dr. H Hulshof. It was later that I learned that Dr. Hulshof was engaged in the elaboration of a kinetic interpretation of the thermodynamic potential. His doctor's thesis had been on the theory of the capillary layer, for which he had proposed the notion that the pressure in this layer was anisotropic. This idea had found much encouragement from the side of his professor, the well-known (older) van der Waals. In some way, however, there had arisen a difficulty about it with Dr. G Bakker, who is better known in the literature for his work on the theory of capillarity. It was Hulshof's conviction that Bakker had heard about it through van der Waals, and had worked it out rapidly and then presented it more or less as his own idea. Knowing the probity and the intrinsic modesty of Dr. Hulshof, I am inclined to believe that he was right. He may have been thinking a long time about this notion of an anisotropic pressure and had been somewhat slower in bringing it into the open, so that Bakker got the start. A curious point is that Dr. Bakker was the teacher of physics at a similar school in the Hague, where my first wife has been a pupil. I became acquainted with Bakker at some Ehrenfest's colloquium; I believe, this was before I knew about the dispute between Hulshof and Bakker.

Our teacher for natural history in Arnhem, AC Oudemans, was a man with great enthusiasm and great knowledge. In his class room he had many collections, minerals, shells, butterflies, beetles, etc. and also cages with various living animals, all of which were kept in an excellent state. During 5 or 10 minutes before he started with the class, we - the pupils - were allowed to go around through the room and look at the animals, or at the collections in their drawers.

JM Burgers at work

Oudemans also had the custom to bring to our attention interesting matters happening around us, for instance, astronomical occurrences, or the capture of an uncommon type of fish in the North Sea, etc.; for this purpose he had a bulletin board with clippings from newspapers or illustrated journals. He himself did scientific work on mites, and he was always busy when there was no class, and after school hours, either with re-arranging parts of the collections, or with the preparation of very fine skeletons, or with his studies on mites. He had also a taste for historical matters, and he wrote a big volume on "The Great Sea Serpent", in which he collected and reviewed all references to it throughout the ages up to modern times.
His many-volume work on mites (the publication of it was continued after his death from his extensive files of notes) started with all historical references to mites, from biblical times to the present. He permitted me to come every week, during an hour after school time, with a box of rock specimens or shells from my father's collection and helped me to find the names, which he either knew by heart or found out by comparison with the school collections. From Dr. Oudemans' textbook on natural history, it was in particular the third part, on mineralogy and geology, which gave much information to my father and me. I remember that a short time after we had bought it, father, having become interested in the characteristics of the six crystal systems, made a set of neat models, from knitting needles (furnished by mother), drinking straws, cut into sections to form the axes, and threads to represent the edges of the main forms, all fitted together with sealing wax - which, as is well known, was an important item in the physicist's outfit sixty years ago.

My teacher of mathematics in the advanced years, Dr. C van Beek, lent me Holzmüller's book on extended elementary geometry. Dr. Hulshof gave me Ch Sturm's "Cours d'Analyse", in which I have been working at the same time that I was busy with Latin and Greek.

Dr. B Meilink, the teacher of physics and later the successor of Dr. Hulshof as principal, who guided his classes with almost no effort and who inspired discipline by his natural and calm way of doing, lent me Maxwell's "Theory of Heat". I can still remember how I was puzzled by the chapter on the "Representation of the Properties of a Substance by Means of a Surface", which I could not understand at that time. Later on he lent me Maxwell's "Treatise on Electricity and Magnetism". As will be understood, this contained much that gave me great difficulties, as e.g. the chapter on spherical harmonics, the title of which made me think of Kepler's harmony of the celestial spheres. Nevertheless, I got much out of the book, for instance, on the theory of electric currents. Dr. Meilink also procured for me a set of lecture notes on mathematics and on physical chemistry from a student at the University of Amsterdam, which I worked through. Further he permitted me to do some practical physics at the school laboratory, as a preparation for university study; this gave me some relief from the course of practical physics in Leiden later on.

We had an excellent teacher for chemistry, Dr. B Holsboer, but although I had dabbled a little bit in chemical experiments, this subject has never attracted me greatly. I was interested somewhat in the formalism of organic chemistry, but all this was long before the modern theory of valence and of the various types of chemical bonds was developed.

At the same time there still was much material for study in father's books. There was, for instance, an almost complete collection of the volumes of a monthly journal "Album der Natuur", which in its later years (it stopped about 1912) brought papers with extensive digests of new subjects in various sciences, for instance, on the phase rule and its application, on colloid chemistry, on the early stages of the mutation theory.

From one of father's friends I got two little volumes of the Sammlung Goschen on metallography, which gave more illustrations of the phase rule and from which I also learned about the texture of metals as revealed by the metallographic microscope.

A volume of the then existing "Scientific American Supplement", which the father of the boys Jansen had sent to us, had articles by RA Millikan on his exact determinations of the charge of the electron. In the journal of The Netherlands Chemical Society the extensive text was published of a lecture given by professor HA Lorentz on the various determinations of Avogradro's number (if I remember correctly, it was mother who directed our attention to it, having read about it in the newspaper).

From another friend I got the money to buy (second hand) the book "Meteorologische Optik" by JM Pernter and FM Exner. In this book I found a presentation of Airy's diffraction theory for the rainbow, to which Pernter had added an extensive calculation of the color distribution, for various droplet sizes, on the basis of a reduced set of Maxwell's color equations. Since father and I were much interested in the polarization of light and its application to the observation of minerals in thin sections under the microscope, I started to work out a calculation of the interference colors which could be observed, e.g., with sheets of mica of increasing thickness. I wrote a descriptive article on polarized light for the semi-popular journal "Der Natuur", in which I gave the results of this calculation. The article was illustrated with several photographs of the structure of granite, basalt and other rocks, made by father with the polarizing microscope, and with drawings which I had made. It must have appeared, I think, in 1913. That I still liked to read on natural history, and in particular on the theory of evolution, will be understood.

We certain made many walks in that period, but I have no specific recollections. It is curious to note that, apart from some very brief visits on bicycle to Emmerich and to Cleve, two cities in Germany close to the border of our province, I had never been outside The Netherlands. We always looked at the international trains coming through Arnhem to and from Germany (often having cars for Switzerland, and sometimes for Genoa or Ventimiglia), and once or twice father made a project with me for a day trip to Köln (Cologne). But nothing came from that. Even in The Netherlands I had seen rather little, some of the cities of our province, not far from Arnhem; we had been several times in Amsterdam and in the Hague, and in a few other places, but that was all.

Although I had read about Germany and its geology, and had been presented collections of rock specimens from the Eifel, from Thüringen, and from Switzerland, I had never seen a mountain and the highest point near Arnhem (about 110 m above sealevel) had been my limit of altitude. Father and mother had made a trip along the Rhine to Frankfurt, with a side trip along the Mosella; and they had been to Paris and to Berlin. I believe all three trips were made upon the invitation of one of mother's cousins and his wife. They told us often about these trips. In 1907 (?) they made a trip to Düsseldorf to see an exhibition of industrial products and machinery. Mother told us about a huge wheel, which went backward and forward alternately and also about the adventures of the return trip; they had taken passage on one of the Rhine steamers (still operating) but owing to fog the boat was delayed very long and they had to sit on the quay for the whole night, and were happy when a booth went open in the morning for market people, where they could get some hot coffee. Their honeymoon trip had been to Brussels and some other cities in Belgium. I have the impression that father had some difficulties with hotels, owing to lack of experience, but they must have seen the famous "Rocher Bayard" near Dinant on the Meuse and the cave of Han on the Lesse.

In May 1914 I had to submit to the medical examination for the military service. Fortunately I was rejected on account of a too narrow measure of my chest. I am very grateful that this has saved me from passing tedious years without scientific and cultural contact in military garrisons, when the first world war broke out in August 1914 and The Netherlands army was mobilized to protect the frontiers (which remained necessary until the end of the war in November 1918). My brother, and I believe also the Jansen brothers, were rejected for their eyesight.

I would add that my education in matters of art was not extensive. We liked to go to concerts and father knew the music of many operas. Some of his friends were good musicians. But father, and even mother, had not much knowledge about paintings. We had been in the famous "Rijksmuseum" in Amsterdam, and in the "Mauritshuis" in Den Haag; but the classical paintings had made little impression upon me. We knew a bit about classical sculpture; father had some good reproductions from the masterpieces in the Louvre Museum in Paris, and our classes in literature and in drawing at school gave attention to art; but it did not come to my heart. It is only later, under the influence of my first wife, that I began to develop more feeling in this direction.

There were some movie theaters in Arnhem to which we went rather often. The foremost of these theaters sometimes had a good scientific film as an item on the regular program. I remember one on the microscopic living world, which was presented very well both photographically and in the way it was arranged. It must have been a French film, in 1913 or 1914, which thus appeared many years earlier than the films which the German firm of Zeiss brought out, to be shown before scientific societies, some years after 1918. In this French film even the strange spherical colonies of the alga Volvox were shown.

Father and I naturally were delighted to see the organisms we knew so well. I also remember a film of a valley in the French Alps, taken with a camera on the front of a locomotive with pictures of the villages and of the stations at which the train stopped.

Leiden (1914 - 1917)

After I had passed the examination in Latin and Greek in August 1914, father brought me to Leiden in the end of September to find a room (students boarded with private families, or lived in rented furnished rooms) and on October 1 I started as a student. In the home where I came to live there was in the first year also a Belgian physicist, Victor (?) Counson, who was following courses in Leiden.

The war, which was relentlessly going on, naturally always was in the background of our thoughts. Newspaper information, as well as the mobilization of the army, and various measures which gradually became necessary to alleviate difficulties caused by scarcity of food, kept the war constantly before us. On very quiet nights (traffic had been cut down through rationing of gasoline) one could sometimes hear the gun fire in Flanders. When various revolutions started from 1917 onward, many of us were interested in their background and in the meaning they might have from the social point of view, whether they might bring improved conditions of living or not. But the study itself brought so many new things and new ideas that it was the university influence which holds the foreground. I could now absorb much more than before at home, and I did this with eagerness.

I had come to the University of Leiden with very little idea how it was operating. The only names which had been known to us in Arnhem were those of HA Lorentz and of H Kamerlingh Onnes; I may have heard the name of a professor of mathematics, and of one or two in the department of classical languages. I was befriended with a student of mathematics, AC Elsbach (died 1932), and I went to him for information.

When I got a list of the courses and saw that Professor Lorentz would lecture at the Physical Laboratory (which I had noticed on one of the streets), I decided at once that I should attend his course. Lorentz had left Leiden for a position at a private institution, “Teyler’s Foundation”, in Haarlem (I shall come back to this foundation later), in order to be relieved from the duties of a regular professor and to have full time for scientific work. He was, however, “extra-ordinary” professor in Leiden and came every Monday morning for a special lecture. Hence, on the first Monday in October I presented myself at the Physical Laboratory (the famous Cryogenic Laboratory of Kamerlingh Onnes), where I was received by a gentleman (I think it must have been Dr. CA Crommelin, chief physicist), who turned me over to one of the workshop boys, and the latter guided me through corridors with all kinds of complicated machinery and big bunches of pipe lines, through a small court, to a lecture room in a separate building at the back of the main laboratory. While waiting in the class room, I saw two gentlemen passing outside, and immediately realized that one of them must be professor Lorentz, since I had heard about the knobs on his forehead, which had developed as a result of his constant thinking. The other one, a dark looking man of somewhat smaller bodily stature, who accompanied Lorentz, later on appeared to be Professor Ehrenfest, his successor as ordinary professor of theoretical physics in the academic year 1914-1915. Lorentz lectured on "Interference and Diffraction of Light", a subject which I could follow without much difficulty, having read about it in an extensive Dutch textbook on optics while still being at home.

University study in Holland was, and still is, very free, much more free than it usually is in the United States. Once having paid the admission fee for the entire university one could go to lectures in any department one liked (or also stay away from anything that one did not like); it was not necessary to have an official adviser and ask for permission to follow this or that course, or to change one's plans.
One could follow a course in ancient Egyptian, if one liked to do so, along with physics and mathematics. Every student at our universities is counted as a fully grown-up person, who selects for hiself.

I had physics from P Ehrenfest, JP Kuenen, HA Lorentz and H Kamerlingh Onnes; mathematics from JC Kluyver, later also from W van der Woude; astronomy from EF van de Sande Bakhuyzen and W de Sitter; geology from K Martin.

The lecture room for theoretical physics at the same time served as a special library for mathematics and physics with complete sets of the Philosophical Magazine, the Annalen der Physik, the Physikalische Zeitschrift, etc., complete works of Cauchy and other mathematicians, of Stokes and of W Thomson, and a lot more.

For a small yearly sum one could become a member of the "Reading Room Bosscha", as it was called; it was not allowed to take books out (many of them were on deposit from the main library, and Ehrenfest insisted that all books should be always available in this room), but one could sit there and read and work. The number of students in physics and mathematics was small in those years. It was an extremely educative and stimulating situation; we always were there before class started and had books before us; usually we came also in the afternoon. In this way one became acquainted with the "founding fathers" of modern physics and mathematics, as well as with the current media of publication. Ehrenfest had been the originator and was the spirit of the "Reading Room" having brought over the idea from Göttingen. It has been in existence for many years, but I am sorry to have heard that a later professor of theoretical physics has stopped it. To us it has meant an opportunity, of which we have profited greatly.

The fact that I came to Lorentz' course drew the attention of Ehrenfest. Soon he invited me to a lecture which he gave before the Chemical Society on Bohr's model of the atom - the first time I heard about it ! - and then he invited me to attend his weekly colloquium, which was held at his house. At this colloquium the current literature in physics was reviewed and extensively discussed.

It is Ehrenfest who has had the greatest influence upon my development and who introduced me into the spirit of real scientific inquiry in physics. Quantum theory was then in its first stages; the theory of special relativity had obtained a definite form a few years before, but, as I gathered later, there was still much to do about the tensor

JM Burgers (second from right) at his lab which should represent matter; in the years 1915 and 1916 Einstein gave the final shape to his theory of gravitation. The work of James Frank and Gustav Hertz on the excitation of atoms by collisions with electrons accelerated through a definite potential (1916 or 1917), was one of the first striking demonstrations of the correctness of quantum theory. The mass spectrograph had been described in principle already in RK Duncan's "The New Knowledge", which had come out in 1908; now, at one of the first colloquia which I attended I heard about the discovery of isotopes.

Ehrenfest made us acquainted with all these subjects, and let us also share in the development of his own thinking. He often needed one or another of his students to talk about some new idea, as he found this helpful to clear up his own mind. So he told me about the development of Einstein's theory of the gravitational field in 1916. Einstein was accustomed to send copies of the proofsheets of his papers to Ehrenfest every time a further article was in press, so that Ehrenfest received the news before it actually had come out. Ehrenfest told us also about the conceptual difficulties which he saw in many theoretical investigations. He brought me into contact with other physicists in The Netherlands, as well as with the few foreign guests who came to visit him (the war prevented normal international travel). I remember G Breit and G Nordström; the latter was in Leiden for a long time and married Miss C van Leeuwen, a student in physics somewhat older than I was. Einstein came in the summer of 1917; I remember that I was sitting with Gunnar Nordström in his room (opposite Ehrenfest's house), when Ehrenfest called at the window and told that Einstein had arrived, whereupon we joined in the reception. Niels Bohr came to Leiden not before 1919.

I also owe very much to a close friendship with three fellow students of that same period who had come to Leiden one or two years earlier: D Coster (died 1950), HA Kramers (died 1951), both physicists; and DJ Struik, mathematician. Much understanding for the meaning of mathematics was obtained from talking with them, in particular with DJ Struik. It was Ehrenfest who had introduced me to them; I believe this was even the first time that he invited me to his home. How much was I Impressed by his study, a large room with three windows in one of the walls, looking out on a part of the garden, and a large couch at the other wall, where I have been sitting so very often. On the shorter wall there was a large blackboard, a strange form of decoration even to me (it was in this room that also the colloquium met in those years). In the bookcases I saw many books, amongst them some Russian books, and I remember Hilton's "Mathematical Crystallography". There were pictures between the windows at the wall, Boltzmann, who had been Ehrenfest's teacher in Vienna, Maxwell, Waiter Ritz with whom Ehrenfest had had a close friendship, but who had died young; Tolstoy, Dostoyevsky (of whom I had never heard) and one or two views from the surroundings of St. Petersburg, from which Ehrenfest had pleasant recollections.

To me this room has been more impressive than the study rooms of any other scientist by whom I have been received. It had a simplicity and austerity, and for me it has a grandeur, since it speaks of the many chapters of modern physics which have been discussed in it, with Ehrenfest's colleagues as well as with the many, many visitors that have come to see him. The room has spoken to me the stronger since I was received there as a close friend, almost as a close relative while also my best friends were at home there. Soon I was also received in the dining room, which so often had full sunshine coming from the garden. Mrs. Ehrenfest had (and has) a very pleasant way of treating us, and of talking; she was almost as inquisitive as Ehrenfest was himself, and she often engaged us for work in the garden of which she was very fond. All this deepened the impression which I had from Ehrenfest's study room; I have found myself almost at home there as it had been in my father's house.

When I was in Holland in May 1961, my wife Anna and I visited Mrs. Ehrenfest, and we were again in the same room. I still am sensitive to its atmosphere and I miss Ehrenfest himself. There were many of the old photographs and of the books, which I had seen on my first visit in October 1914. If ever there would be some truth in the idea that walls do absorb something of the spirit which has reigned in a room, how much would these walls be able to give back!

I mentioned that Ehrenfest introduced me to some students in physics and mathematics, who became my closest friends. There existed in Leiden a "dispuut", a society of students interested in physics, mathematics, astronomy and chemistry, called "Christiaan Huygens", and I think that again it was Ehrenfest who mentioned it to me. Soon I was admitted as a member. The society met every fortnight, from 7 p.m. to about 11.30 p.m., sometimes followed by a nightly walk. There was a longer lecture and a shorter communication, given by members, and often also a jocular improvisation on an assigned subject. The longer lectures were always well prepared and treated advanced topics taken from the field of study of the member who gave the talk. Often the talks went quite deep. Since questions and discussions were fully allowed and encouraged, the meetings were extremely stimulating. They usually were held in the room of one of the members, who had to arrange for tea and coffee, and for sweets, cookies, pies, etc. Coster, Kramers and Struik were members, as was also AC Elsbach. The first time, when I came as a guest, I listened to a talk by C de Jong, on unsolved problems in astronomy. De Jong at that time was already working on a thesis connected with Kapteyn's theory of two-star streams. I also became great friends with Marcel Minnaert, who came from Belgium in 1915; he originally was a biologist, but now studied physics and was later to become the foremost solar physicist in The Netherlands, as successor of WH Julius. There also were some female members, and it was there that somewhat later I found Jeannette Roosenschoon who came to Leiden in 1916 to study physics. She became my wife in 1919. (My second wife, whom I married two years after her death, was the sister of another member of Christiaan Huygens; she studied law. Thus all of us belonged to the same generation). A few times each year "Huygens" arranged walks or excursions; often Ehrenfest joined us. My father enjoyed very much becoming acquainted with the friends I had found in Leiden.

Struik, Coster and Kramers also have been in the house in Arnhem. Kramers became very much befriended with my brother.

Ehrenfest taught us how to read scientific papers, to look for the assumptions made by the authors, and to hunt them out when they were not given explicitly. His powerful analytical mind opened our eyes to many subtleties in physical theory. He always strove to find interpretations of new thoughts, and had striking ways for the illustration of their peculiarities. His method of lecturing consequently was unique. He encompassed and taught theoretical physics as a whole, and in passing gave us insight into a good deal of mathematics bringing cross connections between domains which until then had looked as quite separate.

His regular courses were on Maxwell’s theory and on statistical mechanics, but there were also special courses. A course on some aspects of colloid physics, developed into an exposé of the probability laws for radioactive phenomena. A course on certain parts of theoretical mechanics developed into a highly illuminating survey of the theory of integral equations, in which Ehrenfest gave us a thorough introduction into what later became known as the theory of “Hilbert space” (I9I5). Although Ehrenfest did not introduce the projection operator, the ideas gained from these lectures have helped me greatly when many years later I read Johann von Neumann’s “Mathematische Grundlagen der Quantenmechanik”. In a later year we had a seminar on linear partial differential equations of the second order, in which Ehrenfest stressed the relations between the various types of equations and quadratic surfaces. I had to make many large scale sketches of various sets - of confocal quadric surfaces to illustrate the lectures (one of the sketches for many years has hung in the dining room of Ehrenfest’s house). He often let us give parts of this course. It was still in my first year, that, on one of the rare occasions that he was not well, he asked Kramers and me to present Poynting’s theorem on the flow of energy in the electromagnetic field. We were invited to his home the night before, in order to be properly briefed. I felt very glad to be asked to do this.

Ehrenfest gave constant food to my desire for understanding and he expanded the views and interests I had brought from home. No longer it was my father’s maxims which took the first place in my thinking: Ehrenfest’s influence became the stronger one.

Ehrenfest was fond of music, and was a good piano player. Sometimes he played for us. It seems to have been Einstein who opened Ehrenfest’s ears for Bach’s Preludia and Fugues. Ehrenfest made me acquainted with several of them, which still are my favorites. I also remember one of Beethoven’s Bagatellen, which he often played. Once he had a guest staying for some days at his house, who played Beethoven’s "Sonate für Hammerklavier" with its passionate and sombre "Adagio sostenuto". A few times Ehrenfest arranged some students to play Bach’s Fugues in such a way that each voice was performed by a separate instrument, so that one could follow the tunes more easily.

I also vividly remember that on a morning in the month of May, after a class, he took us to one of the buildings in which the Ethnographical Museum in Leiden was housed at that time: in the garden there was a set of five wonderful statues of the Buddha (still forming a ramous treasure in the collections of the Museum, and now placed in a room of honor), standing under a magnolia tree in full flower, with bright sunshine over everything.

I mention these matters as examples of how much Ehrenfest contributed also to the development of our inner life. Ehrenfest, so to say, distributed all, that which was living and active in him. Sometimes it looked (I believe to see this now, from a distance), as if he gave away everything he had found or observed, without building up a reserve, a kind of stronghold, within himself.

I regret that I cannot give a picture of Ehrenfest as I could do of my father. He was, of course, much more complex than father was, and also much more complex than I am myself. His analytical mind stirred up everything, so that at times it looked as if nothing would be left as it was. On the long run this pushed his students somewhat away from him and I have also experienced this effect. There were things which we did not like to have analyzed. It may look as if this betrays a lack of intellectual interest, but in several cases it was an instinctive protective reaction from our side.
I can enjoy myself with things or in situations without asking whether they have a meaning, whereas Ehrenfest would question every aspect. Ehrenfest had a great personal sensitivity, which I have not always understood. He had a hunger for friendship as if he could not find a sufficiently strong anchor within himself. There was some inner sadness in Ehrenfest, perhaps also a hidden fear, may be due to his Jewish origin.

I remember a meeting in the spring of 1918, which Ehrenfest had arranged to make physics teachers acquainted with recent discoveries. He asked some of us to give talks; I believe I spoke on the work of Franck and Hertz. This meeting naturally gave him great pleasure, but what was strange to us was that he said it had given him more pleasure than the birth of his youngest child in that same year. This surprised us greatly. I spoke about it with Lorentz and asked him whether he could talk with Ehrenfest, and help him to find a way back to feelings which looked more normal to us. But even for Lorentz it was too difficult to penetrate into the deeper recesses of Ehrenfest's mind. None of us could reach deep enough, and each of us had already other problems before himself, which we wanted to consider and to keep for ourselves.

While we perceived that Ehrenfest's self analysis could take dangerous forms and lead to utter despair, we could not help him. At that time I had already become engaged with Jeannette Roosenschoon and, while it had been Ehrenfest who had helped me to become liberated from my father's world, the intimate exchange of ideas with her opened still another world for me. A world, it is true, not bringing the vistas of science, but bringing pictures of personal and social relations which were not less important for development.

We married in the summer of 1919, and it was with my wife that I strove to build up my place in Delft (see later on), and to form a picture of the new aspects in which Europe was presenting after the war and the various revolutions. Then Ehrenfest's influence lost hold, in a similar way as it had happened with my father's influence a few years before. Moreover, the colleagues whom I found in Delft, in particular CB Biezeno about whom I shall speak later, soon assumed an important part in my daily contacts.

It is probably also a result of a difference in mental attitude of more shallowness and a more formalistic attitude on my part in comparison with that of Ehrenfest, that I cannot give a good picture of what was in Ehrenfest's mind when we struggled with the mysteries of quantum theory. The problem of the adiabatic invariants was an important topic. Ehrenfest had the conviction that here was a domain where classical mechanics provided an inroad into the new theory, and he strove hard to grasp the meaning of those cases where unexpected relations presented themselves as, e.g., when the oscillations of a pendulum increase in amplitude beyond 180^0 and pass into a cyclic motion. Another problem was how to count the various configurations of a mechanical system, say a gas with many molecules, so that the proper basis is obtained for the calculation of the entropy, as the most obvious way of counting required a mysterious division by N! to give the proper result. I had to leave quantum theory behind me when I went to Delft to occupy myself with fluid mechanics. I have no direct knowledge of Ehrenfest's first reactions to the work of de Broglie, Schrödinger, Born, Heisenberg and P Jordano. The discovery of the electron spin by Goudsmit and Uhlenbeck gave him great joy.

To come back to my story, the first important extension of Bohr's theory had come in 1916 through the work of Sommerfeld and Epstein on systems for which the Hamilton-Jacobi partial differential equation can be solved by the method of separation of variables. In view of the importance of adiabatic invariance, the question naturally turned up whether the quantities introduced by Epstein, the "phase integrals", would also be invariants. We were convinced that this should be the case, and I succeeded to prove this by the application of a set of transformations of partial derivatives. It was somewhat like solving a puzzle. A paper on this subject was accepted by Professor Lorentz for publication in the Proceedings of the Royal Netherlands Academy of Sciences (Ehrenfest became a member of the Academy in May 1919). After having given a proof for the general case without degeneration I could show that in the "degenerate case" the remaining independent phase-integrals still were invariants. Later I constructed a new proof with the aid of the transformation to action and angular variables, as used by Schwarzschild, and treated in ET Whittaker's "Analytical Dynamics" (this was in 1916-1917).

So much about Ehrenfest. I will now turn to some of my other professors. I must begin to say that with all my admiration for professor Lorentz (an admiration continually strengthened by Ehrenfest), his personal influence was much less. Lorentz had that natural modesty which is afraid to go too deeply into the mind of another person.

JM Burgers study room

He remained much more aloof, and never subjected us to much questioning, nor pushed us to some topic as Ehrenfest could do.

We revered Professor Lorentz, but the distance was too much for the development of the type of friendship we had with Ehrenfest. I came, however, into closer contact with Professor Lorentz during the period January-September 1918, when I was his assistant in Haarlem.

Professor Kamerlingh Onnes was a much more authoritative person. In the year 1914-1915 he still gave a course on the theory of the monocycle, as developed by Maxwell and by Helmholtz in view of a certain analogy with thermodynamic relations. We were with only three students, and once, when the two others had not turned up, he gave for me alone a private lesson on his investigations on superconductivity and on the fact that a magnetic field cannot penetrate into the interior of a superconductor. As I was interested in experimental physics, I also followed a course in glass blowing in the cryogenic laboratory, but I did not become an expert. Gradually I came to carry out measurements with electrical resistance thermometers, and from January 1, 1916 - December 31, 1917, I have an assistant in this laboratory. My main work was to read the galvanometers and to help other students with electrical temperature determinations. Experiments with liquid helium could not be carried out during the war years, but in 1917 a vapor cryostat came into use, working in the domain between liquid neon and liquid hydrogen.

Kamerlingh Onnes wished to have his assistant completely for his laboratory who should do observations during daytime, work them out in the evening and write them up during the weekend and one should not flirt with theoretical studies, because experimental physics required the whole person. To this regime I could not subject myself. I was too much interested in theoretical problems and was too much attracted by Ehrenfest. As my mind was not very inventive, I could not arrive at a program for experimental research. Gradually Kamerlingh Onnes noticed that I had strong attachments on the theoretical side; Ehrenfest talked with him about me, and finally Onnes asked me about my plans. I told him that I felt too much attracted to theoretical studies, and I know that it was a great disappointment to him. He has taken it nobly and did not detract his friendship from me. I may mention in passing, that later on, when I accepted the position for fluid dynamics in Delft, Kamerlingh Onnes said that if ever I should like to do experiments on the viscosity of liquid helium he would be glad to have me come back to him. Unfortunately, at that time I looked upon viscosity only as a datum to be used in the calculation of the Reynolds number for a flow pattern, and thought that to measure the viscosity of helium would be just to add another number to a table of physical constants. From what has been found later, it may be that I have missed a great opportunity.

From my professor of mathematics, it was Kluyver from whom I received most, through his excellent lectures on the theory of functions. I remember with great admiration his course on the Riemann function, about which we read at the same time in the books we found in the "Reading Room".

With van der Woude, who gave geometry and analytical mechanics, I have become much befriended, but I did not follow his lectures; he came a year or so later, and I had already studied much of these topics. It was to the astronomer W de Sitter, who was an expert in Hamiltonian dynamics, that Ehrenfest took me when I had obtained the proof for the invariance of the phase integrals, to discuss the details.

I did the “candidaatsexamen” on May 22, 1915. It was Ehrenfest who had prompted me to do it within a year since I had already much preparation before I came to Leiden. The “doctoraal examen” followed on December 1, 1917.

In October 1917 my brother had also come to Leiden to study chemistry. For some months we lived together with the same family where I had been since my arrival. My brother also became a member of Christiaan Huygens, which had more chemists among its members. But with January 1918 I left Leiden for Haarlem, as Professor Lorentz had asked me to accept the position of “conservator” of the Physical Laboratory of Teyler’s Stichting, of which laboratory he was the director. My brother remained in Leiden until the summer of 1919, when Professor HJ Backer asked him to become his assistant for organic chemistry at the University of Groningen.
My brother’s work there was interrupted by a stay of two years (1920-1921) in Rome as teacher of the sons of the Ambassador of The Netherlands for the mathematical and physical subjects. The present Ambassador of The Netherlands in the United States, his Excellency Mr JE van Royen, thus has been a pupil of my brother. After having returned to Groningen, my brother in 1923 received a fellowship from the International Education Board to work on crystal structures at the Royal Institution in London under WH Bragg. This was followed in 1925 by a Ramsay Memorial Fellowship, and my brother continued to work at the Royal Institution until the summer of 1927, when he was offered a position at the Physical Laboratory of the Philips Factories in Eindhoven. In 1940 he was appointed professor of physical chemistry at the Technical University of Delft. Father has still seen that the two of us were professors at the same University.

To come back to Teyler’s Foundation: this was an institution dating from the end of the 18th century, when there was everywhere a great interest in the physical and natural sciences. Among its early professors had been van Marum, who constructed a powerful electrical machine with which he performed many experiments. The Foundation also had a museum with rich collections of paintings and drawings; and a collection of physical instruments (among them van Marum’s machine); minerals and fossils with a large slab containing the famous reptile “Andreas Scheuchzeri”, which Scheuchzer had held to be a remnant of a man who had died with the Biblical Great Flood.

To work at the physical laboratory of this Foundation was a very honorable position. Two of my predecessors, Dr. GJ Elias, and Dr. WJ de Haas, (Lorentz’ son-in-law) had carried out important experimental work at the laboratory. One after the other they had been appointed professor in Delft, Elias for electricity and Maxwell’s theory; de Haas for physics.

The daily contact with Lorentz was of great value, but nevertheless I felt somewhat lost in Haarlem, although I went weekly to Leiden with Lorentz on the occasion of his lectures. Now that I was on my own, I suffered from some inability to develop a full program of work for myself.

Before I really came to consider this matter seriously within myself, I received an invitation to accept a newly created chair at the Technical University in Delft for aero- and hydrodynamnics, in the Department of Mechanical Engineering and Shipbuilding. The jump away from physics and from atomic problems was a large one, but there was also an attractiveness in the idea of starting a new line of work.

Hydrodynamics was not treated as a part of classical mechanics in Leiden. Ehrenfest had not much feeling for a domain of science which was governed by non-linear equations, although in 1917 he had directed our attention to a little book by R Grammel "Die hydrodynamischen Grundlagen des Fluges" (The Hydrodynamical Foundations of Flight), in which the theory of the two-dimensional circulatory flow around wing profiles was explained. This indicated an interesting field for the application of conformal transformation. In the "Reading Room" I had sometimes looked at FW Lanchester's "Aerodynamic Theory", but this made the impression of an incomprehensible phantasy. Hydrodynamics, as a part of theoretical physics, had a scientific ancestry of high standing, and the names of Lord Kelvin and Helmholtz are connected with many of its intriguing aspects. Even Professor Lorentz had written two important hydrodynamical papers, one on problems of viscous flow which have provided a basis for CW Oseen's theoretical investigations; and one on turbulence, explaining Reynolds' ideas and adding to them some very inspiring developments.

The invitation from the Technical University was made by two professors of the Department mentioned, professor CB Biezeno, who lectured on the theory of elasticity and lectured on strength of construction; and professor CP Holst, who lectured on construction of machinery, and who had a great interest and admiration, and I may say, a fine feeling for theoretical work. They explained to me that what they desired was a scientific attitude towards the subject. Although it was the time when flying and airplanes attracted more and more attention, it was not their idea that I should be an expert in flight as a technical achievement: I should have to bring the basic ideas necessary for understanding and mastering the phenomena of flow, and to work in this domain as a scientist. From the discussions it appeared that to cooperate with them, in particular with Biezeno, was very attractive and would protect me from being immersed in technical and industrial relations. In that period the mathematical methods used in hydrodynamics were still closely related to those applied in the theory of elasticity. The cooperation with Biezeno soon developed into a close friendship, and many are the discussions we have had together, not only on matters of scientific interest, but also on problems connected with the welfare of the Technical University, and on personal matters.

I had, of course, to learn hydrodynamics myself and I started to read various papers on vortex motion, among them Ahlborn's photographic work on vortex motion behind bodies which were towed through a large tank with water. I had still to finish my thesis work on "Het atoommodel van Rutherford-Bohr" (The Model of the Atom according to Rutherford and Bohr). It originally had been a prize essay for Teyler's Stichting, which I had written in 1917. HA Kramers had gone to Copenhagen, to work at Niels Bohr's Institute, in the second half of 1916 or the beginning of 1917, and he had not been aware that this theme had been set; otherwise he probably also would have written an essay. The point of view which I had taken had grown out of the work on adiabatic invariants and was based upon a treatment of the equations of analytical dynamics with the aid of contact transformations, as indicated in ET Whittaker's "Analytical Dynamics". Professor Ehrenfest was my promotor, and the degree was awarded on November 7, l9l8.

The appointment in Delft officially had started October 1, 1918, on which day I had also moved to Delft. On December 2, 1918, I gave my opening discourse with a lecture on "The Hydrodynamic Pressure".

After that I felt myself obliged to abandon the theoretical physics of atomic structure completely. Hydrodynamics needed all attention and it was not possible to serve two masters at the same time. Only after 1926 I made myself acquainted again with the new views on quantum theory, which had developed from the work by Born and Heisenberg and by Schrödinger.

As regards hydrodynamics, the theory of the circulatory flow around airfoil profiles required first attention. Soon we received information concerning Prandtl's work and that of his pupils Max Münk and Albert Betz on the vortex system behind airfoils of finite span. Also Prandtl's boundary-layer theory, first presented in 1904 and later worked out by Blasius (1908) and Hiemenz, had to be studied, as well as Osborne Reynolds' fundamental work on turbulence. The discussion of this work by Lorentz, who had also extended Reynolds' stability calculation, was extremely stimulating.
A remark by one of my mathematical colleagues happened to make me acquainted with the work of Oseen - great application was needed to get into the meaning of his calculations. But in 1920 I began to see a relation between certain aspects of Oseen's work and Prandtl's boundary-layer theory, and I constructed an intermediate picture by making use of a transformation of the equations for two-dimensional flow, given by Boussinesq. It is convenient however, to stop at this point, since many new developments started with the year 1921, when I became acquainted with Dr. Th von Kármán.

Research highlights of JMBC-groups during the period 1992 - 2007

If I have a thousand ideas and only one turns out to be good, I am satisfied

Alfred Bernhard Nobel

1992

AD Schwarz-van Manen
K Krishma
FTM Nieuwstadt

Coherent motions over drag reducing surfaces

The Netherlands Foundation for Technical Sciences and the Foundation for Fundamental Research on Matter have supported research on drag reduction since 1983. This has been carried out as a collaboration project between the Eindhoven and Delft Universities of Technology. The work involved investigations on drag reducing properties of longitudinal microgrooves. This work has provided a firm data base about drag reduction capacity of microgrooves and the details of this work are described by Pulles (1988) and Schwarz-van Manen (1992). In addition a substantial effort went into describing the coherent motions over smooth and grooved surfaces with the intention of providing an explanation for the drag reducing behaviour of the microgrooves.

Drag reduction by longitudinal microgrooves has been confirmed by measurements performed in many laboratories for diverse flow situations. However, the reason for this observation is far from clear. One candidate hypothesis is that the viscous sublayer thickness increases in the presence of longitudinal riblets (Bechert and Bartenwerfer, 1989). A second hypothesis is that the grooves manipulate the coherent motions in the near-wall region in some manner resulting in drag reduction. In the present report we provide a summary of some results obtained on delineating the types of coherent motions measured during the investigation. It will help in identifying the mileage we need to cover before we can claim to have an acceptable theory to explain the phenomena of drag reduction by microgrooves.

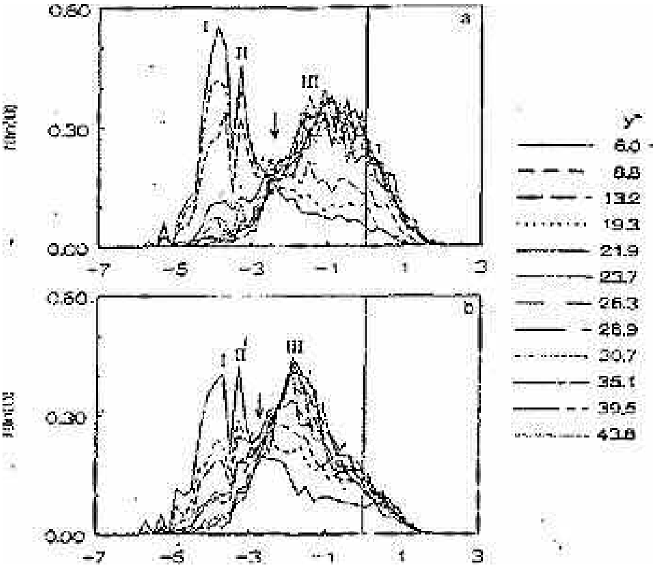


Figure 1 Appearance of three peaks in the log-normal distribution plots, these being predominant in the near-wall region.

The experiments were all performed in the low-speed water channel at Eindhoven at a nominal free-stream velocity of 20 cm/s. The momentum-loss thickness based Reynolds Number at the measurement section was about 2000 (Schwarz-van Manen, 1992). All results are normalized, whenever that was necessary with the appropriate viscous length and time scales. The measurement effort in the present work concentrated in delineating the structural features as a function of height rather than on Reynolds numbers. For each surface over 20 heights in the range $7 < y+ < 300$ were investigated. In the work on coherent motions we have considered three questions in some detail. These were:

(I) the technique of identifying the relevant motions from velocity signals in the streamwise and vertical directions;

(II) the behaviour of these motions over a smooth surface, and

(III) the influence of drag reducing riblet surfaces over these motions.

The quadrant analysis technique used in conjunction with log-normal description of the periods between detected events has one clear merit: the functional dependence of periods on height is quite smooth in contrast to the noisy result one produces by using other approaches.

Moving now to the second aspect we are obviously in a difficult situation. One is considering time dependent motion in three dimensions. But we do not have at our disposal simultaneous time series data at several positions in the boundary layer. Thus the best one can hope to achieve under these conditions is to test the results found here for consistency against some of the models that purport to describe coherent motions. The first point concerns the appearance of three peaks in the log-normal distribution plots, these being predominant in the near-wall region (see fig. 1). As one moves towards the log-law region these two peaks disappear for all practical purposes and are replaced by a third peak.

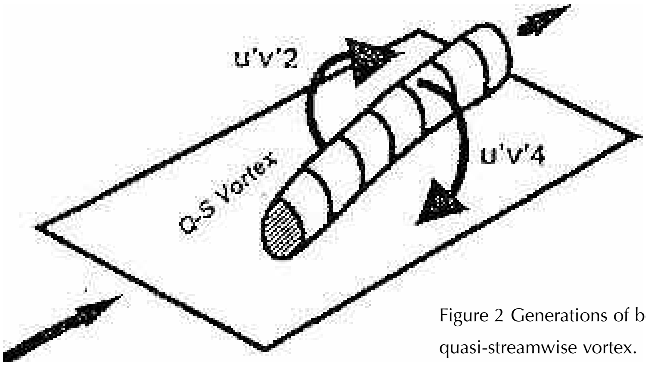


Figure 2 Generations of both ejections and sweeps by a single near-wall quasi-streamwise vortex.

For the moment ignoring the presence of the peaks it is possible to construct the log normal mean periods as a function of height.

This part of the investigation shows that the average periods increase almost by an order of magnitude for ejections in a short height (y+ < 30). More importantly the ratio of periods of sweeps and ejections - except at about y+ = 15 - is different from unity.

The sweeps are less frequent very close to the wall (the ratio can be close to 2) becoming more frequent (the period ratio goes down to about 0.8).

This result really questions the usual statement about sweeps being as frequent as the ejections. We believe that this conclusion is based upon observations at one height.

Our data for ejections show a peak at y+ = 30, a fall between 30 and 100 followed by a constant value for the periods. Since the interest in the present work concerned drag reduction with riblets we have not really explored the outer region of the boundary layer and as such we have restricted our comments to the near wall region.

The result that sweep and ejection periods differ has also implications for the type of picture (see fig. 2) Robinson (1991) produces. The present result seems consistent with the idea that a single near-wall quasi-streamwise vortex can be responsible for producing both ejections and sweeps. However, the picture suggests that sweeps and ejections are equally preponderant. Whatever measure we choose from the present data set - be it the percentage of data points, periods, durations, average flux, probability densities - they are all different for the concerned two quadrants.
This means that the structure gets deformed as one moves up the boundary layer resulting in differences of interactions leading to distinctly different behaviour pattern of sweeps and ejections.

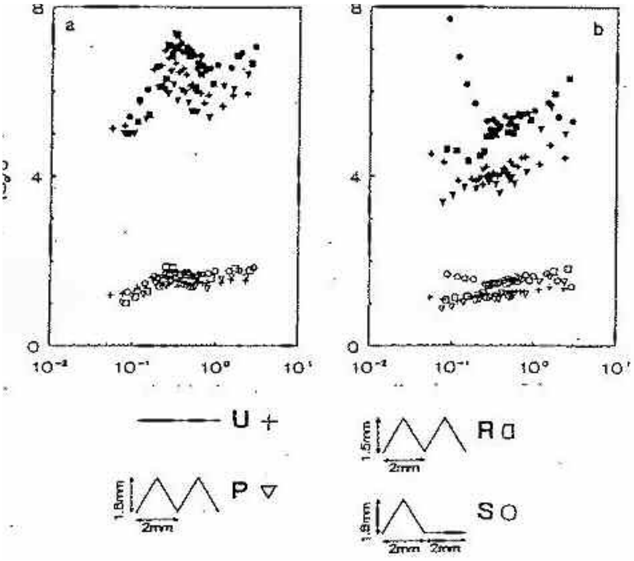


Figure 3 Grouped periods (filled symbols) and durations (open symbols) scaled with outer variables. (a) ejection; (b) sweeps.

Generally stated riblets do not drastically alter any of the structural features of smooth plate. Among the different geometries studied the P surface is the most successful in reducing skin friction - some 18% lesser than the smooth plate. We shall be looking only at this surface in what follows.

Some of the largest changes noticed as far as coherent motions are concerned are in the periods of ejections. They get reduced by as much as 25 to 30%, except in the very close vicinity of the wall. This remark is valid both for single event averages and grouped event averages. The reduction is observed for the entire of measurements carried out in this work for y+ > 20. For y+ < 20, the single event averages register a slight increase but grouped event averages do not show this trend. The sweep event periods show similar trends.

It is in this connection that the burstiness factor introduced by Narasimha and Kailas (1989) comes in handy. It is a measure to quantify the compactness and the intensity of the detected events that contribute to the Reynolds shear stress. This is plotted for both the ejections and sweeps (see fig. 4). The surfaces P and S show a larger burstiness than the smooth plate for both ejections and sweeps. However the S surface shows not much change with respect to the smooth surface for ejections while for sweeps the behaviour is similar to that for P and R surfaces. Since skin friction reduction by riblets is not in dispute, the only interpretation we can give for this remarkable result is that the riblets manipulate coherent motions in such a manner that they channel turbulence into coherent motions. But they are very much more successful in killing motions. This opens up the discussion of the relative importance of coherent and incoherent motions in determining the momentum transport in a turbulent boundary layer.

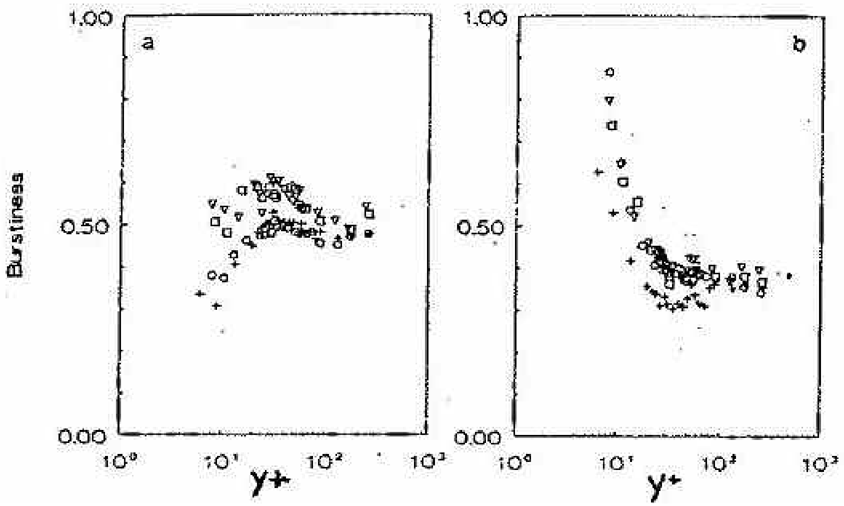


Figure 4 Burstiness factor as a function of height (a) ejections; (b) sweeps. (see fig. 3 for symbols).

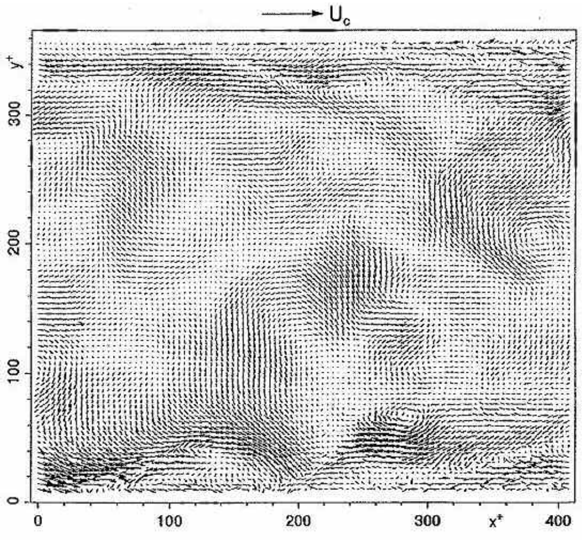
J Westerweel
FTM Nieuwstadt

PIV (Particle Image Velocimetry) in turbulence

The point of departure in the PIV technique is a flow seeded with small particles, say ~1 mm. The particles are illuminated in a plane by means of a laser light sheet and they are recorded by a camera on e.g. a video or photograph. By taking two exposures separated by a small time fraction on the same image one records of each particle two positions displaced by a small distance. By means of a correlation analysis one can measure this distance and after dividing it by the time interval one obtains the velocity vector field in the light plane.

We have applied this technique to a fully developed turbulent pipe flow at Reynolds numbers of Re 6860 (based on the centerline velocity and the pipe diameter). A light sheet with a thickness of about 0.4 mm is provided by two Nd:Yag lasers which are synchronized to give light pulses with a time delay of 0.3 ms.
The position of the light sheet is along the centerline of the pipe spanning the whole pipe diameter. The doubly-exposed picture of the flow is taken with a camera.
The pictures are analyzed by illuminating small spots (called interrogation windows) by a light source and by projecting the image of the spot on a 256 x 256 pixel CCD camera. The auto-correlation function of resulting 2D-pixel array has two non-central peaks. The shift of these peaks with respect to the central position gives the average displacement between the two particle images within the interrogation spot. In this way we obtain the velocity vector at 8500 positions distributed on the light plane through the pipe centerline. The experiments were done in the laboratory of prof. RJ Adrian of the university of Illinois at Urbana-Champaign.

The main advantage of PIV is that we obtain an instantaneous flow field, which allows us e.g. to study spatial structures in turbulence. An example of the observations, which at the same time gives an appreciation of the possibilities of this measuring technique is shown in the figure below.



The picture shows the instantaneous velocity fluctuation, i.e. the mean velocity has been subtracted from each velocity vector. The y+ is the radial coordinate and x+ gives the axial coordinate along the pipe axis. The pictures shows the whole area between the two pipe walls.

The turbulent character of the flow is clear. Regions of high activity are present near the pipe walls. They take the shape of strong shear layers and also of rotating flow motion (vortices). These regions can perhaps be interpreted as coherent structures which are known to dominate the dynamics of turbulence. With PIV we are now able to observe these coherent structures directly. For further details we refer to: Westerweel J, RJ Adrian, JMG Eggels and FTM Nieuwstadt. Measurement with particle image velocimetry on fully developed turbulent pipe flow at low Reynolds number. Proceeding of the 6th International Symposium on Laser Applications in Fluid Mechanics, 1992, 20-23 July, Lisbon.

RW van den Berg
HEA van den Akker
WJ Beek

Non-linear dynamics of two-phase flow

A study has been carried out on the flow in a U-shaped tube filled with water (fig.1). Gas bubbles are supplied at a constant rate in the middle of the tube, causing an oscillating motion. The pulsed flow is a typical example of two coupled phenomena: the fluid in the tube is oscillating due to the pulses and determines the direction of the entering gas bubbles (left [L] or right [R]) which in turn supply the energy for the oscillating motion. The bubble sequences are described by the ratio $T_b/T_o = 1/\phi$, T_b denoting the time between two consecutive bubbles, and T_o the period of the undisturbed oscillation by the fluid. For example, if $\phi = 7/2$ seven bubbles enter the tube during two oscillations of the fluid. Experimentally, it has been verified that a gas bubble always rises in the leg in which the fluid is flowing upward. Fig. 2 shows plots of the intervals between consecutive bubbles for each leg. For $\phi = 3.69$ a period 7 sequence occurs (LRRLLRL).

The dynamics of this (laminar) flow is simulated by a kicked mass/spring-model, which is valid if interaction between consecutive gas bubbles is ignored:

$$\ddot{x} + \sqrt{\frac{2g}{L}}\,x + \frac{16\eta}{\rho D^2}\dot{x} = A\,\frac{abs(\dot{x})}{\dot{x}}\,\delta(t - nT_b) \qquad (1)$$

With g the acceleration due to gravity, L the total length column, x the position of the surface relative to the equilibrium state, η viscosity, ρ density and D the tube diameter. At multiples of T_b the system experiences a pulse in the flow direction produced by an entering gas bubble, represented by the periodic Dirac function δ. The discrete parameter n describes the number of periodic pulses. The amplitude A is proportional to the stress exerted on the fluid. This tentative model predicts the dynamic behaviour of the system rather well, although T_b, is assumed to be of constant value. Due to the forced oscillating motion of the fluid in the tube and a time delay before the pulse is transmitted, T_b will show in fact a sinusoidal character.

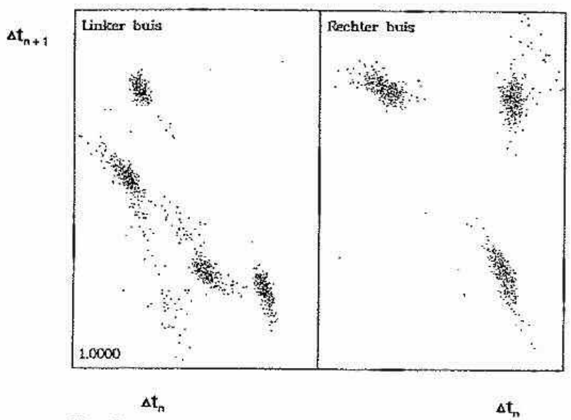


Fig. 2

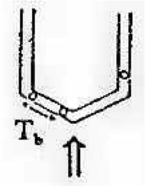


Figure 1 and Figure 2

Two coupled difference equations have been derived, describing the position in the phase space $(x, \dot{x})$ at pulse n, which is dependent on the parameters mentioned in (1) and the position in the phase space at pulse n-1.

An interesting feature of the system is the occurrence of phase locking: the system prefers to be locked at a certain frequency ratio $T_b/T_{oc} = 1/\Omega$ A slight disturbance in T_b forces the system to adjust T_{oc}, resulting in the same value for Ω as before the disturbance occurred. However, if the disturbance is of a larger magnitude, the system might jump to another locked mode. The physical implication of phase locking is evident: if the system is locked in a certain mode, the sequence of consecutive gas bubbles (left or right) will show the same perioditity in some range, independent of ϕ. Fig. 3 shows the results for $\phi = 3.69$. At that flow rate the system is locked in mode Ω=7/2. The numbers at the data points refer to the bubble sequence observed.

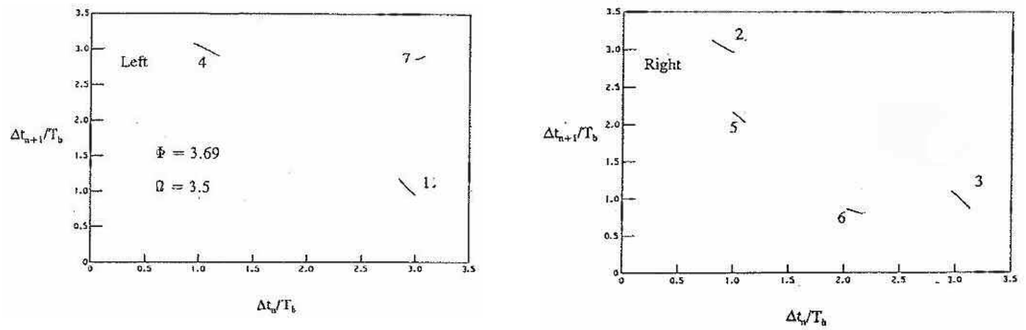


Figure 3

The most exciting phrase to hear in science, the one that heralds new discoveries, is not 'Eureka!'(I've found it!), but 'That's funny...'

Isaac Asimov

1993

AM Mollinger
FTM Nieuwstadt
JM Bessem
B Scarlett

Measurement of the lift force on a particle in the viscous sublayer : a new device

The objective of this study is the measurement of the lift force on a small particle lying on a flat surface over which a turbulent boundary layer is present. The size of the particle is such that it is embedded in the viscous sublayer. The lift force is one of the four force components experienced by the particle, which are in addition to lift, the weight, adhesion and drag force. The lift force is in particular important when one aims to describe phenomena such as suspension (entrainment). In nature the entrainment and transport of particles by an airflow may be observed in many situations, but also human activitycauses entrainment. Human interest in entrainment stems mainly from the negative aspects of entrainement, economic losses due to ersosion of ore stockpiles, or the presence of particles in clean rooms. Many models for entrainement are avialable however there is no good validation possible because there is almost no experimental data available of the fluctuating lift force.

We have developed a new device which is capable of measuring the fluctuating lift force on a particle of 100µm, which is lying within the viscous sublayer of a turbulent boundary layer. The boundary layer develops over a flat plate of 6m long, in a closed windtunnel. At about 4m from the leading edge the lift force device is installed, this insures a fully developed natural boundary layer. There are only two other experimental techniques known to measure the lift force on relatively small particles (order of mm's), both experimental techniques are roughly the same but Hall (1988) did his experiments in air and Radecke and Schulz-Dubois (1988) did their experiments in water.

The principle of the measuring device is illustrated in figure 1. The particle id 100µm) is a hollow spherical glass particle which is glued on top of the silicium cantilever. The cantilever (length 200µm, width 30µm, and a thickness of 0.5µm) is placed flush with the toplayer of the measuring plate. Just below the cantilever there is a window which has to insure that there is no flow possible between the flow over and under the measuring plate. Due to the wind flowing over the particle the cantilever bends upwards. Since all properties of the cantilever are known a displacement of the point of the cantilever can be directly translated into a lift force. For the measurement of the displacement of the cantilever a laser with additional optics is installed under the cantilever. The laser optics are able to measure the displacement with a resolution of about 0.01µm. The laser can be traversed with the help of three small electro-powered traversing units to the desired position. A camera, with prism, is installed next to the laser in order to see where the laser spot is positioned on the cantilever, and if the laser is in focus.

The results of the experiments concerning the mean lift force are shown in figure 2. It is not only possible to measure the mean lift force (approx 10^{-8} N), but also the fluctuating part of the lift force was measured. The following relation between the dimensionless lift force ($F^+ = F/ \rho\, v^2$) and the dimensionless radius ($a^+ = au_*/\upsilon$) was found: $F^+ = 40\,(a^+)^{1.8}$ where u_* is the wall shear stress velocity.

This relation is comparable with the relation found by Hall (1988). The measurement of the fluctuating part of the lift force is important because with this information it is possible to evaluate a number of entrainment models.

It is possible to change the experimental setup in the future so that is possible to measure not only the lift force but also the drag force on the particle. The necessary changes are a different laser with a four-quadrant light sensitive element and a different shaped cantilever, which is sensitive for lift and drag forces.

References

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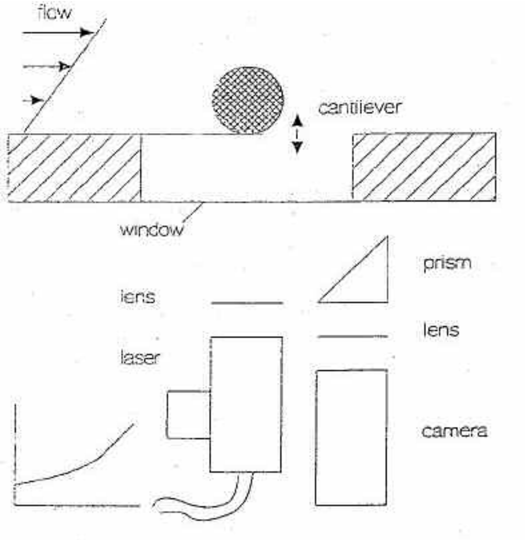

Figure 1 Schematic of the experimental setup

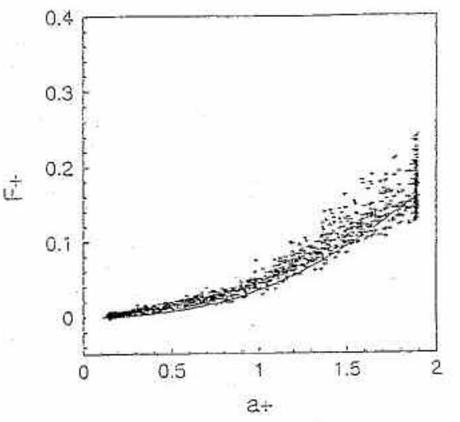

Figure 2 Dimensionless lift force as a function of the dimensionless radius

A van der Ploeg
EFF Botta
FW Wubs

Preconditioning for sparse matrices with applications

Since physical experiments are often very difficult and costly, physical problems are often represented by partial differential equations to be solved by discrete numerical methods. The computation of an accurate approximation to the original continuous problem will usually lead to systems of linear equations in which the number of unknowns can be very large. currently, for many practical three-dimensional applications, the size of the linear systems is typically of the order of 1-10 million unknowns. Fortunately, the coefficient matrices arising in such computations are very sparse. We consider the solution of x from the large sparse system of linear equations $Ax = b$ for a real non-singular $N \times N$ matrix A and a given vector b. In order to take advantage of the sparsity of A, the system $Ax = b$ is often solved by iterative methods. In general, the speed of convergence of these methods strongly depends on the eigenvalue distribution of the coefficient matrix. Therefore, a conjugate gradient-like method is often applied to the preconditioned system $C^{-1}Ax = C^{-1} b$ instead of to the original system $Ax = b$. The non-singular matrix C is called the preconditioner. Subject of our investigations is the construction of preconditioners for systems of linear equations as they occur in a number of practical problems. Primarily, we consider preconditioning techniques based on an incomplete LU-decomposition (ILU) of A, because of their simple definition and high efficiency. A number of techniques have been developed which can be used for matrices with an arbitrary sparsity pattern. This allows the use of complicated geometries and an irregular node numbering. Several numerical experiments in [1] demonstrate that the best preconditioners are often obtained by an ILU-decomposition in which the sparsity pattern of $L+U$ is based on a drop tolerance ε. In this technique, which is denoted by ILU(ε)-preconditioning, a splitting (LU, - R) of the scaled matrix is constructed, in such a way that all entries of $R = A - LU$ are in absolute value smaller than ε. Sometimes the preconditioner can be improved by forcing the row sums of R to be zero (MILU(ε)-preconditioning).

We also considered the system $Ax = b$ arising after linearization of the incompressible Navier-Stokes equations. Since A contains zero elements on the main diagonal, a straightforward sparse incomplete decomposition for this system is not possible. We therefore consider the equivalent system $QAx = Qb$, in which Q can be regarded as a pre-preconditioner. Next, a sparse incomplete decomposition of QA is constructed in a similar way as the construction of the factors L and U of the ILU(ε)-preconditioning.

ILU(ε) can be combined with a renumbering of the unknowns, resulting in a preconditioning technique which shows, in many cases, the optimal order of computational complexity when combined with any conjugate gradient-like method: the number of iteration steps does not increase with mesh refinement. This leads to a method which is much easier to implement than multigrid techniques, where proper smoothers and restriction and prolongation operators are required. The new preconditioning technique only requires an ordering of the unknowns based on the different levels of multigrid, the choice of a drop tolerance controlling the size of

R = *A* - *LU*, and an ILU(ε)-preconditioning. Therefore, this technique is referred to as Nested Grids ILU-decomposition (NGILU). The reordering enables us to choose the drop tolerance in such a way that both high and low frequencies in the residual can be eliminated. This is illustrated by the results of Fig. 1 and 2. These figures show the results of Bi-CGSTAB combined with several preconditioners for a discretised aquifer problem (example 4 in [2]). The PDE contains convective parts and a strongly discontinuous diffusion coefficient. The convergence rate of Bi-CGSTAB combined with an NGILU-decomposition is excellent, even when the coefficients in the PDE are strongly discontinuous. Fig. 2 shows that the convergence behaviour is relatively smooth, which is advantageous to the construction of stopping criteria when the linear solver is used as an inner-iteration method, for example, within some Newton method. For further details we refer to [1].

If the numbering within the levels is lexicographical, and if Dirichlet boundary conditions are used, we obtain for the inner grid points of a rectangular 8 x 8-grid with constant mesh size:

1	2	3	4	5	6
7	28	8	29	9	30
10	11	12	13	14	15
16	31	17	36	18	32
19	20	21	22	23	24
25	33	26	34	27	35

The points with numbers i to 27 belong to the first level. Similarly, the two sets of points 28 to 35 and 36 belong to the second and third level respectively. (note that the number of inner grid points in one direction does not necessarily have to be a power of 2). The sparsity pattern of the coefficient matrix arising after a standard discretization of the Poisson equation on a uniform 10 x 10-grid with Neumann boundary conditions everywhere is shown below. The unknowns have been numbered level for level, and within the separate levels we have used a red-black ordering. The size of the dots represents the absolute value of the corresponding matrix entries.

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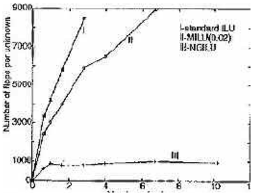


Figure 1 Computational effort vs grid refinement

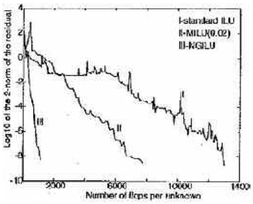
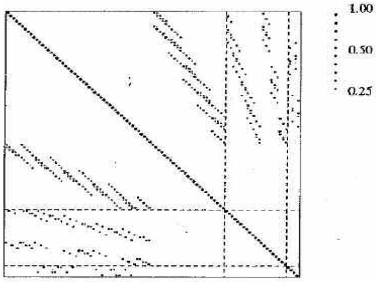


Figure 2 Convergence behaviour



M Zijlema
CGM Kassels
A Segal
P Wesseling

Computation of turbulent flows in boundary-fitted coordinates

In June 1993 the 2nd ERCOFTAC-IAHR Workshop on Refined Flow Modelling which was held at UMIST in Manchester was organized, which aimed to identify numerical and turbulence modeling capabilities for turbulent flow problems. One of the testcases which has a relative complex geometry is turbulent flow across a staggered tube bundle. This is of practical importance in heat exchangers. In the centre of the bundle the flow becomes periodic and it is sufficient to consider only a small part of the domain as sketched in Figure 1. Results have been obtained with the ISNaS code developed by our ISNaS (Information System for solving Navier-Stokes equations) group at TUD.

The ISNaS code is based on a co-ordinate invariant finite volume discretization on a staggered non-orthogonal grid of the incompressible Navier-Stokes equations. It permits an easy and accurate implementation of boundary conditions and therefore it makes the computation of flows in complex geometries possible.

Space discretization is done by an integration of the momentum equations over a cell to yield an equation containing cell-face fluxes which have to be approximated by central differences and bilinear interpolations. To ‘ensure a divergence-free velocity field a second order pressure-correction method is used. To solve the nonlinear system of equations we use a Newton linearization with an iterative GMRES method. Time discretization takes place with the implicit Euler method. Furthermore, it has been decided to use a standard high-Re k-ε model with wall functions in order to compute turbulent flow. The transport equations for turbulent energy k and its dissipation rate ε are solved in a decoupled way. Unlike the momentum equations, the convection terms in k-ε equations are approximated with upwind differences, to ensure positivity of k and ε. For the same reason, care has to be taken in linearizing the source terms (Zijlema, 1993).

The solutions were obtained by using a 2D non-orthogonal boundary fitted mesh. Because the flow is fully periodic, we use anti-symmetrical periodic boundary conditions at the inlet and outlet planes (Segal et at, 1993).

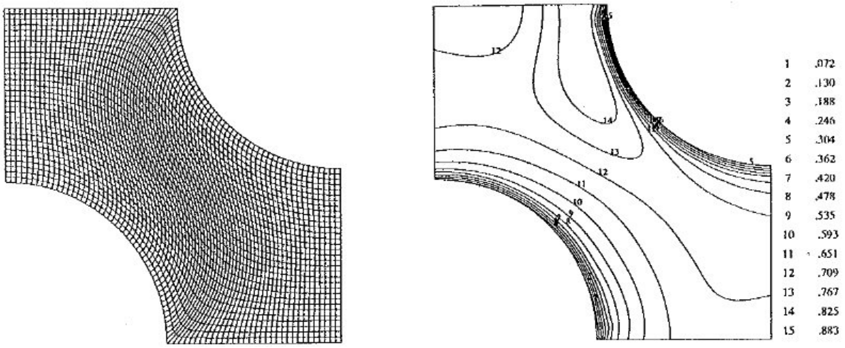


Figure 1 Finite volume grid and contour lines of turbulence intensity

The difference between the pressure at inlet and the pressure at outlet is determined by the imposed flow-rate Re_{in} = 18,000. Results of our computation are shown in Figure 1.

Results of computational solutions contributed by participants of the Workshop are plotted in Figure 2 which shows predicted velocity profiles across the recirculation region behind the lower tube and the impingement region in front of the upper tube (our result is marked with "DELFT/MZ"). These results have been obtained with the *k-ε* model. It can be concluded that qualitive trends are well resolved by our code. Moreover, the agreement between our results and other results can be said to be satisfactory. Concerning the separation process which is of particular interest our code correctly predicts a very small recirculation zone, which is remarkably good for a *k-ε* model.

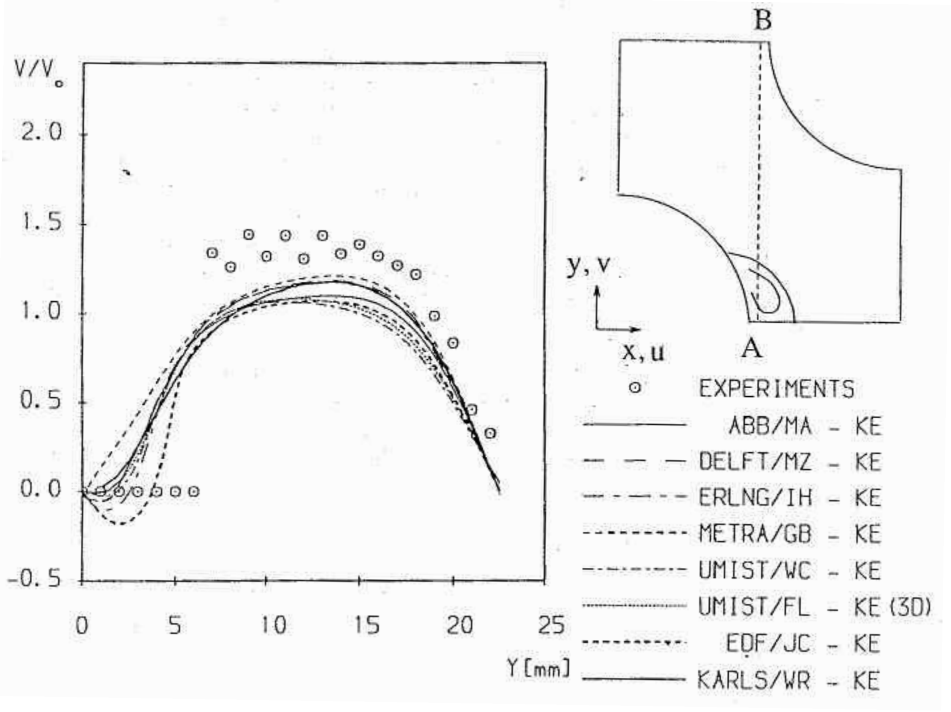


Figure 2 Velocity profiles across section AB in tube bank

RJA Janssen
CJ Hoogendoorn

Instabilities in a natural-convection flow in a cavity

Instabilities in the natural-convection flow inside a cavity (box) as shown in figure 1 have been studied. The cavity is differentially heated over two of its vertical walls (with a temperature difference ΔT); the horizontal walls are perfectly conducting (i.e. the temperature profiles depend linearly on x) whereas the front/back lateral walls (at z = 0,D) are insulated. For fixed ratios D/H and H/W , the flow inside the cavity depends on the Rayleigh and Prandtl numbers. In many technical applications, the flow is in the transition regime between laminar and turbulent and this originally motivated the present study which specifically investigates the instabilities that arise in the beginning of the transition in the flow. The study is conducted by performing direct numerical simulations of the flow in the cavity. The calculations are performed on the CRAY Y-MP in Amsterdam using grids with up to 120^3 grid points.

For air (Pr = 0.71), the first instability (resulting in time-periodic flow) is a buoyancy-driven (i.e. thermal) instability, somewhat similar to the, instability responsible for Rayleigh-Bernard convection. Flow visualization shows that the perturbations originate in the unstably stratified boundary layers along the horizontal walls of the cavity. Large fluctuations (with a peak-to-peak amplitude of up to 0.3 ΔT) occur in the flow as a result of this instability. Instantaneous temperature and velocity fluctuations (calculated by subtracting the time-averaged values in every grid point from the instantaneous values) in the plane x/W = 0.048 are shown for Ra 2.5 x 10^8 in figure 2. The dotted contours correspond to negative temperature fluctuations. The velocity and temperature fluctuations are clearly correlated with a double, vortical structure centered on the hot and cold spots which suggests the formation of 'thermals' in the flow. These thermals arise at fixed z-locations, resulting in a spatial periodicity in the z-direction in the flow.

The instability can be understood in terms of a simple model in which all convection in the flow is neglected and only the linear instability of an unstably stratified, diffusive thermal boundary layer is considered. Using the horizontally averaged mean temperature in the boundary layers along the horizontal walls, this conduction model predicts a dimensionless frequency equal to 0.26 which is very close to the value 0.266 calculated in the direct numerical simulation.

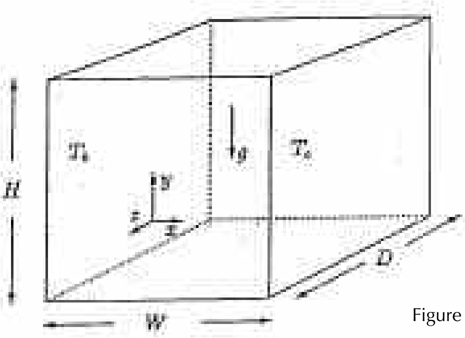


Figure 1 Configuration under study

For water ($Pr = 7$), also a buoyancy-driven instability occurs but the perturbations originate near the front/back walls (at $z = 0, D$) even when the depth D of the cavity is increased to $8H$. Furthermore, the hot and cold spots do not stay at fixed z-locations but travel in the lateral direction.

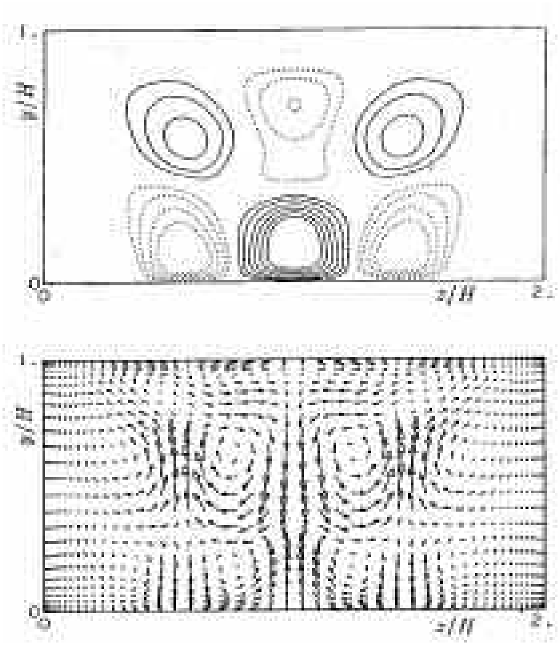


Figure 2 Instantaneous temperature and velocity perturbations in the vertical plane $x/W = 0.048$ near the hot cavity wall.

DF de Lange

Observations of cloud cavitation on a stationary 2D profile

Cavitation is important in the design of ship propellers, regarding the production of noise and erosion of the propeller blade surfaces. Both effects are caused by the same process; the implosion of cavities, which goes with a very high peak pressure in the final stage.

In our research we are mainly interested in the aspect of noise radiation by cavitating ship propellers. Although the collapse of single cavity bubbles explains the generation of high frequency noise, it is not adequate to explain the high sound level at frequency region around 1 kHz. Previous research in our group as well as by others, have shown that this part of the spectrum can be explained by the collective collapse of a cluster of bubbles: a bubble cloud.

Cavitation on a propeller or a hydrofoil can roughly be divided into three types: bubble cavitation, sheet cavitation and vortex cavitation.

We direct our attention to sheet cavitation. When the pressure along a blade sharply decreases below vapour pressure (e.g. at the leading edge of a propeller blade), the flow can detach at a (practically) fixed position and reattach at a downstream position, thus forming a rather flat sheet cavity, which remains attached to the blade. In view of the sound production, we are in particular interested in cloud cavitation, which is a special sub-type of sheet cavitation. When observing sheet cavitation experimentally, several researchers found that under certain conditions large bubble clouds break off regularly. These break-offs occur even at steady uniform inflow conditions. Although mechanisms have been mentioned to cause the break-off, it is not clear from literature which is the actual cause. Formation of a re-entrant jet was noted by a number of researchers, and.thought to be causing the break-off.
Others claim That some kind of instability of the cavity interface causes part of the cavity to break off.

In order to simplify the problem as much as possible, we study a cavitating 2D profile in a steady uniform flow. The observation experiments have been done in the cavitation tunnel of Delft University of Technology. The observation section measures 30 cm square and 50 cm in length. Experiments are performed with two NACA 16 profiles, with thicknesses of 6% and 9%, and a chordlength of 20 cm. The profile is made of plexiglass, in order to be able to observe the flow inside the cavity. Velocities range from 3 to 8 m/s.

Observations are mainly done by means of a High Speed Video (HSV) set, with a frame rate of 500 frames or 1000 half frames per second. For illumination, the set includes two stroboscopic light heads. From the HSV observations the structure of the cloud cavitation and the break-off mechanism became clear: The cause of the break-off was the formation of a re-entrant jet, and the subsequent collision of the jet with the cavity interface.

The break-off cycle is drawn schematically in figure 1. In figure 2 a sequence of HSV frames is shown. In the top right edge of each frame, the time is given in cosec.

The break-off cycle can be described as follows:

(1) A sheet cavity, smaller than some equilibrium length, starts to grow.

(2) At a certain length the growth will cease, and a re-entrant jet is formed at the closure of the cavity. (3)This jet is directed towards the leading edge of the profile/cavity. The velocity of the (front of the) jet is of the same order of magnitude as the main velocity.

(4) The re-entrant jet reaches the cavity near the leading edge and collides with the cavity interface. (See also first photograph in figure 2.)

(5) The rear part of the cavitation sheet forms a more or less spanwise cylindrical bubble cloud. The cloud contains a large amount of circulation, originating from the momentum of the jet, being opposite to the main flow.

(6) The front part of the original cavity is reduced to a tiny sheet cavity, which will again grow and start over the cycle from point 1. The cloud will be transported downstream.

The mechanism of cloud formation will be analysed by numerical modelling. For this, the flow is assumed to be a potential flow, and the numerical method is based on the boundary integral method.

Several researchers have approached the problem by using a Taylor expansion to transform the boundary conditions from the cavity interface to conditions on the profile surface or its camber line. Though we also used this method for the calculation of a steady sheet cavity, we have to abandon this approach for the calculation of unsteady sheet and cloud cavitation. The major drawback of this method is, that the local cavity thickness is a single valued function, which excludes modelling of a re-entrant jet. Therefore, we are presently working on a numerical method in which the boundary conditions are imposed on the moving cavity interface, involving re-paneling of the boundary in each time step.

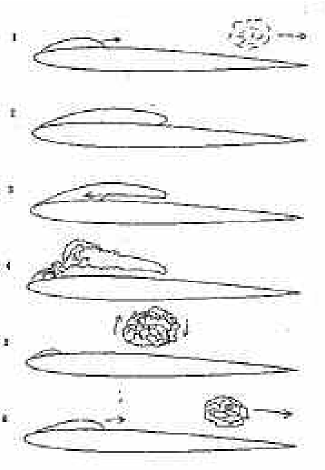


Figure 1 Schematic cloud break-off cycle

Figure 2 High speed video observations of the break-off cycle

SR Donohoe
WJ Bannink

High speed surface reflective visualization system

Objective

A high speed Surface Reflective Visualization (SRV) system is developed to provide a plan-view perspective on the vortex flow above a non-cambered sharp leading edge delta wing in compressible high subsonic flow (Mach number range of 0.6 - 0.85).
In this flow regime the flow above a delta wing exhibits strong interactions between the leading edge vortex system, conical embedded shocks located beneath the vortices and the trailing edge shock system. The influence of these shocks on vortex breakdown as well as the basic mechanisms of vortex breakdown itself have yet to be fully understood. The plan-view visualization provided by the SRV system provides new insight into the vortex breakdown phenomenon in the compressible flow regime.

System Configuration

The SRV system is a derivative of a double-pass schlieren/shadowgraph system in which the model surface itself is a flat mirror surface (see Figure 1). A parallel bundle of light is projected via a parabolic mirror into the test section along a path perpendicular to the model surface and is subsequently reflected from the model surface back along nominally the same path. Passing through the flow field above the model surface, the light is refracted as a function of the integrated density gradient existing perpendicular to its path. The incident and returning light bundles pass each other at the junction shown in the inset of Figure 1. The incident and returning light bundles are displaced from each other such that the incident bundle reflects via a tiny mirror (diameter 5 mm) while the returning bundle passes just next to this tiny mirror before reaching the schlieren knife located in the focal plane of the parabolic mirror.
In order to observe the high speed shock-wave and flow field fluctuations associated with vortex breakdown, high speed photos are made using the Impulsphysik Strobodrum camera with a maximum photo speed of 4500 Hz. The spark light source used for these tests is an Fischer-R138 Nanolite with a spark duration of nominally 18 nsec.

Results

Preliminary results have been obtained with the SRV system using both high speed spark and continuous light configurations. Figure 2 is an example of a high speed SRV visualization of a flow field exhibiting vortex breakdown, embedded cross-flow shocks and a trailing edge shock-wave system. In this case the system is configured with the schlieren knife edge parallel to the model chord. Vortex break down is visible at approximately 60% of the chord, where the organized vortex structure ends.
Moving from the center of the wing outboard toward the leading edge an expansion through inboard half of the primary vortex is visualized as a broad dark colored ray on the starboard side of the wing. Embedded cross-flow shocks (visible on the starboard side of the model as a sharp light colored line) are apparent outboard of the main vortex structure on either side of the wing. The trailing edge shock system is visualized by the dark lines convex to the wing apex intersecting the symmetry plane of the wing at approximately 50% and 92% of the chord.

Future Prospects

The preliminary results referenced above were very encouraging. Currently work is being done to enable use of both direction and magnitude indicating color schlieren diaphragms with the SRV system. If successful, the system is expected to resolve questions regarding the geometry of vortex breakdown in the compressible flow regime.

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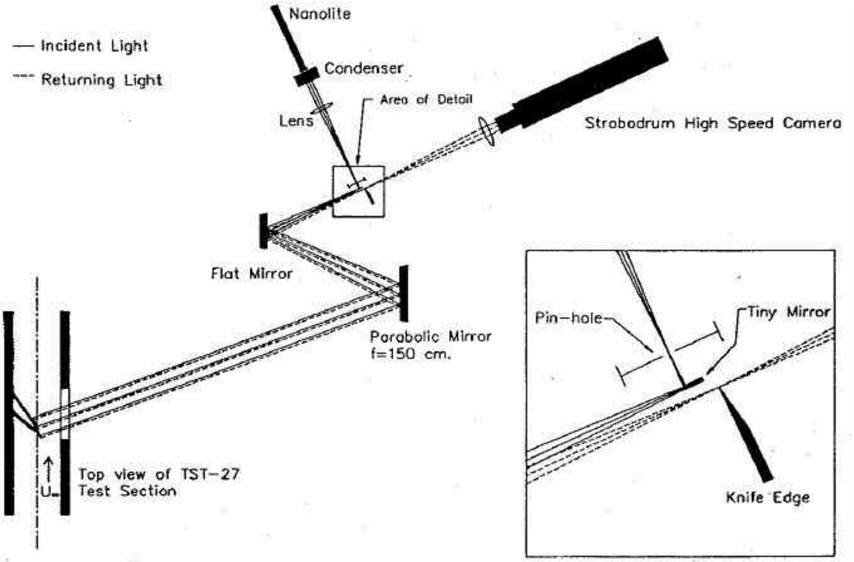


Figure 1 Surface reflective visualization (SRV) system configuration

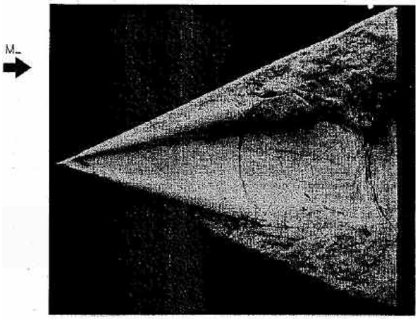
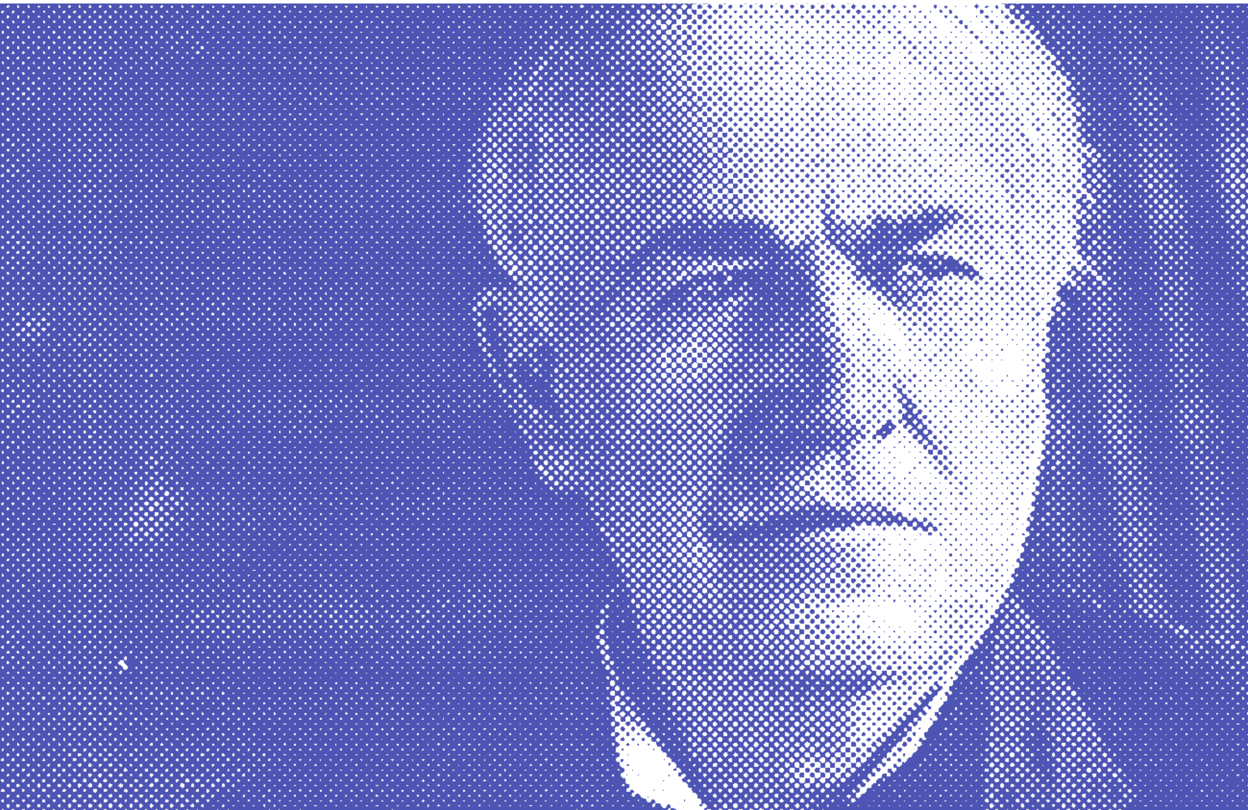


Figure 2 Surface reflective visualization above delta wing with spark light source and schlieren knife edge parallel with the model chord, $\alpha = 20$·, $M = 0.8$

I have not failed,
I've just found
10,000 ways that
won't work

Thomas Alva Edison



1994

PD Minev
FTN van de Vosse
AA van Steenhoven

Transient natural convection in a 2-D enclosure

The instabilities in the natural convection flow in a rectangular cavity are studied. The flow is triggered by a heat source placed on the bottom of the vessel. It is supposed that all the properties of the fluid are constant except for the density in the buoyancy term supposed to be linearly dependent on the temperature which yields the so-called Boussinesq approximation of the momentum equations. On all the walls of the cavity a no-slip condition on the velocity is imposed. The side walls are supposed to be adiabatic. The top wall is kept at a constant temperature. On the bottom wall a local heat flux with a Gaussian distribution centered at the midpoint is prescribed. This distribution of the heat flux is preferred because its representation with high-order methods (used in the present study) is more independent of the mesh size than a simple step function used by some other authors.

The Navier-Stokes equations are solved in primitive (velocity-pressure) variables. First, they are discretized in time by a second order backward differencing and the convection part of the equations is splitted from the diffusion part by means of the so-called operator-integration-factor procedure. The velocity and temperature on time levels n and n-1 are convected to the level n +1 by means of a third-order explicit Runge-Kutta scheme. Then the temperature is "diffused" implicitly and used in the source term of the saddle-point (Stokes-like) problem for the velocity and pressure resulting from the operator-integration-factor procedure. The velocity and the pressure are evaluated by means of a projection procedure applied on the continuous (in space) system of equations. The whole procedure finally requires solving of three convection-diffusion equations for the velocity and temperature, respectively, and one Poisson equation for the pressure. They are discretized in space by means of the spectral element method using the same grid for the velocity and the pressure.

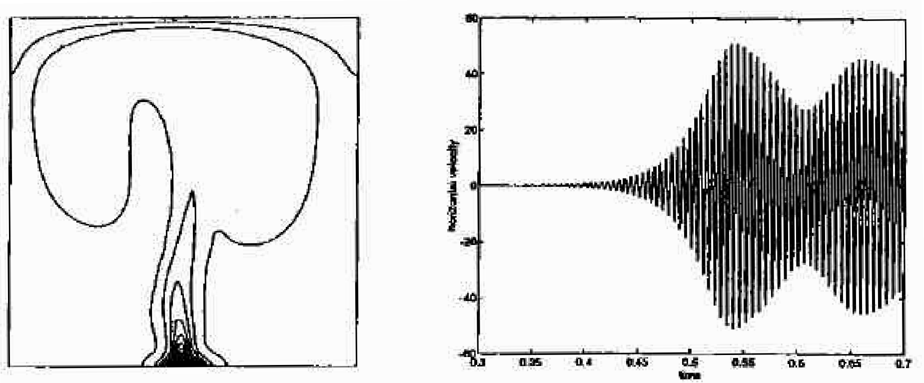


Figure1 R = 1.3 x 10^8, a) isotherms at t=0.7; b) time series of horizontal velocity at (0.5, 0.5)

The algorithm is tested on the flow in a differentially heated cavity with respect to an existing benchmark solution and other available data for the periodic regime of the flow.

At present only the case of an air-filled cavity is studied. At Rayleigh number about R = 1.3x10^8 the flow undergoes its first bifurcation towards a quasi-steady swaying regime (fig.1). It is however very unstable and just a slight increase of the Reynolds number causes a second bifurcation of a pitchfork type. The initial vortex dipole is transformed in one big vortex occupying most of the cavity. This flow pattern improves the heat transfer rate with about 30 % (see fig. 2). The one-cell flow is relatively stable and one needs a large increase of the Rayleigh number up to R = 10^9 in order to trigger instability. It is due to the interaction of the main vortex with the small corner vortices. The initial single-frequency pattern is followed of a rapid transition to chaos when the Rayleigh number is increased above 10^{10}.

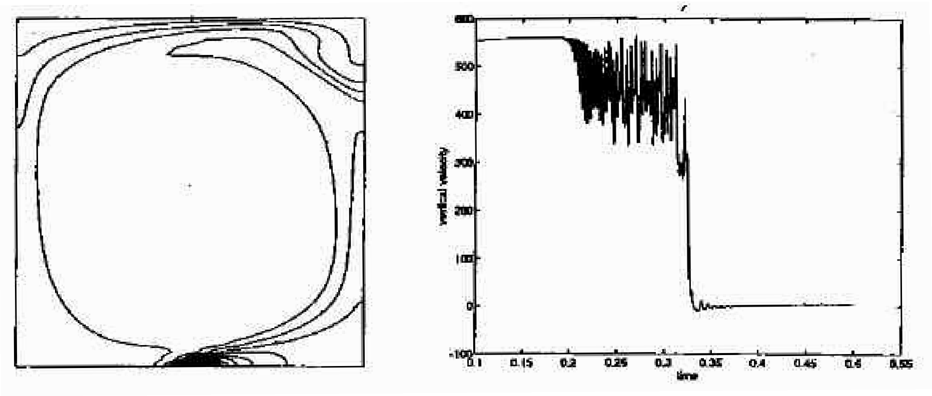


Figure 2 R = 1.6 x 10^8; a) isotherms; b) time series of the temperature at (0.5, 0)

JE de Vries
PJJ Stroomer
ThH van der Meer
CJ Hoogendoorn

Turbulence-chemistry interaction in diffusion flames

Combustion is a hot item in computational fluid dynamics. It involves many chemical and physical processes, that need to be modelled, such as turbulent flow, radiative heat transfer, chemical reactions of combustion, and chemical reactions by which soot and pollutants like NO_X are formed. Most of these processes are coupled and non-linear. One of the major problems is the correct treatment of turbulent fluctuations of temperature and species concentrations. Single probability density functions (pdf's) and joint pdf's of thermo-chemical variables are used to calculate the source terms (due to chemical reactions and radiative heat transfer) in the equations governing conservation of species concentration and energy. The complexity of these simulations is so large that we are far off from exact simulations. With the computer codes of today it is possible to predict the average flow and temperature field of combustion systems, heat transfer in furnaces and trends in NO-formation.

To investigate the interaction between turbulent fluctuations and chemical reactions, in our heat transfer section simulations as well as experiments are performed of an axisymmetric turbulent diffusion flame. Figure 1 shows the configuration. We have chosen for a flame in a three flow system. Two shear layers exist in which turbulence is generated. The interaction of this turbulence with the flame is the main topic of research.

Laser diagnostics (Laser Doppler Anemometry (LDA), Laser Induced Fluorescence (LIF) and Coherent Anti-Stokes Raman Spectroscopy (CARS)) are used to measure averaged values, probability density functions and turbulent time and length scales of velocity, species concentrations and temperature. The LDA measurements revealed the turbulent mixing of the three flow system. They show the large velocity fluctuations caused by the inner shear layer (between central fuel jet and primary air) as well as the outer shear layer (between primary and secondary air).

The planar LIF measurements of the OH radical clearly show the flame front including local extinction phenomena (see figure 2b).

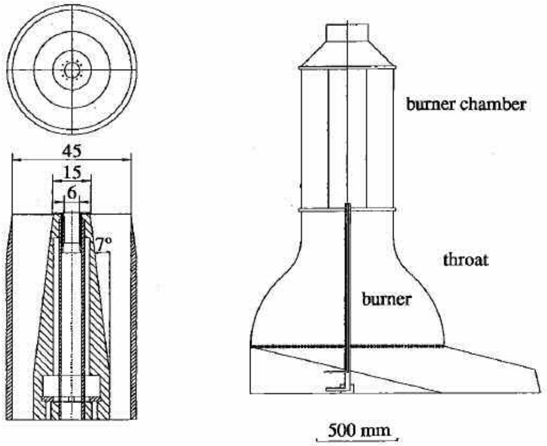


Figure 1 The experimental configuration with details of the burner

This local extinction is believed to be caused by the deformation of the flame front by turbulence and the fast removal of heat from the flame front by turbulent mixing. Local extinction, but also intermittency, results in peaks in the pdf's at zero concentration. Next to this peak the pdf's generally are rather flat at larger concentrations. This suggests that the modelling will need a combination of a Dirac delta function an a top-hat distribution. In some cases however, the peak at zero concentration is rather wide, and a (3- function is more appropriate. Since the LIF measurements resulted in instantaneous (within 6 ns.) values of the OH concentration along a line or in a plane, spatial correlations could be obtained. From these correlations integral and Taylor micro length scales were determined. The integral scales are smallest (1 - 2 mm) at the locating of the maximum OH concentration and largest (6 -10 mm.) at the outer regions (see figure 3). Apparently at the position of the flame front OH reacts within an eddy life time and in this way the correlation length is decreased. Comparison of turbulence intensities, temperature and OH-concentrations elucidates that interaction between turbulence and reaction zone increases with downstream position. There the outer shear layer penetrates the flame front.
The temperature measurements using CARS show very large temperature fluctuations with root mean square values up to 600 K. This emphasizes the importance of the effects of turbulent fluctuations on the non-linear processes in combustion.

Figure 2 2D instantaneous images of OH-concentration by LIF

a) low RE-number b) high RE-number c) medium RE-number with preheated air and fuel

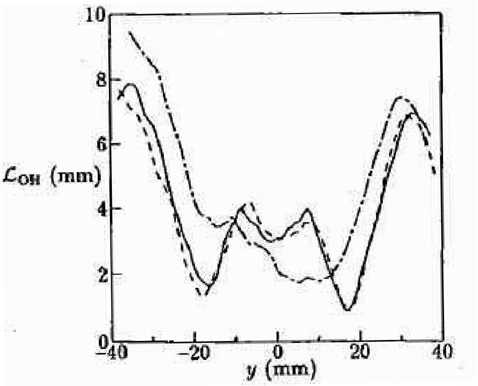


Figure 3 Radial profiles of integral length scales for three flames

Rheology of weakly aggregating polystyrene latex dispersions

R de Rooij
A Potanin
D van den Ende
J Mellema

The investigation of aggregating dispersions is of great interest from both practical and fundamental point of view. In industrial applications knowledge of the behavior of such dispersions in equilibrium or under flow conditions is of great importance. Clear examples are (the handling of) food products and paints. To understand their properties one has to examine the relation between the macroscopic flow behavior and the micro structure.

To reduce the parameters that influence the behavior we have taken a model dispersion consisting of monodisperse polystyrene latex particles with a diameter of about half a micron dispersed in water. The particles were coated with a dense layer of surfactant molecules with a thickness of about 3.5 nm. The electrostatic repulsion between the particles due to the surface charge density was screened by adding an excess concentration of electrolyte. Then there remains the Van der Weals attraction and the short range steric repulsion due to the surfactant layer. This results in a weakly aggregating dispersion which is ideally suited for our investigations: the determination of the viscosity, η, as a function of the shear rate, $\dot{\gamma}$, in a steady shear flow as well as the transient behavior of η as a function of time after a step in shear rate.
These macroscopic properties are coupled to the microscopic structure by modeling the aggregates as monodisperse fractallike spheres containing chains of particles and considering the strength of both the intra- and the interaggregate chains and their contribution to the macroscopic stress. With this model the experimental results have been interpreted.

In figure 1 the measured flow curves, η as a function of $\dot{\gamma}$, are given for different volume fractions ϕ. The symbols indicate the measured values while the lines result from a single fit of the model to the experimental data.

From this fit values for the fractal dimension of the aggregates, df=2.2, and the maximal relative strain of a particle chain, Cf=0.005, have been obtained.

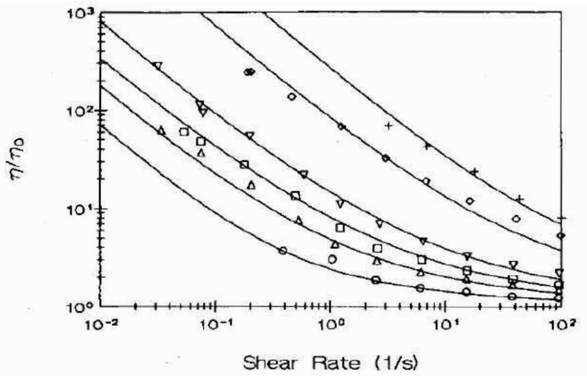


Figure 1 η as a function of $\dot{\gamma}$ for different volume fractions ϕ = 0.011(o); 0.022 (Δ); 0.032 (□); 0.045 (∇); 0.097(◆) and 0.15 (+). Symbols indicate experimental values, lines represents the model calculations.

In figure 2 the time dependent behavior of the viscosity is given after a step down in shear rate from $\dot{\gamma}_1 = 95$ to $\dot{\gamma}_2$ for $\phi = 0.045$ and different values of $\dot{\gamma}_2$. To eliminate the influence of the shear history the sample was sheared at $\dot{\gamma}_1$ for more than two hours, before the step down to $\dot{\gamma}_2$ was applied. In order to model the transient behavior of the viscosity the restructuring of aggregates has to be considered.
A rigorous description of this restructuring process is very complicated. Hence only the latest stage of this process has been modeled, where growing aggregates absorb small clusters of particles being left from the breakup and grow processes at earlier stages. In the model this absorption of particles is calculated assuming diffusion limited aggregation. The model was fitted to the measured time dependence with the cluster size and the fractal dimension as parameters. The cluster size obtained was R/a=3, where R is the mean radius of the cluster and a the particle radius. For the fractal dimension we obtained again: df=2.2. This value corroborates the value obtained from the fit in figure 1. The resulting fit is satisfactory for times longer than 200 s. At shorter times not. This is not surprising since the model is valid only at the latest stage of aggregate growth. With our model we are able to describe the basic features of both the steady state viscosity as a function of shear rate and volume fraction and the transient behavior after a step down in shear rate in terms of microstructural parameters. So a first but firm step has been put on the way to the understanding of the flow behavior of more complicated current dispersions.

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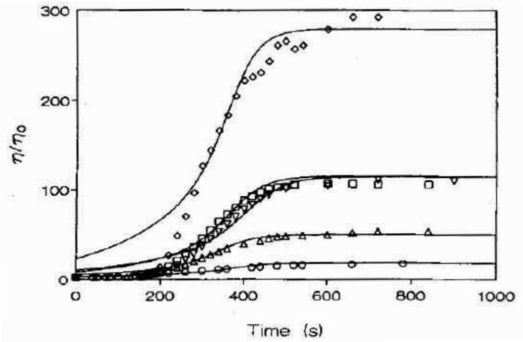

Figure 2 The relative viscosity as a function of time after a step down in shear rate from $\dot{\gamma}_1$ = 95 to $\dot{\gamma}_2$ = 0.763 (0); 0.201 (Δ); 0.093 (□); 0.077 ( ) ▽and 0.031 (◆) for v=0.045. The step was applied at t=0 s.

AJHM Reniers
JA Battjes

Shear instabilities in longshore currents

In 1989, Oltman-Shay et al. discovered significant oscillations in the wave-driven nearshore velocity field in the surf zone along an Atlantic beach in the USA.
The associated particle velocities can be of the same order as those of the wave-driven flows, but typical frequencies are much lower than the frequencies of the incident wavefield. Bowen and Holman (1989) suggested that the oscillations might be due to shear instabilities in the wave-driven longshore current, and they derived a corresponding model.

The aim of the present project is to investigate possible instabilities in wave-driven longshore currents under controlled conditions in a laboratory, and to determine their mechanics and characteristic properties. This had not been done before so we could not build on past experience. Because it was not certain that instabilities would develop at all, or to measurable intensities, we chose a combination of conditions which -within the constraints of the available wave basin - were maximally conducive to the occurrence of instabilities, as inferred from stability analysis of the longshore current.

To this end, waves were propagated in a basin at a large angle to the normal (30°) of a smooth, concrete beach of about 33 m length and a barred profile (fig. 1). Horizontal particle velocities were measured with twenty electromagnetic flowmeters (EMF). Eight of these were positioned in a cross-shore array (fig. 1) to measure the shear in the longshore current field, and twelve in a longshore array to measure growth and alongshore wavelengths and phase velocities of possible perturbations.
The observed wave-induced longshore current had a maximum,mean velocity of nearly 0.5 m/s.

The experiments were successfull. Strong oscillations were observed in the velocity field (fig. 2). Fig. 3 shows frequency spectra of particle velocity in three positions along the beach.

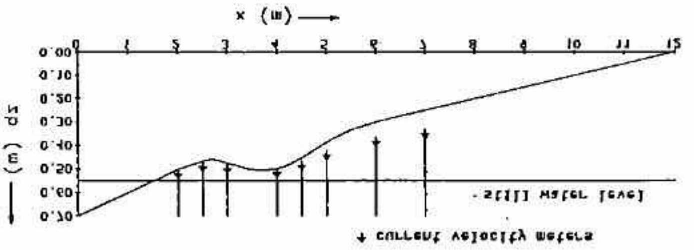

Figure 1 Bottom profile and cross-shore array of EMF's

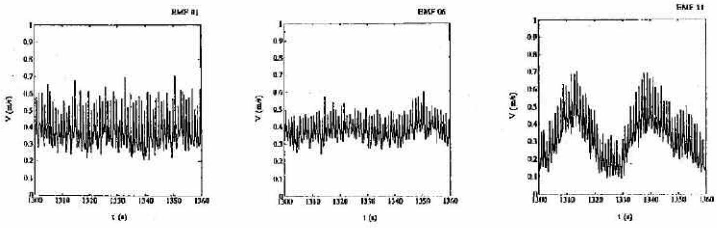

Figure 2 Records of longshore velocity in three stations along the beach, at 3.75 m (EMF 1), 15.25 m (EMF 6) and 27.75 m (EMF 11) downstream from the inflow opening, respectively

The growth of a low-frequency peak (around 0.04 Hz, compared to 1 Hz for the incident waves) can be observed. The energy contained in this peak was found to grow exponentially in the downstream direction. Frequency-wavenumber spectra were estimated from the records of the longshore array of velocitymeters using a Maximum Entropy Method. The results indicated a frequency-independent alongshore phase velocity of about 0.30 m/s. The fact that this is far less than the phase velocity of gravity waves, and of the order of magnitude of the mean longshore current velocity, shows that the oscillations are due to shear instabilities advected with the flow, not independently propagating waves. The observational results have been compared to a theoretical model for the prediction of the unstable modes, their growth rate and phase velocity (Falques and Iranzo, 1994). The range of unstable wavenumbers was well predicted (fig. 4) as well as their phase velocity (error less than 10%), but the growth rate was grossly underpredicted. This requires further investigation. The experiments have been performed at Delft Hydraulics, financed by the European Union (LIP project 19M). Mr. Reniers is financed by the JM Burgers Centre (EZ grant, project P-01).

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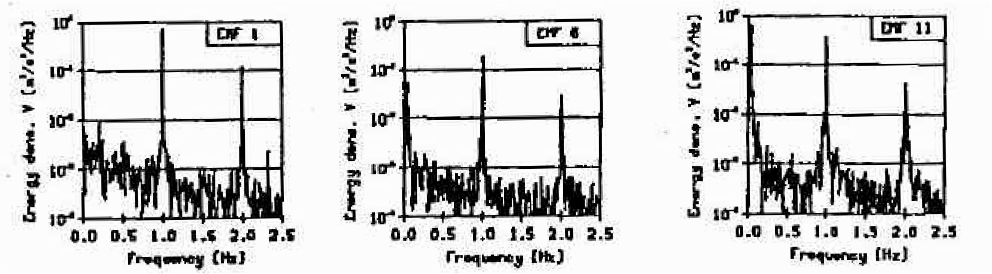

Figure 3 Frequency spectra of the records shown in figure 2

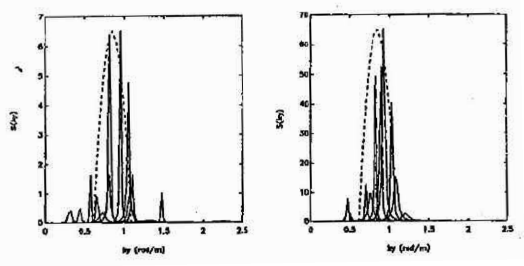

Figure 4 Wavenumber spectra of longshore velocity for a set of discrete frequencies (drawn curves), showing the wavenumber range of unstable modes, and (at arbitrary scale) the theoretical prediction of the growth rate in the theoretical wavenumber range of unstable modes (dashed curves). Left panel: upstream half of the beach; right panel: downstream half of the beach. The unit of spectral density is $(m/s^2)/(m^{-1}$ Hz); note the difference in scale of spectral density in the two panels.

OU Velasco Fuentes
GJF van Heijst

Two-dimensional vortices with background vorticity

The main motivation of the study of two-dimensional vortices arises from geophysical fluid dynamics: the large-scale atmospheric and oceanic flows are to a first approximation two-dimensional, mainly due to the Earth's background rotation, density stratification and the shell-shaped geometry of the flow domain. The spherical shape of the Earth leads to a latitudinal variation of the background vorticity. For flow phenomena on a limited scale (less than approx. 100 km in NS direction) the variations in this background vorticity are negligible. For larger scales (in the range 100-1000 km, typically) the planetary vorticity can be approximated by a linear function of the latitude (β-plane approximation). Near the poles, the planetary vorticity is a quadratic function of the distance to the pole (γ-plane approximation).

Velasco Fuentes (1994) has studied both the dipolar and tripolar vortex. The dipole vortex consists of two compactly packed patches of oppositely signed vorticity, and it translates in the direction defined by its axis. When the vortex is symmetric, it moves along a straight path; when one of the halves is stronger than the other, the dipole trajectory is a circle. The tripolar vortex is an arrangement of three compact vorticity patches of alternating sign. In the symmetric case the arrangement is linear, and the circulation of the central vortex is exactly twice that of the satellites. Laboratory experiments have been carried out in a rotating fluid tank. Gradients in the background vorticity were established by depth variations in the fluid (free-surface and bottom topography). Flow visualization and particle tracking techniques (based on digital image analysis) were applied in order to determine the trajectories and vorticity distributions of the individual vortices as well as the advection of passive fluid parcels.

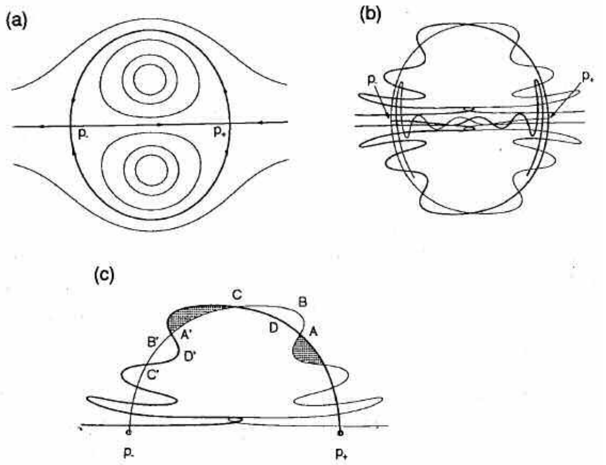

Figure 1 (a) Streamlines of an unperturbed point-vortex dipole. (b) The heteroclinic tangle in the perturbed case; the thick line is the unstable manifold and the thin line is the stable manifold. (c) The transport mechanism in the hetereoclinic tangle: region ABCD is mapped onto A'B'C'D'.

The flows were studied theoretically by use of a modulated point-vortex model, in which the modulation of the vortex strengths is based on conservation of potential vorticity. This technique was also applied in numerical simulations of the flows. Two different types of numerical simulations have been performed: (i) the contour kinematics method, according to which material lines, defined by some hundreds of passive tracers, are advected by a set (max. 4) of modulated point vortices; (ii) the vortex-in-cell method, which uses some thousands of active particles (modulated point vortices) to describe the flow.

The meandering motion of a dipole on the β-plane and γ-plane has been analysed theoretically. The motion of a passive tracer induced by a meandering point-vortex dipole is governed by a set of equations that is equivalent to a periodically perturbed, integrable Hamiltonian system and the advection properties of the meandering dipole could thus be described analytically by using dynamical systems theory. Of particular interest is the mass exchange between the dipole halves as well as between the dipole and its environment (entrainment, detrainment}. The amount of mass that is exchanged was found to be proportional to the gradient of the background vorticity and the amplitude of the dipole's meandering trajectory. On a γ-plane the tripole shows a complicated quasi-periodic behaviour. This unsteady motion leads to mass exchange between the three constituting vortices and also between the tripole and its surroundings.

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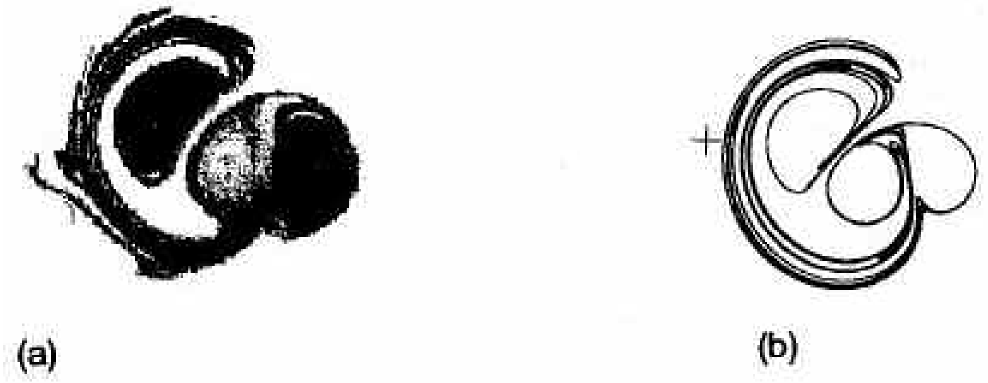

Figure 2 (a) Plan-view of the experimental tripolar vortex (dye visualization) and (b) the numerical contour-kinematics simulation with three modulated point vortices.

JB Flór
GJF van Heijst

Coherent vortex structures in stratified fluids

Two-dimensional (2D) turbulent flows have the characteristic property to organize into large, coherent vortex structures. Due to their slow dissipation such vortices dominate the flow evolution to a large extent. Motivated by their relevance to geophysical flow systems, the characteristics of coherent vortices as well as the organization properties of flows in a stratified fluid were investigated experimentally and numerically.

In stratified fluids, vertical motions are suppressed by the buoyancy force. In such fluids a local perturbation (such as a pulsed horizontal jet) leads to a mixed region that, after the gravitational collapse of the mixed fluid, acquires a flat, pancake-like shape in which the (planar) motion is quasi two-dimensional. The selforganization property of such flows is manifest in the emergence of coherent vortex structures. Laboratory experiments were performed in which principally the dynamics of monopolar and dipolar vortices could be measured. It was found that unstable monopolar vortices may under certain conditions give rise to the formation of higher-mode structures such as the tripole and the triangular vortex with three satellites. Quantitative and qualitative information about the flow evolution (velocity and vorticity distributions) were obtained from dye visualization and particle tracking techniques.

The Lamb-Chaplygin dipole model was found to descibe the observed dipolar structures quite well. By two analytical models, based on the 2D Lamb-Chaplygin model, the viscous decay of these vortex structures due to vertical diffusion of vorticity, could be described, and the results compare well with the observations. The same applies to the decay of-monopolar vortices.

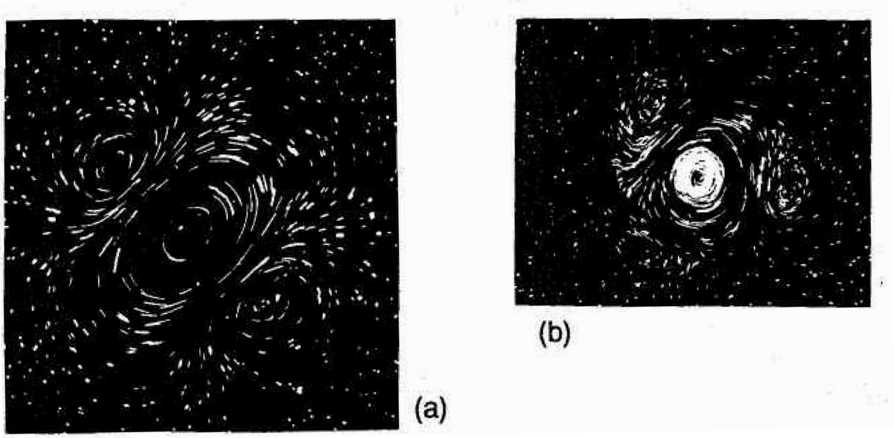

Figure 1 Streak pictures of (a) a tripolar vortex and (b) a triangular vortex with three satellites. Both vortex types were found to arise from an unstable monopolar vortex in a linearly stratified fluid.

Additional experiments were performed in order to study the selforganization of quasi-2D turbulent flows on a finite domain with solid lateral boundaries. It was found that the flow evolution to a quasi-final equilibrium state is determined both by the initial vorticity distribution and the domain geometry. On a rectangular domain a cellular vortex pattern was observed to form, with generally the number of cells equal to the length/width ratio of the domain; this is similar to what is observed in the spin-up of a homogeneous fluid in the same container. Viscously generated vorticity at the solid walls and mutual interactions between the vortex cells usually led to small oscillatory drift motions of the individual cells. These drift motions provide an essential mechanism for the exchange of fluid between the individual cells ("anomalous diffusion"), as has been demonstrated convincingly by dye visualizations. This aspect of chaotic advection in cellular flow patterns induced by small (time-dependent) perturbations will be studied in more detail in a future project.

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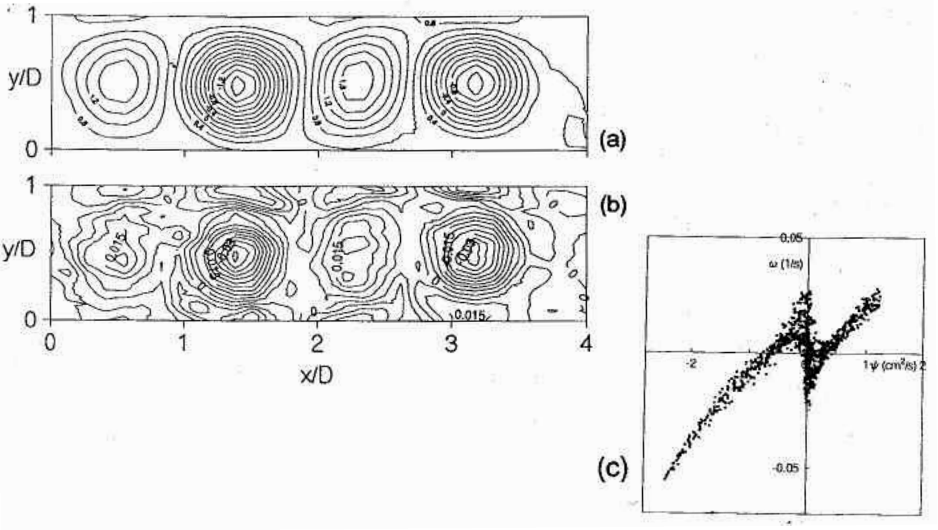


Figure 2 Contour plots of (a) the stream function ψ and (b) the vorticity w as measured in the cellular flow pattern arising after random forcing in a rectangular tank with length/width ratio 4. Graph (c) is the so-called (ω,ψ) scatter plot of the two central cells.

F Alkemade

The vorton method

Coherent structures in turbulent flows are generally considered as deformed vortex lines or rings. A well-known example of these is the horseshoe or hairpin vortex, which has been observed in turbulent boundary layers; see figure 1 a.
During experiments, the 'hairpin' usually appears to be at an anlge of 45 degrees with the flat plate. These vortices have been related to the so-called bursts. These are vehement and unpredictable 'explosions' of transport of momentum, perpendicular to the plane along which the flow is occuring. An important question here concerns the parameters of the flow with which the frequency of the occurrence of bursts can be influenced. Horseshoe vortices have been related to vortex rings.

A possible relation is sketched in figure 1 b. The head of the hairpin narrows and due to vortex reconnection a vortex ring-like structure will pinch off.

One method to investigate these kinds of vortex structures is the vorton method. In fact, this method is a three-dimensional analogy of the well-known two-dimensional point vortex method. Continuous distributions of vorticity are constructed from small building blocks, the vortons (see the vorton ring in figure 2). These vortons can be seen as arrows: they have a location and a strength and direcion of vorticity.
By solving the equations for the displacement and deformation of the vortons numerically, the behaviour of 'vorton structures' can be studied.

By means of the vorton method a vortex configuration has been investigated which may give insight into the behaviour of certain coherent structures in turbulent boundary layers. The configuration which I have studied is shown in figure 2.
Figure 3 shows that the shear flow has an important influence. The ring moves away from the plate, but the deformation due to the flow causes a reorientation of the ring towards the plate after some time. At about t = 0,085 s, the ring 'touches' the plate and some vortons pinch off. The other vortons form a horseshoe-like string, which soon deforms. Thereafter, a vortex ring, smaller than the original one, pinches off.

To investigate the appearance of a burst-like phenomenon, the maximum value of uv has been calculated as function of time t (u is the velocity in direction x and v in direction y). This expression is a measure for the local transport of momentum perpendicular to the plate. Indeed, some peaks of the value of u v appeared to occur in time. It also appeared that the characteristic velocity of the shear flow influences the time up to bursting. This suggests that the burst frequency can be influenced by external parameters (i.e. parameters not related to the wall) and this information may be useful in the study of drag reduction.

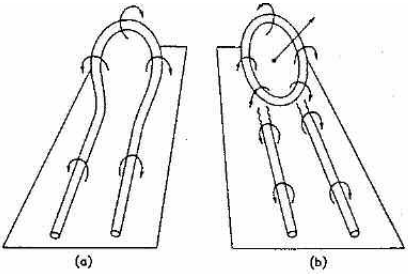


Figure 1 (a) A horseshoe vortex in a boundary flow above a flat plate (the flow is directed away from the reader).
(b) Strangling of a horseshoe vortex and formation of a vortex ring due to vortex reconnection. From: SJ Kline, NH Afgan (Eds.), Near- wall turbulence, Hemisphere New York, 1988.

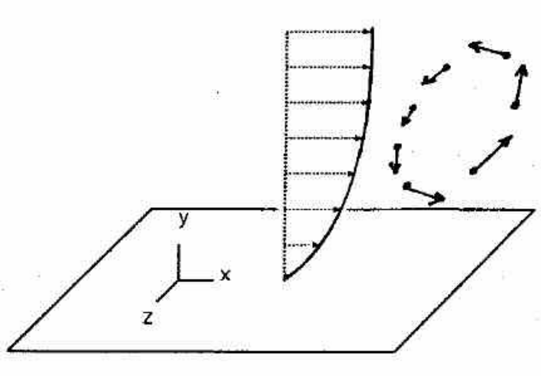


Figure 2 A vortex ring made up of vortons, i.e. a vorton ring (on the right), is placed above a (imaginary) flat plate and in a shear flow with parabolic velocity profile.

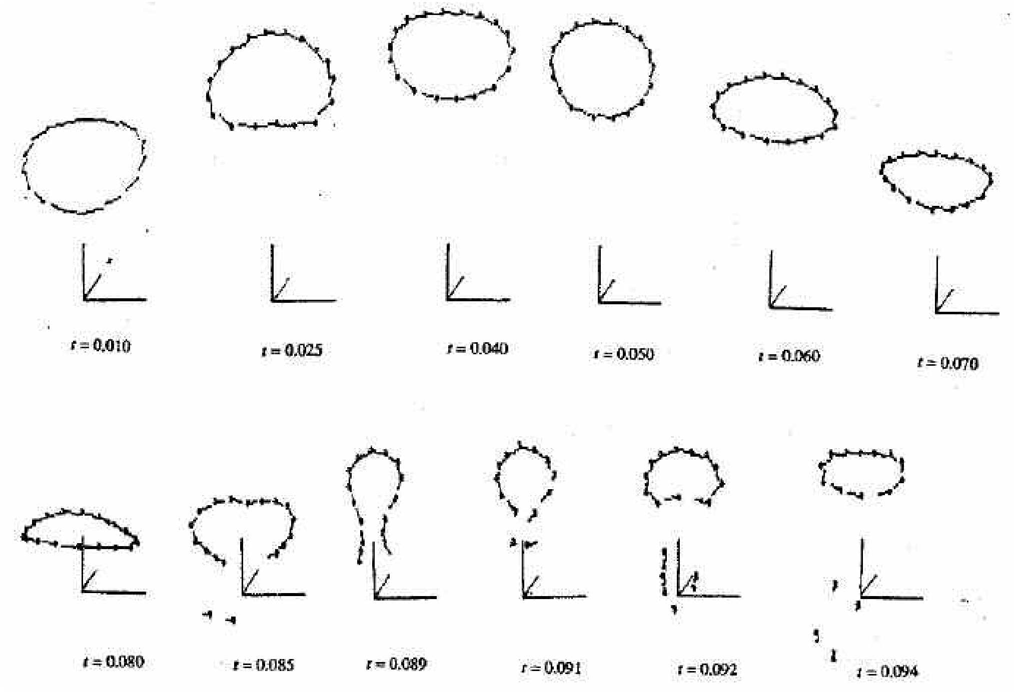


Figure 3 Development in time of the deformation of a vorton ring as sketched in figure 2 (seen along the x-axis). The arrow points of the vortons have been replaced by small circles; t is time (in seconds),

JA Keuning

The non-linear behaviour of fast monohulls in head waves

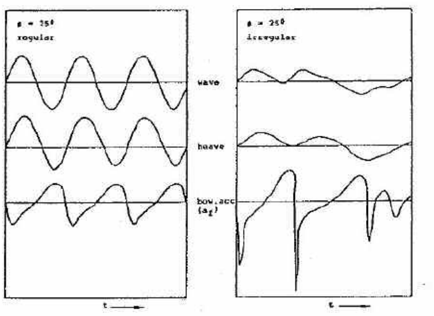
This study on the non-linear behaviour of fast monohulls in head waves has been carried out at the Delft Shiphydromechanics Laboratory. Research on the dynamic behaviour of fast planing boats at the Laboratory started as early as 1970 with the work of JJ van den Bosch and J Gerritsma.

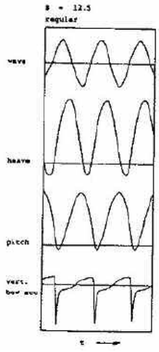
The occurrence of high peaks in the vertical accelerations experienced by fast ships whilst sailing in head seas is the limiting factor for the safe operation. However the methods most commonly used for the calculation of the motions and accelerations of ships in waves are based on linear mathemathical models and these appeared not to be capable of predicting these peak values in the vertical accelerations with great accurracy. Therefore in the frame work of this study an adapted computational model has been sought for the prediction of the motions and vertical accelerations of these ships. The aim was to use this model to be able to predict the operability of these fast monohulls in an early design stage. To do this the new computational model would have to incorporate a number of phenomena which are considered to be of importance for the non-linear behaviour of these fast monohulls and which were presently not accounted for by using linear computational models. Most methods to predict ship motions in waves are based on linear models. This implies that the ship is considered to perform small amplitude motions around its “calm water zero speed” reference position. It is known however that fast ships may develop a considerable hydrodynamic lift. This hydrodynamic lift results among other things in a change of the reference position of the ship with respect to this “calm water zero speed” position: i.e. the sinkage (stationairy heave) and the trim (stationairy pitch). In addition to this the continous change of this hydrodynamic liftforce on the ships hull whilst performing its motions in the waves appeared to be a major contribution in the forces. The wave exciting and hydrodynamic reaction forces also have a considerable non-linear character due to the change in instantenous submerged hull geometry of the ship while performing large relative motions with respect to the incomming waves.

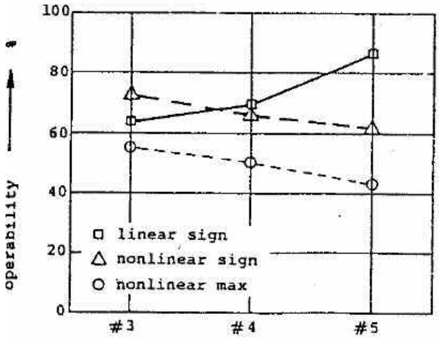
In the new computational model special attention has been given to:

- the computation of the sinkage and the trim of the ship due to the high forward speed. A method to predict sinkage and trim of an arbitrairy monohull at speed based on results of extensive experiments has been developped;
- the computation of the hydrodynamic lift force distribution along the length of the ship using the known result for sinkage and trim at speed;
- the influence of the large relative motions of the ship and the bow flare of these ships;
- the vertical added mass and its distribution along the length of the ship at high forward speed. In the model the added mass has been evaluated as time depended;
- the wave exciting forces computed over the actual submerged volume of the hull in its relative motion with respect to the wave.

The first aim of the development of the new computational model in this study was to check whether the implementation of these effects was important for a more accurate prediction of the motions and accelerations of these fast monohulls in head waves. Hereto the emphasis has been placed on a proper but often more emperical discription of the effects mentioned rather than on an exact mathematical formulation hereof (if at all possible at the time). As an example some sample results of the computer code FASTSHIP based on the non-linear computational model are shown in the figure. The results refer to two hard chined planing boat hulls with 12.5 and 25 degrees deadrise at midship respectively. These are two of the models of the Delft Systematic Deadrise Series consisting of some 15 different models all tested extensively in 80 different design conditions in calm water and a limited number in both regular and irregular waves in the frame work of this project. The forward speed for which the results are shown corresponds to approximatly 25 knots for a 15 meter boat. Shown are the heave- and pitchmotion and the vertical acceleration at the bow in both regular and irregular waves. The non-linear respons of the boats is obvious and matches the results obtained from model experiments with identical models in the towing tank of the Delft Shiphydromechanics Laboratory. In addition the dependency of the non-linear behaviour on the deadrise angle may be observed from these results. The results of this computational model have been validated using the results obtained from model experiments. The improvement in particular for the vertical accellerations over the linear computational models has been shown. It was shown that the implementation of the discribed effects into the non-linear computational model improved the predictions considerably. In particular the high peaks in the vertical accellerations were much better predicted. From full scale experiments aboard actual fast ships at sea carried out in the framework of this project this proved to be of importance. From these tests it was found that the occurrence of these peaks was the limiting factor for the save and comfortable operation of fast ships at sea. So the capability to predict these is of considerable importance. The impact of these non-linearities on the operability calculations for fast monohulls in head waves, as commonly carried out in the design process, have been demonstrated by using both linear and non-linear computational models for these calculations. From this comparison it was shown that the use of linear models may lead to opposite trends of operability with respect to the change of certain design parameters.







Once you eliminate
the impossible,
whatever remains,
no matter how
improbable, must
be the truth

Sherlock Holmes

1995

JG Wissink
RWCP Verstappen
AEP Veldman

Direct numerical simulation of turbulence : an evaluation of numerical methods

Direct numerical simulation (DNS) of turbulent engineering flows - i.e. computing numerical solutions of the unsteady Navier-Stokes equations that resolve the evolution of all dynamically significant scales of motion, without using any turbulence model - more than exhausts the largest available computing resources. The enormous appetite for floating point operations and bytes limits DNS to low Reynolds numbers.
To enlarge the class of turbulent flows that can be attacked with DNS, the cost-effectiveness of the numerical simulation methods must be improved. With this object in view, we have pursued a step-by-step evaluation of spatial discretization methods. The leading question is: which combination of spatial discretizations of the convective and diffusive terms of the incompressible NavierStokes equations is the most cost-effective, given the level of accuracy needed for DNS.

High-order central discretizations and high-order upwind-biased discretizations performed the best of all methods considered here. The type of high-order discretization for the convective term is found to be of minor importance:
a fourth-order central discretization, (with a fourth-order interpolation to cope with the staggering of the grid) and a seventh-order upwind-biased method combined with a sixth-order interpolation performed equally well, fourth- or higher-order central discretizations turned out to be the most efficient for the diffusive term.

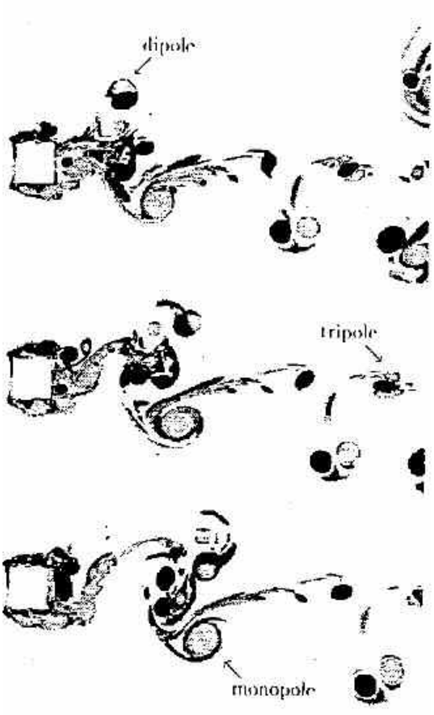


Figure 1 Three succesive snapshots showing the evolution of the vorticity field of the 2D flow around a square cylinder at Re= 10,000 a tong time after the breaking of the symmetry. The light-gray areas correspond to positive vorticity; the darker areas correspond to negative vorticity, The initially small vortical structures in the near wake of the cylinder amalgamate to form typical vortical structures, such as monopolar, dipolar and tripolar vortices.

The best spatial discretization has been used to investigate the bifurcations of the 2D flow around a square cylinder. At zero angle of attack, first a Hopf-bifurcation to a periodic state occurred, and after that (between Re = 200 and Re = 220) the flow became quasi-periodic. At an angle of attack of seven degrees the second bifurcation led to a period-doubling. Figure 1 shows some typical 2D vortical structures. A 3D DNS of the flow around a square cylinder exhibited a rather strong span-wise vortical structure at Re = 250. This structure is found to distort the typical 2D vortex street.

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J van Berkel

Thermocline entrainment in stratified energy stores

Notwithstanding the present-day application of thermally stratified energy storage little is known about the mixing phenomena that occur in such a store. Storing thermal energy in a startified manner saves spice and yet preserves temperature.
Typical examples can be found in solar energy systems, utility chilled and hot water systems and co-generation plants. For these short term stores one of the most stratification detrimental phenomena is mixing during charging and discharging.
This research is focused on mixing in two layer storages. It aims to clarify the physics involved and to derive guide lines for the design of efficient storage bulks.

The research objectives are pursued in a linked numerical/experimental way.
The overall flow pattern in stratified stores is identified using laboratory scale models and a 2D Finite Volume program. The thermocline entrainment process is of primary interest. For easy and accurate observation and analysis of this process, the store configuration has been abstracted to a configuration in which the thermocline advances due to entrainment only, featuring a submerged vertical jet, originating from a slot in the tank bottom, impinging on the interface between a cold and a hot water layer (Van Berkel, 1995).

Using a laboratory model, flow visualisation (shadow graph and dye colouring) revealed the thermocline entrainment processes in relation to the Ri-number.
Thermocouple measurements and Particle Tracking Velocimetry are used to quantify the temperature and velocity fields. The mixing process is simulated using 2- and 3D Finite Volume programs providing further insight in the mixing process, see the figure below.

The experiments and simulations show the presence of a meandering, submerged,

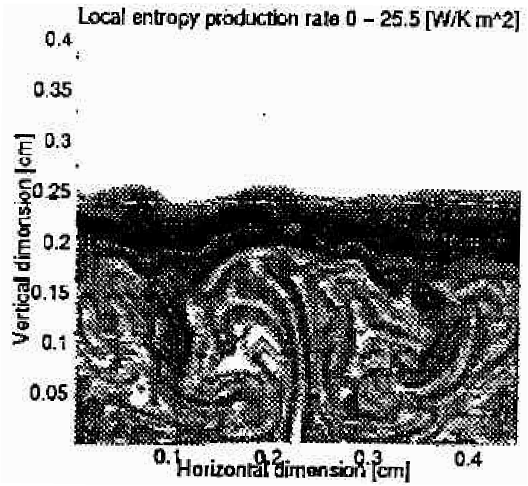

Figure 1 Grey scale colour plot of the local entropy production rate, illustrating the mixing process.

turbulent fountain impinging on the thermocline. In the baroclinic shear layer between the thermocline and the jet, vorticity is generated, resulting in overturning secondary motions (Kelvin Helmholtz waves). In addition, tertiary (stream wise) Görtler waves are generated in the jet deflection area.

It has become clear that the actual mixing process takes place as a result of stimulated diffusion of thermal energy, caused by thermocline separation of fluid particles and subsequent stretching and folding in the chaotic sub-thermocline flow field.

Using the increased insight and the models developed, a case study store geometry is optimized with respect to minimisation of costs associated with 1) loss of available energy due to entrainment and 2) loss of effective storage volume.

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M Dirkzwager
FTM Nieuwstadt

The development of an axial cyclone for separation of oil-water dispersions

In oil industry there is a growing interest in new types of separators for the separation of oil-water dispersions. At older production sites is, beside the oil, an increasing amount of water produced. This process, together with severe environmental demands, leads to a demand for new types of separators. Cyclones are established separators for the separation of two components with different densities. The most common type of cyclone is a tangential cyclone, a cylindrical geometry in which a rotating flow is established by tangential inlets through which the mixed components enter. In this geometry the heavier part moves outwards, the lighter part towards the centre. Within the cyclone the flow direction at the axis reverses. The lighter component exits axially at the top of the cyclone and the heavier component at the bottom.

This research project has the objective to develop an axial cyclone to separate oil-water dispersions. In an axial cyclone the swirl is generated in the flow by means of vanes mounted on an ellipsoid body, called the swirl element. This swirl element is centred in a somewhat wider pipe section so that the annular region where the vanes are mounted must contract at the end of the swirl element to fit to the diameter of the pipe. The research has been focused on the design of an swirl element which generates enough swirl to separate water/oil dispersions and which performs this without droplet break-up an with a low pressure drop.

The shape of the central body was optimised using a stream function method. This method uses a superposition of axisymmetric sources and sinks which enables us to calculate the pressure distribution along the pipe wall and the ellipsoid body. The method was used to design a geometry in which adverse pressure gradients are avoided. The vanes mounted on the body were designed using the package ISES to deflect the flow over an angle of about 70°.

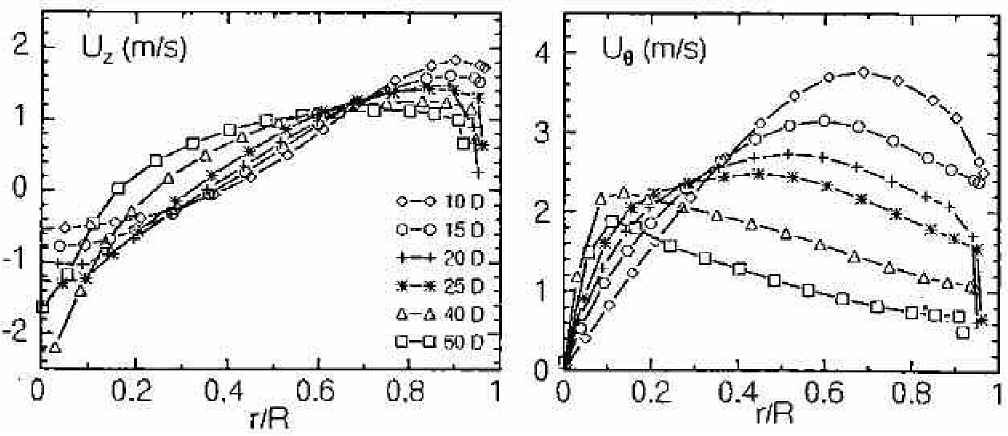


Figure 1 The mean axial (left) and tangential (right) velocity, measured at 10, 15, 20, 25, 40 and 60 diameters after the swirl element. Re = 5.0 . 10^4.

Both optimisation methods led to a swirl element which results in a swirl number Ω of approximately 3, $$\Omega = \frac{2\int_0^R U_x U_\theta r^2 dr}{R^3 U_b^2}.$$

To investigate the cyclone designs an experimental set-up was build. This pipe set-up is vertical with a total length of 10 m and an inner diameter of 50 mm. The flow behind the swirl element has been investigated by LDA measurements performed with a 2-D Ar$^+$ LDA system equipped with fiber optics. The LDA fiber probe is mounted in a traversing system which itself is placed on a vertically movable platform. This enables us to perform LDA measurements at different positions behind the swirl element.
A special pipe section is constructed which enables 2-D LDA measurements in the curved pipe geometry.

Figure 1 shows profiles of the mean axial and tangential velocity measured in the experimental set-up. A reverse axial flow at the centre exists because damping of the swirl leads to an adverse pressure gradient at the centreline. At larger distances behind the swirl element, the reverse flow region becomes smaller and its intensity stronger (maximum at 40 D). Although the flow rate of the reverse flow region is small, it is an important flow feature with respect to the separation process. The lighter component which moves towards the centre will be captured in this reverse flow. The tangential velocity profile is dominated by a solid body rotation at 10 diameters behind the swirl element and transforms later on to a so-called free vortex profile. i.e. the vorticity concentrates at the centre of the pipe. At the pipe axis the vorticity vector is stretched in the reverse flow to a maximum at 40 D, the position where the reverse flow has its maximum. The radial and axial pressure distribution was determined by pressure drop measurements and the radial component of the Navier Stokes equation. The measurements indeed show an adverse pressure gradient at the centre line in the region where the reverse flow accelerates. They also show that the axial wall friction increases exponentially with increasing swirl. In future further research will be performed on the separation process.

JT van der Eyden
ThH van der Meer

Double diffusive natural convection flows in underground coal gasification

Underground coal gasification (UCG) is a means of recovering otherwise unmineable deep and thin coal layers. Air is injected through an injection well in the coal layer, where a combustile gas is produced. This gas can be used at the surface for production of electricity or it can be converted to products like gasoline or methanol.

In the coal layer an open cavity will be formed. A cross-section of the cavity is shown in figure 1. At the bottom the air is injected through an ash and rubble pile. The oxygen will react with the CO present in the open cavity. At the coal walls the CO2 will be reduced to CO. A hot oxidation zone is formed at the bottom of the cavity and relatively cold reduction zones at the side walls. Heat and chemical species are transported from the oxidation to the reduction zone by the natural convection flow in the cavity, caused by temperature and composition differences. These transport processes are of key importance for the maintenance of the whole UCG process. In cooperation with the faculty of Mining and Petroleum Engineering a study of double diffusive natural convection flow in a cavity is performed.

The shape of the cavity is simplified to a trapezium (figure 2). The bottom wall is kept at high temperature and a heavy gas is injected, to mimic the oxidation zone. The side walls are kept at low temperature and a light gas is injected, to mimic the reduction zone. Using a numerical model the flow is calculated in the trapezium.

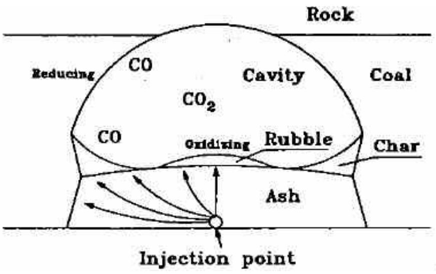


Figure 1 Cross-section of the gasifier

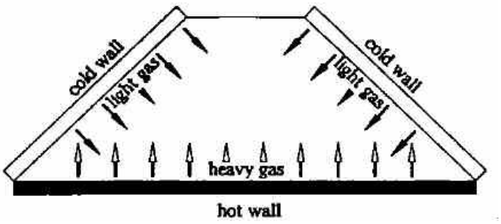
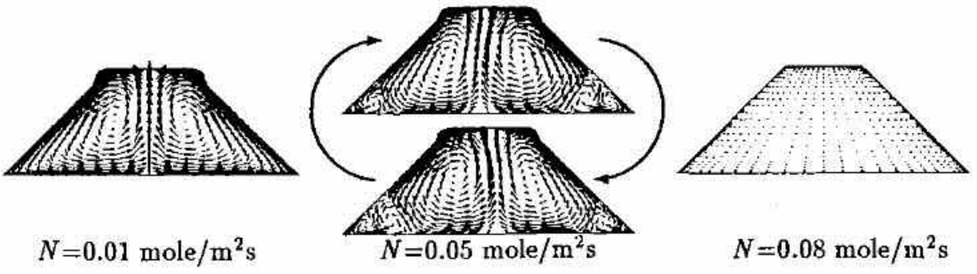


Figure 2 Trapezium cavity



N=0.01 mole/m^{2}s

N=0.05 mole/m^{2}s

N=0.08 mole/m^{2}s

Figure 3 Velocity field for different gas injection rates N

The Reynolds averaged Navier-Stokes equations and convection diffusion equations for temperature and concentration are solved. The standard k-ε model is used to model turbulence.

In figure 3 the velocity field in the trapezium for different injection rates of the gasses is shown. At a low injection rate the temperature induced buoyancy is dominant. Two Bernard type convection cells are present. The flow is downward along the cold side walls and upward in the middle. At a higher injection rate the flow becomes unstationary. An oscillating flow with a period of 20 seconds is found.
The increased influence of the concentration buoyancy, opposing the temperature buoyancy, makes the two convection cells unstable. For even higher injection rates the concentration induced buoyancy becomes dominant. The flow is now upward along the side walls and much lower velocities are found.

H van Santen
CR Kleijn
HEA van den Akker

Mixed convection instabilities in chemical vapour deposition reactors

Chemical Vapour Deposition (CVD) reactors are widely applied in the semiconductor industry for the deposition of thin films on silicon wafers. Presently, wafer sizes increase while the demands on film properties like uniformity become more stringent. New CVD processes therefore have to be designed carefully.

The flow in CVD reactors usually is in the mixed convection regime. This type of flows may give rise to complex phenomena like multiple stable flows (two or more flow fields may be possible with a unique set of boundary conditions), symmetry breaking (an asymmetric flow field satisfies perfectly symmetric boundary conditions) and transition to transient flows. As these phenomena may influence the performance of CVD processes, they have been studied with various numerical techniques.

For the study of multiple stable flows, the Navier-Stokes equations describing the flow in CVD reactors have been approximated using the finite volume discretisation on a staggered grid. The resulting system of non-linear equations has been solved with a Newton solver. Opposed to pressure correction methods this solver allows to calculate the linearly unstable flows implied by the existence of multiple stable flows. The large linear system that has to be solved in each Newton step is solved iteratively using the GMRES solver in combination with an ILU(E) based preconditioner. Advanced continuation techniques are used to track a solution along a solution branch in the parameter ranges with multiple stable solutions and turning point instabilities. Figure 1 shows a solution branch that resulted from 2D axi-symmetric calculations of the flow in a realistic CVD reactor. At a Grashof number Gr = 1000, the transition from forced convection dominated flow to natural convection dominated flow and vice versa shows a hysteresis effect.

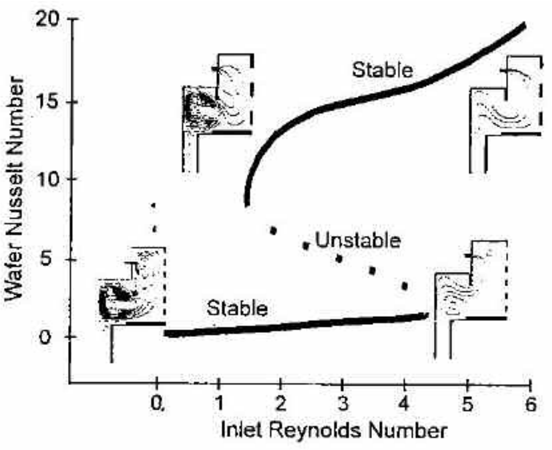


Figure 1 Solution branch in a 2d axi-symmetric CVD reactor

The flow that actually occurs in this parameter ranges is determined by the start-up conditions of the CVD reactor.

To study symmetry breaking effects and the transition to transient flows, a 3D pressure correction based code has been written, second order accurate in time and space. Full field solvers are used for each variable. The resulting systems of equations are solved using parallelized RILU preconditioned GMRES and CG. Figure 2 shows the results of a calculation in a simple axi-symmetric geometry. Figure 2(A) shows the velocity field in the symmetry plane of the asymmetry. The asymmetric flow field is rotating at a very low frequency (compared to the rotation frequency of the wafer) around the axis of symmetry of the reactor. Figure 2(B) shows the velocity in a fixed point of the reactor as a function of time illustrating this slow transient. Increasing either the inlet Reynolds number or the rotation Reynolds number will suppress both the transient and the symmetry.

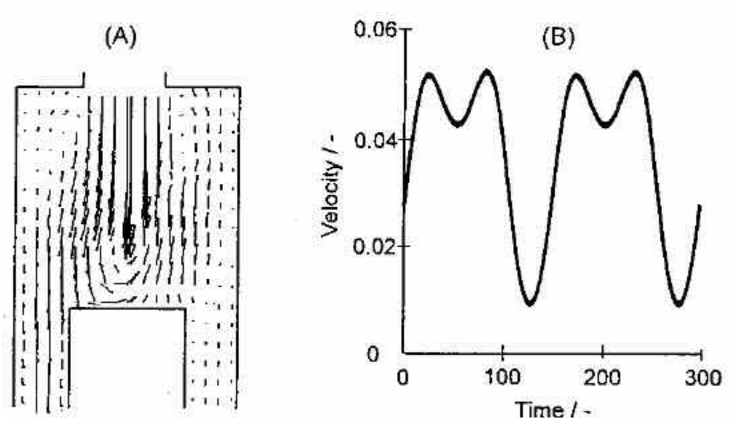


Figure 2 Asymmetric periodic flow in a symmetric reactor. Re = 50. Gr 1000, Re, = 10
(A) Flow pattern in the symmetry plane of the asymmetry: (B) velocity in some point.

WSJ Uijttewaal
RVA Oliemans

Particle dispersion and deposition in direct numerical and large eddy simulations of vertical pipe flows

The motion of particles was studied in a DNS of turbulent pipe flows (Re=5300). Since the capacities of todays supercomputers set limitations to the Reynolds numbers that can be achieved for such flows, simulations at higher Reynolds numbers were performed using Large Eddy Simulations with a Smagorinsky sub-grid model (Re=18300,42000) (Eggels 1994).

Large numbers of particles with a characteristic time scale of motion, made dimensionless with friction velocity and kinematic viscosity, ranging from 5 to 10000 were released in the flow with the assumption that the presence of the particles does not affect the turbulent flow field (dilute system). The equation of motion for the particles accounts for non-linear drag, gravity, and Saffman-type lift forces.
Other forces that affect particle motion like, added mass, pressure gradient and Basset history where supposed negligible for solid particles or liquid droplets in a gas flow (density ratio 1000). The turbulent diffusion, concentration distribution and deposition characteristics of the particles were analysed, applying various conditions for gravity and lift at three different Reynolds numbers, where the range of particle sizes results in particle relaxation times much smaller than the turbulent integral time scale of the continuous phase as well as particle time scales that are much larger.

The most important findings of this study concern the turbulent diffusion, deposition, and the concentration distribution (Uijttewaal 1995). Figure 1 shows that the relative particle diffusion coefficient hardly depends on the tube Reynolds number once the particle relaxation time is divided by the integral Lagrangian time scale of the turbulent motions. For particle time scales smaller than this integral time scale, diffusion is equal or even slightly larger than the diffusion of the continuous phase, while the more inert particles that are not able to follow the large scale turbulent motions exhibit a gradually decreasing diffusivity. The deposition process will in general be governed by the chance a particle has to reach the tube wall.

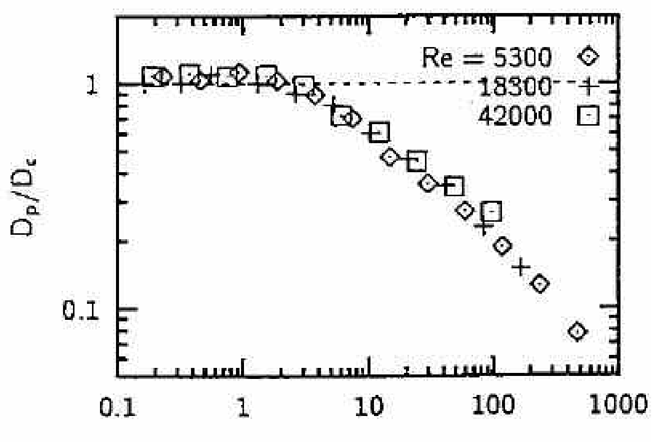


Figure 1 Ratio of diffusion coefficients of particles with that of the continuous phase determined for displacements perpendicular to the tube axis in the core region of the tube ($r < 0.7\ R_O$). Particle relaxation times are scaled on the integral time scale of the continuous phase turbulence. No gravity or lift forces are applied here.

This chance is determined on one hand by the mobility of the particle in the core region of the tube (diffusivity) and by the ability to maintain its velocity while coasting towards the wall through the more or less quiescent (regarding the wall normal motions) near-wall layer ($y^+ < 20$) on the other hand.

The latter property can be recognised in the right-hand side of figure 2. The shape of the three curves resembles that of figure 1 and obeys the same scaling, indicating that diffusivity is dominant for deposition of the large particles and that the near-wall layer does not significantly affect particle motion. The left-hand side of the graphs shows that small particles are lacking Inertia to be able to cross the near wall layer, resulting in reduced deposition coefficients. The deviating curve for the highest Reynolds number at small τ^+ indicates that the resolution of LES is not sufficient to account for the contribution of the smallest turbulent scales to deposition. A direct consequence of the fact that small particles do not reach the wall, is an accumulation of particles close to the wall. The particles posses enough momentum to penetrate the near-wall region. Once arrived the turbulent fluctuations they are subjected to are not intense enough to either re-entrain them into the core region or deposit them at the wall. In order to be able to work with somewhat higher particle concentrations ($> 10^{-6}$), further study will be needed to account for the effect particles have on the turbulent motions.

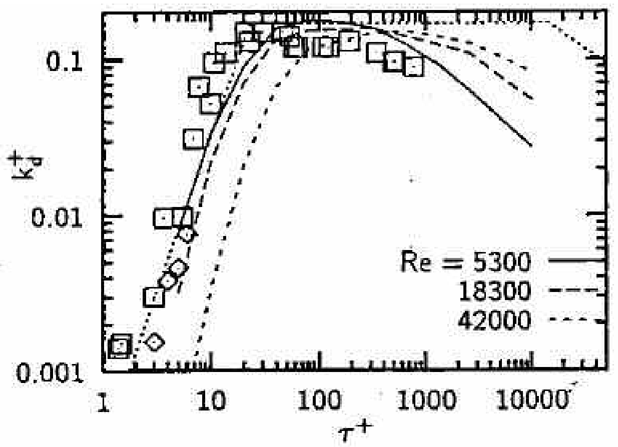


Figure 2 Deposition coefficients from simulations with different Reynolds numbers in the absence of gravity and lift forces, compared with: individual experimental data by Liu & Agarwal (1974), a general curve (dotted line) based on large numbers of experimental data (McCoy & Hanratty 1977), and deposition in a DNS simulation of channel flow (McLaughlin 1989).

KR Westerterp
VV Dil'man
AE Kronberg
AH Benneker

Wave concept in the theory of hydrodynamical dispersion

The commonly encountered continuous model of chemical reactors is the diffusion model. This model is based on the assumption that the mass flux additional to the flux due to averaged convective flow - the dispersion flow - arises from a diffusion-like phenomenon. So it can be expressed in the form of Fick's law of diffusion, only another proportionally factor, called the dispersion coefficient, is used instead of the molecular diffusivity. However the fine structure of the diffusion model is substantially deficient in details. The model is not capable to describe many simple phenomena even qualitatively.

The objective of the project is to develop a physically realistic alternative to the conventionally used Fickian and Fourier type dispersion models. The main idea of our approach is similar to that of Maxwell in his general consideration of the phenomena of viscosity. It is shown that the governing equation for the dispersion flux must have the same form as the Maxwellian constitutive equation for viscoelastic fluids.
The application of the new approach for one dimensional reactor modelling has been demonstrated. A hyperbolic system of two first order equations for the concentration averaged over the cross section perpendicular to the flow and the dispersion flux, called the “wave model”, is obtained via different ways of reasoning. The salient aspect of the proposed wave model rsts in the governing equation for the disperion flux instead of the commonly used Fick's law. This equation describes mixing due to stochastic as well as deterministic fluid displacements. The disperion flux in the wave model is a second, additional to the concentration independent variable which characterises the point concentration distribution in space. In comparison to the diffusion model the wave model contains two additional parameters: the relaxation time and parameter of velocity asymmetry. The first parameter characterises the time during which transverse variations of concentration are reduced to a fraction of their initial value and the second parameter takes into account the possible anisotropy of the dispersion process. All parameters of the wave model can be easily calculated for a broad class of processes where Taylor or shear dispersion is the predominant mechanism of axial mixing. In other cases they can be found in standard experiments. The new model avoids the conceptual shortcomings inherent to the Fickian dispersed plug-flow model: it predicts a finite velocity of material propagation and does not involve backmixing in the case of unidirectional flow. It also effectively resolves the well known problem of boundary conditions which now are set at the reactor inlet only. The significant advantages of the new model over the diffusion model have been demonstrated. For instance, old experiments which could not be explained with the diffusion model, are reconsidered and explained: the change with time of the variance of a concentration pulse when the flow direction is reversed and the difference in values of the apparent axial dispersion coefficient and the backmixing coefficient in a rotating disk contactor.

Moreover, the significance of the wave concept has been also demonstrated by comparing the predictions of the wave model in a wide range of situations to available experimentel data, to numerical calculations with the two-dimensional reactor models and to other available methods. It is shown that the wave model has a much wider region of validity than the dispersed plug-flow model, has a distinct physical background and is more simle for reactor calculations. The main results also hold true for multidimensional situations and equally well apply to hydrodynamical heat dispersion.

LHJ Absil
DM Passchier
JL van Ingen

Laser-Doppler anemometry for turbulent flows in aeronautics

Since its introduction in 1964, Laser Doppler Anemometry (LDA) has proven to offer the potential of being a non intrusive, reliable measuring technique for turbulence measurements. With increasing turbulence level in the flow the demands on the LDA and the experimenter increase considerably. In 1995 the first author presented a PhD-thesis on the LDA technique.

To evaluate the applicability of LDA for accurate measurements in low-turbulence flows, measurements were performed in the turbulent far wake behind a circular cylinder. At several downstream cross sections, distributions of the mean velocity and turbulence quantities were measured. Some comparisons with Hot-Wire Anomometer (HWA) results were made showing that for turbulende levels below stations in the wake, time and spatial correlations were measured. Because of the low turbulence level, various LDA bias effects could be neglected, but the influence of noise in the measurements was relatively high. The random shot noise generated by the photomultipliers was found to be the most important noise source. The influence of uncorrelated noise contributions could be reduced by applying a cross-correlation technique.

The second flow concerned the wake flow behind a flat plate developing in a strong adverse pressure gradient. Because this flow features regions of high turbulence levels and flow reversal, it was particularly suited for studying bias effects appearing in LDA measurements. Clear evidence of the presence of velocity bias in this flow was found. Several bias detection and correction methods have been evaluated.

The third test case for the application of LDA was a typical flow of interest for aircraft aerodynamics, i.e. the flow in the vicinity of the trailing edge of a modern supercritical NLR 7702 airfoil. This flow provided a great challenge for the application of LDA, since it featured high turbulence levels, instantaneous flow reversal and measurements close to a solid surface. Very detailed measurements were performed in the upper and lower surface boundary layer and in the near wake.

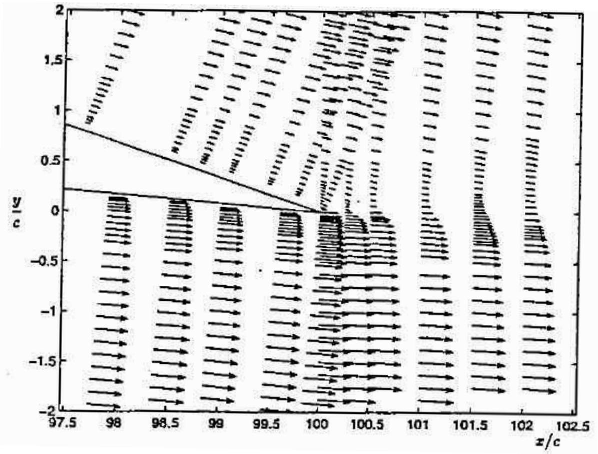


Figure 1 Arrow plot of the mean velocity vectors in the trailing edge flow of an NLR 7702 airfoil at $Rc=1.5 \times 10^6$ and $\alpha=4°$.

A reliable data set on trialing edge flows was obtained, which can be used for the development of turbulence models and the validation of CFD codes. In this high turbulence flow LDA was found to be superior to HWA.

From these investigations it could be concluded that LDA is an accurate and reliable measuring technique for velocity measurements in general turbulent flows. However, its complexity has shown to be a major drawback. An essential requirement for successful measurements with the LDA is that the experimenter is aware of the many subtle tricks and peculiarities of the techniques.

The opposite of a
correct statement is
a false statement.
The opposite of a
profound truth may
well be another
profound truth

Niels Bohr

1996

JP Meeder
FTM Nieuwstadt

Large-eddy simulation of plume dispersion and chemistry

In environmental issues there is a growing interest in simulations of photochemical pollutants. For regulatory purposes, so-called air quality models are used to simulate dispersion and chemistry processes on an urban or regional scale. The typical grid size used in these models varies from a few to a few tens of kilometres. Due to the relatively large grid size, these models should include the effects of emission inhomogeneities, for instance point sources or line sources.

The objective of the research project is to develop a suitable parameterisation scheme to include such inhomogeneities in a proper way. Large-eddy simulation is a very useful technique to study point source plumes and line source plumes in an atmospheric boundary layer. We consider both non-reacting cases and reacting cases where plume species reacts with ambient species, for example the photochemical reaction between nitrogenoxyde and ozone.

An example of a continuous point source release in a neutrally stratified boundary layer is shown in the Figure. The characteristics related to the dispersion and chemistry obtained by our LES are in good agreement with experimental data. Furthermore, the results reveal that a subgrid model for the concentration fluctuations is needed. This model accounts for the inhomogeneous distributions of the non-reactive or reactive species in each grid volume. We propose two different closure schemes and show their results for a relatively slow and fast reaction. It appears that this subgrid chemistry term is especially important close to the source for fast reactions.

An important measure of inhomogeneous mixing is the so-called intensity of segregation. In fact, this intensity is the correction factor applied to the reaction rate based on the homogeneously mixed case. Strong segregation of the species can be related to a strong reduction of the reaction rate based on the homogeneously mixed case. Such a strong segregation and thus reduction of reaction rate occurs for relatively fast reactions, for instance between nitrogenoxyde and ozone.

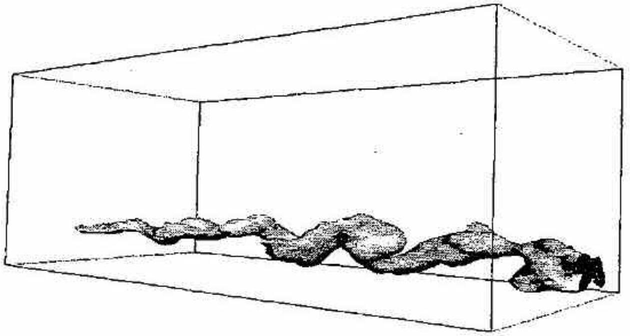


Figure Isosurface of plume concentration

Based on the LES results averaged over the total domain, we can develop a scheme which is suitable to handle the emission inhomogeneities in air-quality models. It is expected that incorporation of such a parameterisation scheme in an air-quality model will lead to a realistic prediction of the chemistry of plumes. A PhD-thesis with a full report of the results is in preparation.

RR Trieling
GJF van Heijst

Two-dimensional vortices in strain and shear flows

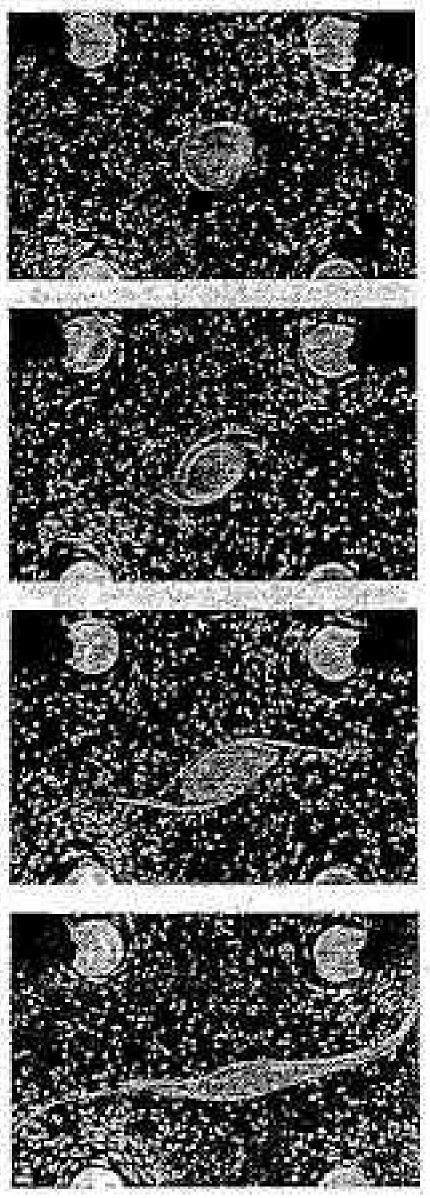
Two-dimensional vortices abound in large-scale geophysical flow systems, such as the planetary atmospheres and the world's oceans. In these situations, two-dimensionality is mainly caused by planetary background rotation and density stratification, as well as by constraints imposed by the geometry of the flow domain. An important question concerns the stability of these vortices when embedded in a straining or shearing background flow field. Large-scale vortices in the Earth's atmosphere and oceanic eddies may experience such a non-uniform ambient flow by their mutual interaction or by the global zonal currents.

In the present study, the evolution characteristics of two-dimensional vortices in strain and shear flows were investigated experimentally, and a comparison was made with analytical and numerical models.

Experimentally, two-dimensional vortex structures were studied both in rotating and in stratified fluids. Apart from flow visualization studies, which were necessary to observe the qualitative behaviour of the flow field, quantitative information was obtained by video recordings of small tracer particles. Image analysis techniques were used to measure vorticity distributions and to follow individual particles.

As an example, on the right-hand side of this page, a sequence of photographs is given which show the strain-induced evolution of a monopolar vortex in a stratified fluid. The ambient flow was generated by four rotating horizontal discs, whereas the monopolar vortex (coloured with fluorescent dye) was created by locally inducing a swirling motion. The experiment clearly reveals the elongational deformation and 'stripping' of the vortex, i.e. long filaments of dye were peeled off from the edge of the vortex. Similar results were obtained for monopolar vortices in a shear flow.

Theoretically, the laboratory observations were compared with analytical and numerical models. As a first approach, the vortex structures vortices were modelled numerically by point vortices surrounded by contours of passive tracers. As a second approach, numerical techniques of contour dynamics as well as a finite-difference method for solving the full two-dimensional vorticity equation were applied. Generally, the theoretical predictions were in good agreement with the experimental observations.



I Hadzic
K Hanjalic

Modelling the transition phenomena with statistical turbulence closure models

Reynolds averaging, which serves as a basis for most single-point turbulence closure models, conceals by its virtue the dynamics of flow disturbances, the incipience, development and amplification of local instabilities and the actual mechanism of natural laminar-to-turbulent transition. For that reason the statistical single-point closure models have been regarded as inappropriate tools for dealing with the problem of transition. However, because an alternative to single-point closures for computation of industrial flows is still not in the offing, there has been much activity in accommodating statistical models to handle at least some forms of transition phenomena, such as by-pass transition caused by the diffusion of free stream turbulence into the boundary layer. It is generally accepted that the turbulence closures offer more flexibility and better prospects for predicting real complex flows with transitions then any classical linear stability theory. The ability to predict a change-over from one regime to another (not necessarily the actual transition mechanism) at appropriate location and under appropriate conditions, and consequent modifications of mean flow parameters - without having to introduce any artificial triggering - will often serve the purpose of computing complex industrial flows involving transition.

Figures 1 and 2 show some results of computation of by-pass transition in a laminar boundary layer developing over a finite thickness plate with round leading edge of 5 mm and free stream turbulence of 5.5%. Experiments indicated that the transition is preceded and enhanced by a thin laminar separation bubble. Predicting the correct shape and size of the separation region, which is crucial for predicting correctly the transition, was found to be a major challenge in which most conventional low-Re-number models failed.

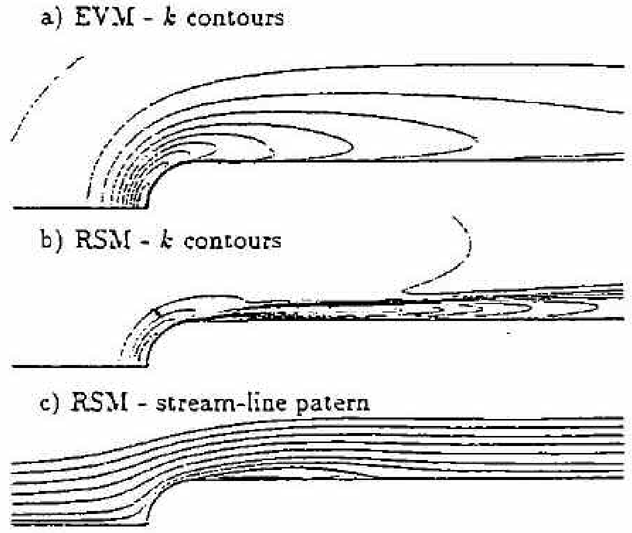


Figure 1 Contours of k and stream-lines in the case T3L4 (with 5.5% fst) obtained with k - ε and RSM.

The low-Re number k - ε model of Launder Sc Sharma predicts a high level of turbulence kinetic energy in the stagnation region which persists for downstream and keeps the boundary layer fully attached to the wall. Fig. 1a.

In contrast, the low-Re-number Reynolds-stress model (RSM, $\overline{u_i u_j}$ - ε), developed by the authors, predicts the laminar separation bubble and the transition at its downstream end. Fig. 1b and 1c. In the latter case the predicted mean velocity and streawise fluctuations show close agreement with experiments (Figure 2).

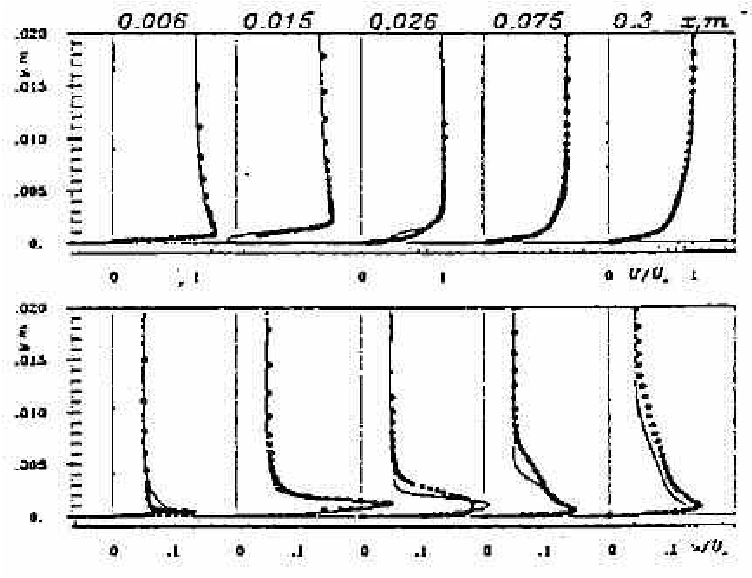


Figure 2 Mean velocity and streamwise fluctuation profiles. Symbols: Experiments Rolls-Royce ASL. Lines: RSM Computation.

APG van Heel
MA Hulsen
BHAA van den Brule

Simulation of viscoelastic fluid flow using Brownian configuration fields

The field of viscoelastic fluid research has recently shown some exciting developments, which offer opportunities to study fluid models that are out of reach of the conventional macroscopic approach. In this new microscopic approach a polymeric liquid is modelled as a collection of polymer molecules in a solvent. These polymers, modelled as beads connected by springs, are convected and deformed by the flow, and are subject to Brownian motion. The new simulation possibilities stem from the fact that macroscopic simulations are restricted to polymer models which yield a closed-form constitutive equation for the stress in the fluid. In the microscopic approach this restriction disappears because the stress in not determined from a constitutive equation, but instead directly from the configuration of the ensemble of polymers in the solvent. Therefore, since many microscopic polymer models do not yield a closed-form constitutive equation, the possibilities for modelling real-life polymeric fluids are increased tremendously by this new microscopic approach.

The first brute force calculations using the microscopic approach were extremely time-consuming and suffered from accuracy problems, in particular with mesh refinement. To overcome these problems, we have developed a new approach for calculating viscoelastic fluid flow using microscopic models. In this approach we replace the collection of individual polymer molecules by an ensemble of configuration fields, representing the internal degrees of freedom of the polymers. Similar to the motion of real molecules, these configuration fields are convected and deformed by the flow, and are subjected to Brownian motion. We incorporated this description in a finite element calculation.

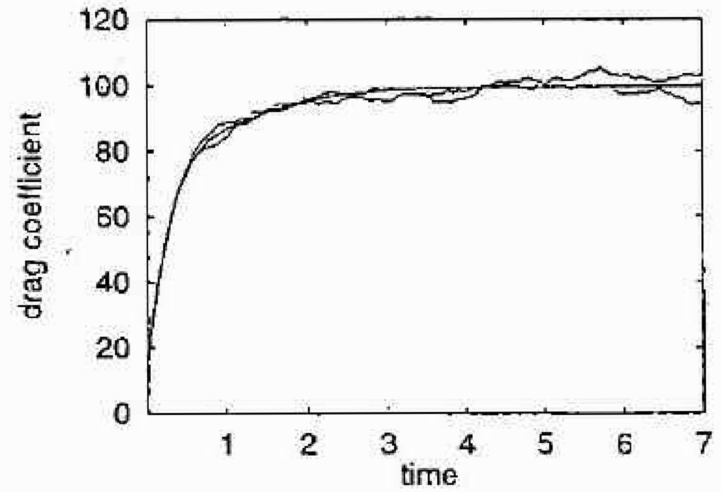


Figure 1 Drag coefficient as a function of time for startup of the flow of an Oldroyd-B model around a cylinder confined between two flat plates. The smooth curve is the macroscopic result and the fluctuating curves are two independent realisations of the Brownian configuration field approach

An important advantage of our approach is that the above-mentioned difficulties associated with mesh refinement and particle tracking of individual polymer molecules are avoided.

In order to validate our approach, we calculated the start-up flow past a cylinder between two parallel plates. In this simulation we used the Hookean dumbbell model, in which the beads are connected by a linear spring. This particular microscopic model results in a closed-form constitutive equation, viz. the Oldroyd-B equation, and can therefore also be simulated using the conventional macroscopic approach.
Two typical Brownian configuration field results for the drag force on the cylinder, using 4000 fields are shown in Fig. 1, together with the macroscopic result, which corresponds to the limit of an infinite number of fields.

While the previous results could equivalently be obtained by the macroscopic approach, the real potential of our Brownian configuration field approach is best illustrated by means of a model which can not be simulated using the macroscopic approach. For example, a microscopic model which does not yield a closed-form constitutive equation is the so-called FENE model, in which the polymers can only be stretched to a maximum length. In Fig. 2 we illustrate our Brownian configuration field results for this model by the drag force on the cylinder. This also demonstrates the influence of the maximum polymer length on the resulting drag force the cylinder experiences.

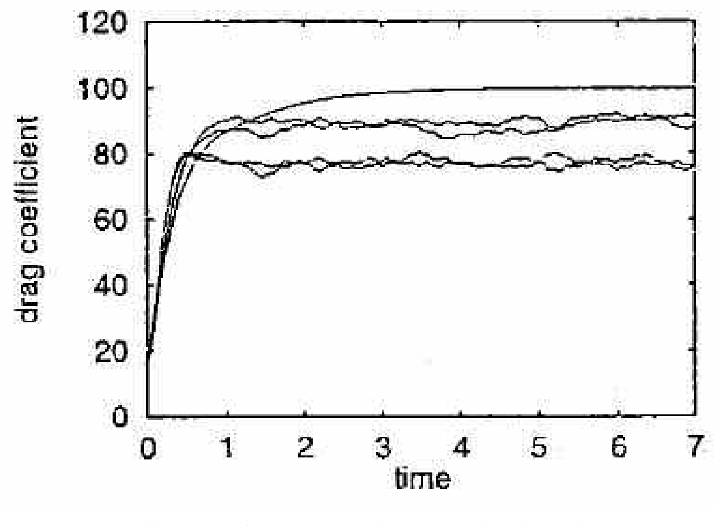


Figure 2 Drag coefficient as a function of time for start-up of the flow of an FENE-model around a cylinder confined between two flat plates. The smooth curve is the result for the Oldroyd-B model (no restriction on the polymer length).
The lower curves are the results for the FENE mode] with two different values of the maximum polymer length, each shown for two independent realisations.

R Delfos
RVA Oliemans

Air entrainment from slug bubbles in a vertical tube

Slug flow is a flow pattern encountered in many practical applications, for example during oil production or in chemical reactors. In (vertical) slug flow large gas bubbles that span the tube diameter (Taylor bubbles) rise through a mixture of liquid loaded with dispersed small gas bubbles, the liquid slugs. The volume fraction of gas in a slug is determined from a balance of liquid and gas fluxes into and out of the slug. At the lower end, a slug continuously loses gas and liquid that are overtaken by the next Taylor bubble. At the top, a slug gains liquid from the film running down the Taylor bubble above it. With this film usually air is entrained from the Taylor bubble into the slug to form small bubbles. Part of these re-coalesce with the Taylor bubble in its wake.

To study the entrainment and the re-coalescence we built an experimental set-up in which water flows downward such that a single Taylor bubble stays stagnant in the flow. A fixed air flowrate is blown into the Taylor bubble nose through a thin tubelet. A picture is shown in fig.l. The Taylor bubble grows in length until the bubble loses as much air by entrainment at its base as it gains at the top.

The measurements (some are shown in fig. 2) show that considerable entrainment occurs only when the Taylor bubble surpasses a critical length that depends on both the flowrate and the turbulence level of the liquid flow approaching the Taylor bubble. At this length the liquid film flow undergoes a transition from laminar to turbulent flow. When the Taylor bubble length is increased the gas loss increases fast until a maximum is reached at some 120cm length, beyond which there is a slow decrease of air loss.

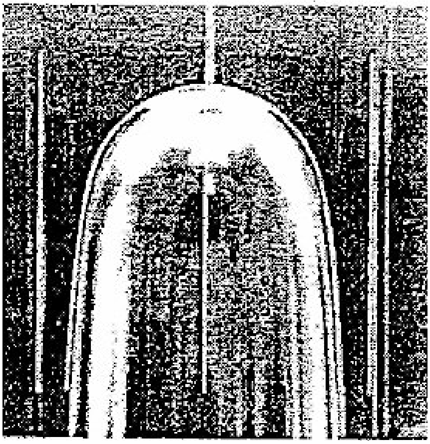


Figure 1 The nose of a Taylor bubble in the set-up, and its theoretical shape

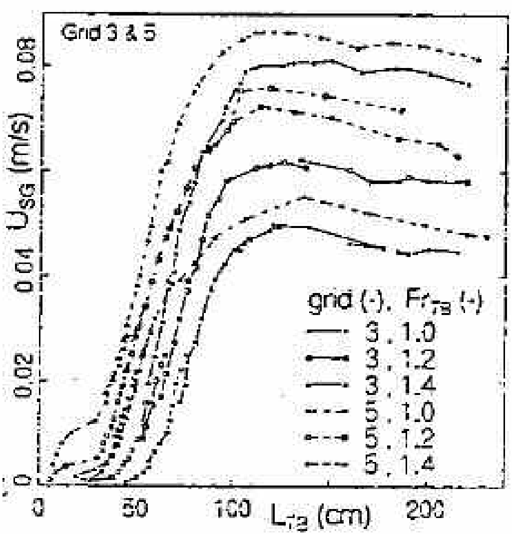


Figure 2 Air loss from a Taylor bubble measured in our experimental set-up

Up to a length of 200cm a fully-developed state still has not been reached.

The entrainment is explained from the roughness of the liquid film surface. When the film flows laminar, its surface is sufficiently smooth for the receiving slug to absorb the fluctuations of the film surface by oscillating with it. If the film flow becomes turbulent, there are larger disturbances on the film; the accelerations become too large, and behind every wave air is sucked from the Taylor bubble into the slug below. We developed a model for the film velocity and the turbulence level that allowed for the experimentally observed transition from laminar to turbulent flow. With this model the measured gas loss curves as a function of Taylor bubble length and flow conditions could be reproduced in a qualitative way, as shown in fig. 3. Quantitatively the entrainment is predicted within 50% of our measured gas loss rate. Some measurements from the literature under similar conditions were reproduced by our model with the same accuracy.

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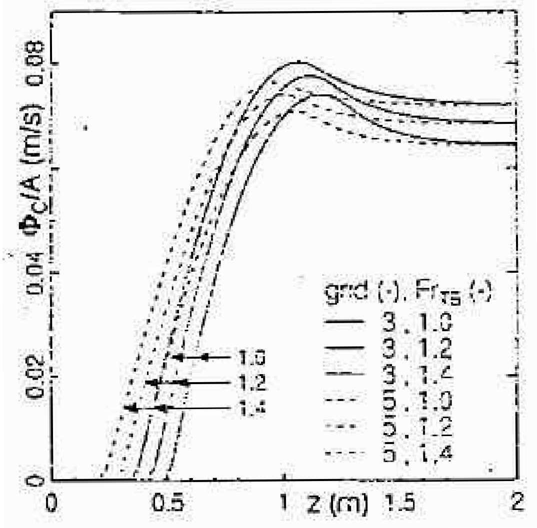

Figure 3 Air loss from a Taylor bubble calculated with entrainment model

HJWM Legius
HEA van den Akker

Transitional gas-liquid pipe flow through a vertical bend

Two-phase flow pipe systems, which are encountered in such diverse fields as petrochemical, nuclear and off-shore industry, may under certain operating conditions suffer from flow instabilities and pressure pulsations. Since geometrical obstructions such as bends, T-junctions and contractions can have a significant effect on the flow, it can often not be considered as steady-state or even fully developed. Standard flow regime maps, which are used to plot the various possible phase distributions in steady-state flow, cannot be applied to these situations.

As a typical case, gas-liquid flow through a vertical bend has been studied both experimentally and numerically. The test facility is shown in fig.(1). According to existing flow regime maps, stratified flow or horizontal slug flow will be present in the horizontal flow line and bubbly flow or vertical slug flow in the riser, depending on operating conditions. In the case of regular slug flow, a pulsation frequency of approximately 1 Hz is predicted by existing correlations.

However, due to the presence of the bend, slug formation in the riser is facilitated and bubbly flow is not observed under any conditions. The slugs in the vertical pipe generate disturbances on the liquid height in the horizontal pipe. These waves travel upstream and may be damped or amplified. By interaction of these waves and waves reflected at some part of the pipe system, e.g. the pipe entrance, additional low frequency pulsations are also observed. The frequency of these pulsations depends on the dimensions of the pipe system.

A second effect of the upstream moving waves is that they increase the liquid height in the horizontal line and destabilise the flow- Therefore, transition to slug flow by a Kelvin-Helmholtz mechanism occurs at much lower flow rates than predicted by flow regime maps.

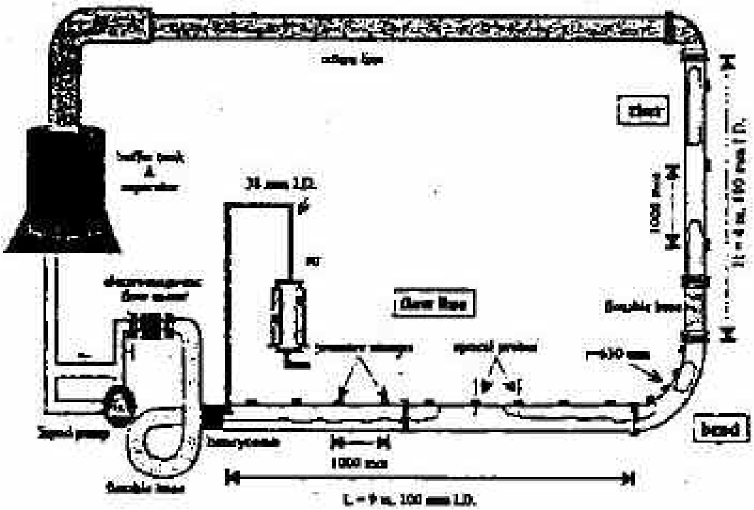

Figure 1 Test facility

Furthermore, slugs formed by this process are much longer than regular slugs and their frequency is again dictated by the pipe geometry.

An in-house developed two-phase flow code, SOPHY-2, has been used to simulate the behaviour of this pipe system. A second-order time and space accurate finite difference scheme (TVD) has been used to discretise and solve the two-fluid model implemented in this code.

The conditions under which kinematic waves are able to move upstream and destabilise the flow were determined for a range of process conditions. The calculated wave velocities have been verified using a 200 Hz digital camera. Additional measurements have been performed using pressure transducers and optical fibres to determine slug length and frequency. A new flow regime map for the horizontal pipe has been constructed which is shown in fig. (2). The existing Weisman-Kang criterion for transition between stratified smooth and stratified wavy flow, given by the dotted near-vertical line, and the transition between stratified and slug flow, given by the near-horizontal line, have been compared to transitions calculated by SOPHY-2. The latter are given by the drawn lines. The newly determined transition lines describe the flow conditions rather well both at low and high flow rates. At intermediate flow rates, a hysteresis phenomenon is observed which is not captured by the model. The calculated pulsation frequencies agree very well with observed frequencies.

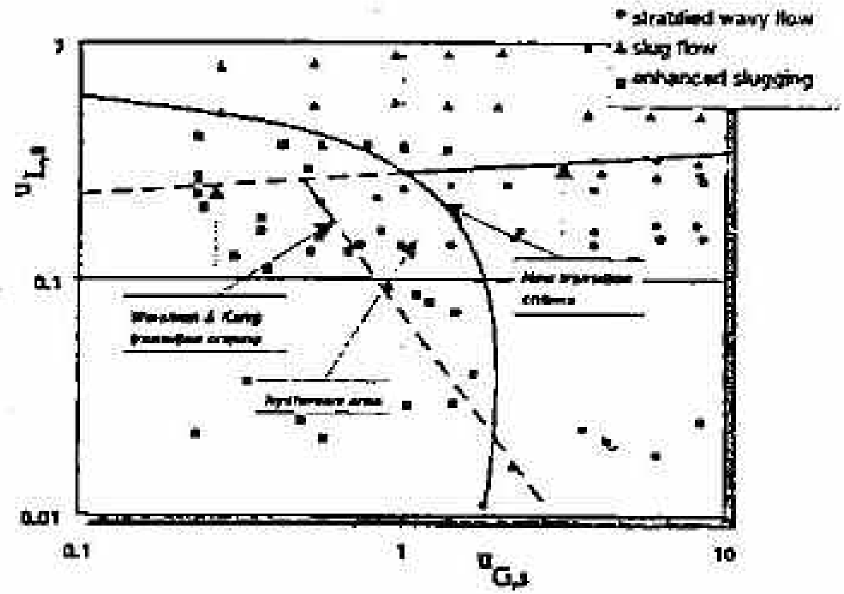

Figure 2 Regime for the flow line

WJ Bannink

The hypersonic test facility Delft

Wind tunnel testing dates back to the beginning of the twentieth century and has always been an important tool in the development of flight. The major functions of wind tunnel ground testing may be described as: the understanding of aerodynamic flow; the development of a database; the study of parametric configurations; the substantiation of predictions (for example validation of computational results).

The role of ground testing is particularly pronounced in hypersonics where knowledge of the flow field behaviour and the available tools are rather limited. The increased complexity of hypersonic flow is largely due to the high stagnation temperatures involved which result in a thermally imperfect atmosphere surrounding the vehicle and in triggering chemical reactions as well as important aerodynamic heating and is also due to the low density of the outer atmosphere at high altitudes. It is noted that, as Mach numbers increase, the power requirements for operating a wind tunnel increase immensely. Hence, short duration hypersonic facilities are used with running times of a few to hundreds of milliseconds. The categories of hypersonic vehicles in the present era of ballistic launch/lifting reentry systems, hypersonic air transport, aero assisted orbital transfer vehicles and vehicles that will enter the atmosphere of other planets will operate over a wide variety of flight trajectories, in a large part of which they will encounter Mach numbers up to and in excess of 30 over a wide range of Reynolds numbers and atmospheric conditions. To fully simulate flight of a reentry vehicle including finite rate chemistry is a most prohibitive task.

Consequently, aerodynamicists have resorted in partial simulation studies, subdividing hypersonic aerothermodynamics into three regimes:

- the regime from Mach 6 to 12 or 15 dominated by Mach and Reynolds number as simulating parameters,
- the hypervelocity regime with very high total temperatures yielding thermally real gas effects and chemical reactions in addition to high heating rates, and
- the rarefied regime characterized by values of $M/(Re)^{1/2} > 0.01$.

It is in the context of the partial simulation mentioned above that the High Speed Laboratory of the Faculty of Aerospace Engineering has chosen for a modest and economic facility based on the Ludwieg tube principle.

Ludwieg originally designed the facility for the transonic speed regime at high Reynolds numbers [I]; in 1968 it was applied to hypersonic speeds at the DLR in

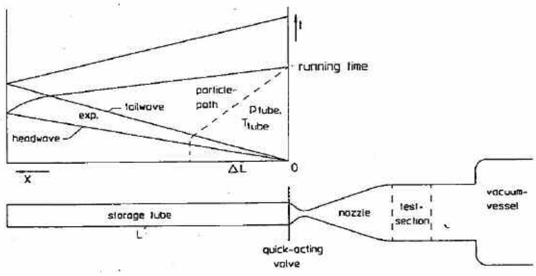

Figure 1 Schematic of Ludwieg tube with wave diagram

Gottingen [2]. Koppenwallner redesigned the Ludwieg tube in an ingenious way, so that it could be built and operated extremely economical [3]. The attractiveness of Ludwieg facilities may be found in the. relatively high running times (0.1- 0.3 sec), the reasonable size of the test section (of the order of 50 cm) and the high Reynolds numbers ($5\text{-}50.10^{6}$ per meter). The working principle in shown in Fig. 1. In a long tube of constant cross-section gas is stored at high pressure and temperature. The tube is closed at one end and at the other end it is interconnected by means of a quick acting valve to the actual wind tunnel part consisting of laval nozzle, test section, diffusor, vacuum tank. As soon as the valve upstream of the nozzle is opened a centred expansion wave travels into the supply tube at the speed of sound. Behind this wave constant flow conditions are established which serve as reservoir conditions for the nozzle flow. The expansion wave is reflected at the upstream, closed end of the supply tube and returns to the nozzle. As soon as it reaches the nozzle the maximum possible running time is over.

The design targets pursued in the concept are based on moderate costs using state-of-the-art technologies, off-the-shelf parts and independence from external infrastructure. The facility needs a total power of 25 kW for storage air heating, compressor and vacuum pump. A side view of the facility is shown in Fig. 2. Its overall length is only 16m thanks to the folded supply tube which itself has a length of 29 m. De tunnel is equipped with a conical nozzle having an apex angle of 15° debouching into a cylindrical test section of 35 cm diameter. Mach number variation is achieved by variable throats for discrete nominal Mach numbers of 6, 7, 8, 9, 10 and 11. The aerodynamic properties may further he summerarized as: stagnation temperatures from 600 K to 850 K; depending on the Mach number the stagnation pressures may vary from 3 to 100 bar and the Reynolds numbers based on the test section diameter from 0.4 to 5.5.106. The running time of the facility is 0.12 sec., approximately. The supply tube may be filled with air or nitrogen, occasionally helium may be used. About 6 runs per hour are possible.

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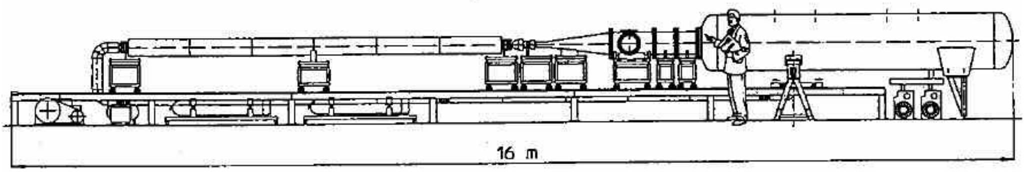

Figure 2 Side view of HTFD

That's the nature of research - you don't know what in hell you're doing

'Doc' Edgerton

1997

BA van Haarlem
FTM Nieuwstadt

DNS of particle deposition towards a free and no-slip surface

The turbulent flow of gases and liquids containing small suspended particles is a challenging topic in fluid mechanics which has many practical applications. Examples may be found in geophysical flows such as the disperision of aerosol particles in the atmosphere but even more so in engineering problems such as the management of dust in clean rooms or chemical conversions using catalyst particles. In all these cases the nature of the turbulence determines the way in which the particles are dispersed. Moreover in bounded flows the turbulence also determines the resuspension and deposition of the particles onto surfaces. It is the latter topic, the removal of particles through deposition on which we have focused in our simulations.

When particles are sufficiently large they do not follow the flow motions due to their inertia. In this case the near wall particles may disengage from the fluid motions and coast to the wall by the mechanism of so called free flight. For the simplest case of a smooth and flat no-slip surface there is quite some data available on which to base models of this deposition process. For more complex situations however there is little detailed information available. By performing a Direct Numerical Simulation (DNS) of a flow domain bounded on one side by a no-slip surface and on the other side by a free-slip surface we make a first step towards determining the effect of different turbulence structures than those encountered near a simple no-slip wall on the process of deposition.

To study the particle motion we use a combined Eulerian-Lagrangian approach in which the DNS of the Eulerian flow field supplies the instantaneous and local fluid velocities which are necessary to compute the trajectories of a large ensemble of small particles To calculate the Lagrangian trajectories of these particles we adopt a simplified equation of motion in which the acceleration of the particles are influenced by Stokes drag alone. This simplification allows for a study without complications of the driving forces behind the particle dispersion, in particular turbulent diffusion and turbophoresis. Where the latter mechanism expresses the tendency for particles to

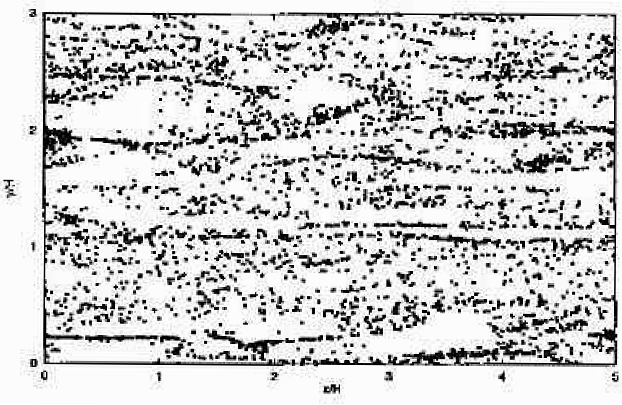

Figure 1 Instantaneous particle distribution near the no-slip surface. The mean flow is in the x-direction

migrate towards regions of low turbulence intensity. Different properties of the turbulence near each surface indeed have quite a different influence on the behaviour of the particles as may be seen in Fig. 1. In this figure we show instantaneous particle distributions in a plane parallel to both the free-slip (right) and no-slip (left) surface. Near the no-slip surface the particles are seen to accumulate in the low speed streaks, while near the free-slip surface the particle distribution is influenced by large attached vortices which due to centrifugal effects create the roughly circular voids. Apart from these qualitative differences we also find strong differences in the statistics of deposition. In particular we find that as particle inertia is increased the larger rate of deposition switches from the free slip surface to the no-slip surface. Furthermore we have calculated the exact contributions of turbulent diffusion and turbophoresis to the total particle fluxes and compared these with models proposed in the literature. We find that simple models of the turbulent diffusion fail both in quantitative and qualitative prediction of the diffusion fluxes, which implies that particle fluxes can not be determined in terms of local variables.

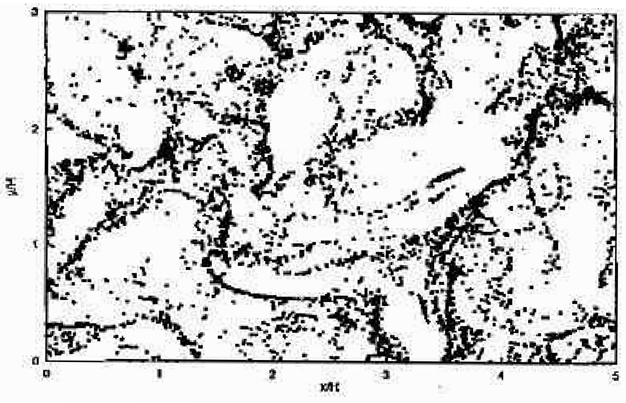

Figure 2 Instantaneous particle distribution near the free-slip surface.

W Cazemier
RWCP Verstappen
AEP Veldman

POD and low-dimensional models for turbulent flow

Coherent structures catch the eye in virtually every visualization of a turbulent flow. But, what is precisely meant by ‘coherent structures’, and how can one decompose an arbitrary turbulent or transitional flow into a coherent and an incoherent part? An answer to these questions has been given by Lumley. He identified coherent structures by means of proper orthogonal decomposition (POD). Among all linear decompositions of a velocity field $u(x, t)$, the proper orthogonal decomposition $\sum_i a_i(t)\sigma_i(x)$ is the most efficient in the sense that it captures the largest possible amount of kinetic energy for any given number of modes (for details, see [1]).

We have computed the first 80 topoi $\sigma_i(x)$ and chronoi $a_i(t)$ of a lid-driven cavity flow (Re = 22, 000). For this we have taken 700 snapshots from a direct numerical simulation (DNS). The picture along side shows the first 10 topoi. On average (over time), they capture 65% of the fluctuating energy; the first 80 capture 95%. Having a way to educe coherent structures in a transitional or turbulent flow, the next question that can be posed reads: how do these structures move, interact, survive, ...

To unravel the dynamics, we have constructed an 80-dimensional dynamical model by projecting the Navier-Stokes equation onto the space spanned by the first 80 σ_i’s. The ability of this model to mimic the DNS for a range of Reynolds numbers (Re = 5,000 - 22,000) has been studied numerically by means of a bifurcation analysis. The results can be summarized as follows. The linear stability of the 80-dimensional model is almost identical to that of Navier-Stokes. The first (Hopf) bifurcation takes place at about the same Reynolds number (Re ~7,800) and the unstable eigenvectors display the same mechanism: a centrifugal instability of the primary eddy. The stability of periodic solutions of the 80-dimensional model is analyzed by means of Floquet multipliers. The agreement with the available DNS-data is good, albeit that the stability analysis of periodic solutions of the 80-dimensional system also reveals some complicated bifurcations that have not yet been confirmed by means of a direct numerical simulation.

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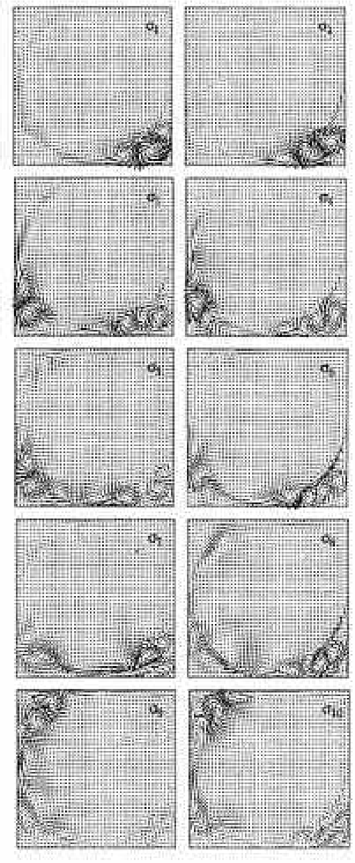


AHM Eisenga

Dynamics of a vortex ring in a rotating fluid

A vortex ring is often used as an elementary vortex structure to study the evolution and interaction of more complicated three-dimensional flow structures. Many principal mechanisms of vortex dynamics (e.g. intensification of vorticity by vortex stretching and self-induced motion due to the curvature of the vortex core) can be investigated using vortex rings. Vortex rings have a relatively simple symmetric structure, which allow for a detailed study of their motion and dynamics.

Previous studies on vortex rings were devoted mainly to the interaction between two rings or the collision of a vortex ring with a wall, with the vortices created in a fluid at rest. Such studies are useful to gain insight in, for example, the interaction between coherent vortices in turbulent boundary layers and the interaction of such vortices with the wall. However, in a turbulent boundary layer (and in many other practical situations) vortex structures are embedded in an ambient flow by which they are advected, deformed and stretched. The present study was focused on the motion of a vortex ring in a background flow; in order to be able to gain detailed insight in the flow dynamics a very simple background flow has been considered, viz. a solid-body rotation.

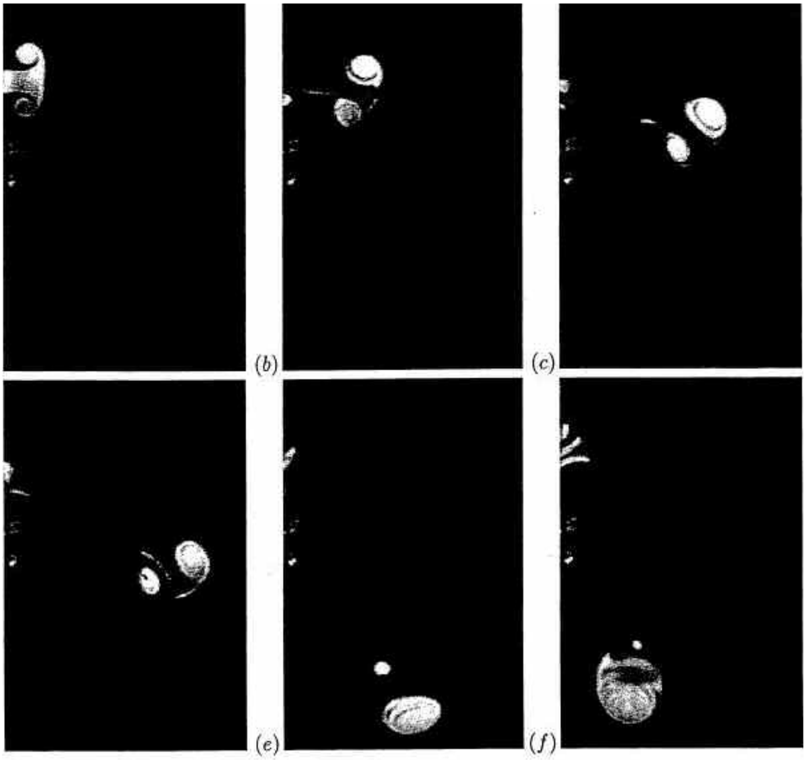
Preliminary laboratory experiments of a vortex ring generated in a fluid at rest yielded quantitative values for the characteristic flow parameters of the rings. For these experiments a vortex ring generator was used consisting of a cylindrical box with a circular hole in the top lid. A steadily propagating (laminar) vortex ring was created by ejecting a fixed amount of fluid (water) during a short time through this opening. Flow visualisations using fluorescent dye provided a clear view of the developing flow structure. The velocity and vorticity fields in the ring core were measured by tracking the motion of small tracer particles in an illuminating light sheet through the ring core. In addition to the experiments, numerical simulations were performed to mimic the laboratory experiments and to compute the three-dimensional flow structure and related flow quantities that are difficult to measure.

A one-to-one correspondence between experiment and numerical simulation has been pursued.

As a next step, the dynamics of a vortex ring moving in a uniformly rotating background flow was investigated. Relative to a corotating frame of reference the vortex ring experiences Coriolis forces, which affect the flow evolution drastically. A rotating fluid can easily be generated experimentally by using a tank filled with water and placed on a rotating table. Two different cases have been distinguished. In the first case vortex rings are directed parallel to the rotation axis of the system, in the second case the vortex rings are directed perpendicular to this axis. In both cases stretching and tilting of vortex lines from the uniform background vorticity by the relative flow of the vortex ring result in the formation of secondary vortical structures interfering with the primary ring. In the first case this secondary structure consists of a secondary vortex ring with opposite circulation formed in front of the primary ring and linked to it by an axial swirl.

In the second case two tail vortices of opposite rotation appear behind the propagating vortex ring. Numerical simulations were very useful to study the developing three-dimensional flow structure and to distinguish several principal mechanisms of vortex dynamics.

Photographs of a dye-visualisation experiment (see figure) show the motion of a vortex ring in a rotating fluid, where the vortex ring is directed perpendicular to the rotation axis. Due to this background rotation the path of the vortex ring is curved relative to the rotating frame of reference and its trajectory is deflected in the direction opposite to the sense of rotation of the system. One of the horizontally extending tail vortices behind the vortex ring, as well as the ring's loss of symmetry are clearly visible.



Dye visualisation of the evolution of a vortex ring moving perpendicular to the axis of the background rotation.

It is not the brains
that matter most,
but that which
guides them - the
character, the heart,
generous qualities,
progressive ideas

Fyodor Dostoyevsky

1998

G Ooms

Appointment Burgerscentrum professors

In order to further improve the quality and relevance of the research and advanced courses of the JM Burgers Centre (JMBC) it was decided early 1998 to attract some top-experts in different areas of fluid mechanics to the research school. Of course, considerable funds were necessary for the realisation of this idea. To that purpose the scientific director and local directors approached the Boards of the Technological Universities and asked for financial support. The Boards were impressed by the achievements and importance of the JMBC and were prepared to sponsor some top experts and appoint them as Burgerscentrum professors at their universities.

The criteria for the selection of such professors were

- A Burgerscentrum professor has to be an internationally recognised expert in one of the areas of fluid mechanics, or must be a top-talent on his way to become such an expert.
- A Burgerscentrum professor must spend during a considerable period (at least three years) a significant part of his time (at least 25 %) with the JMBC.
- During that period research is the first priority of a Burgerscentrum professor. However it is also expected, that he contributes to the advanced courses of the research school.
- A Burgerscentrum professor is appointed with one of the JMBC groups. However he should also visit the relevant other groups and co-operate with the researchers of these groups.

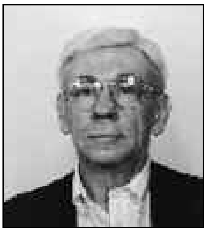
Using these criteria the scientific director and local directors (of course with the support of others) then tried to identify and select suitable candidates. They were very successful in this respect.

At the end of 1998 the following Burgerscentrum professors were appointed

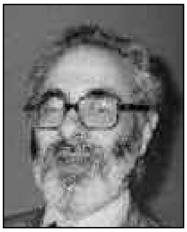
- Prof.dr. D Montgomery (TUE/Dartmouth College USA). David Montgomery is a specialist in the statistical mechanics of turbulence.
- Prof.dr. A Prosperetti (UT/Johns Hopkins USA). Andrea Prosperetti is well known for his work on multiphase flows.
- Prof.dr.ir. BHAA van den Brule (TUD/Shell The Netherlands). Ben van den Brule has carried out very original work on the microscopic approach to polymer flow simulation.
- Prof.dr. JCR Hunt (TUD/Cambridge UK). Julian Hunt is, for instance, interested in meteorological and environmental problems. He is an expert in turbulence and dispersed multiphase flow.
- Prof.dr. SB Pope (TUD/Cornell USA). Steve Pope is a well-known expert on turbulent combustion. As he cannot spend more than about 10 % of his time for JMBC, he is not formally appointed as professor at TUD.

The new Burgerscentrum professors have made a good start in the JMBC; in particular the contribution of some of them to the 1999 Burgersdag was impressive. In future yearly reports we will certainly pay more attention to them and their work.

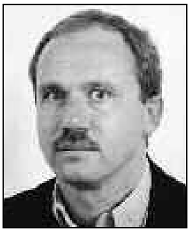
During a visit to the Energy Research Centre Netherlands (ECN), the scientific director of the JMBC was informed that also ECN wants to sponsor a Burgerscentrum professor. ECN has a preference for an expert in the area of computational fluid dynamics of multiphase flows. A number of JMBC groups have expressed an interest in this possibility and are preparing proposals for the appointment of another Burgerscentrum professor.



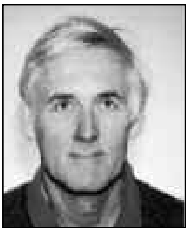
David Montgomery



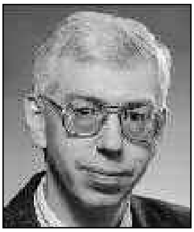
Andrea Prosperetti



Ben van den Brule



Julian Hunt



Steve Pope

DJEM Roekaerts

Statistical properties of turbulent gaseous flames

In 1998 Pieter Nooren and Huib Wouters presented their PhD-thesis presenting remarkable results on simulation[1,2] and measurement[1] of turbulent gaseous flames. The simulation method used is a Probability Density Function (PDF) method, providing a statistical description and which is an especially attractive closure model for reactive flows, because the mean chemical source terms appear in closed form and do not present a turbulence modelling problem. To calculate the PDF, Monte Carlo (MC) simulation is used, which is closely linked to the Lagrangian description of transport and therefore provides original opportunities for modeling. The problems involved in the development of the method are both theoretical and numerical and a crucial role is played by detailed validation with experiments. To speed up the validation process a series of International Workshops on Turbulent Nonpremixed Flames is organised, where groups from all over the world present their experimental and modeling results for a set of benchmark problems, one of which is the "Delft turbulent natural gas diffusion flame". At the third workshop last summer in Boulder Colorado, our group has contributed both modeling and experimental results. Michel Versluis, Ronnie Knikker, Min-Cheng Zong and Theo van der Meer presented new and very accurate CARS measurements of temperature in the Delft flame and demonstrated very good agreement between these measurements and Raman-Rayleigh measurements made by Pieter Nooren et al. in Sandia. Tim Peeters gave a review of all Delft flame results.

In the last few years several groups worldwide have made major steps forward in the modeling of turbulent diffusion flames using MC-PDF methods. At TU Delft systematic studies were made on the performance of different micro-mixing and chemistry models in the description of piloted and bluff-body stabilised natural gas jet diffusion flames and consistent combinations of second moment closure and Lagrangian methods were developed. Results to be highlighted are: 1. The MC-PDF method has been applied using a representation of detailed chemistry via intrinsic low dimensional manifolds (collaboration with U Maas and D Schmidt of the University of Stuttgart). 2. A consistent formulation of the hybrid Monte Carlo PDF method in which stochastic algorithms are combined with finite difference methods has been extended to a general class of second moment closures. 3. The consistent formulation of the hybrid Monte Carlo PDF method has been applied in a study of bluff body stabilised methane flames. 4. Preferred models were identified based on a comparison also of the PDFs of temperature and chemical species, i.e. not restricted to only a set of mean values, as done earlier. As a result of this work a well-documented and flexible computer code PDFD has been developed.

The development of PDFD started from the code PDF2DS by SB Pope (Cornell University), to which several models for convection, micromixing and reaction have been added. PDFD is used in combination with the code BIGMIXD for modeling of turbulent flames by finite difference methods.

Nevertheless, there are many open problems left in flames with strong turbulence-chemistry interaction, in more complex flow fields and with other physical effects (soot formation, high radiative losses).

The Foundation for Fundamental Research on Matter (FOM) supports the continuation of projects in three directions: 1. new experiments on turbulence-chemistry interaction, 2. new model development for gaseous flames in particular including multiscale turbulent mixing models and models for soot formation and radiation, 3. model development for turbulent reactive sprays. By the JM Burgers Centre, SB Pope is invited for a number of visits to The Netherlands, in order to participate in this research programme. A first visit took place in December 1998.

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RVA Oliemans
BM Mols

Horizontal annular dispersed gas/liquid flow

In horizontal annular dispersed flow in a tube one wonders what role droplet deposition plays in the formation of the liquid film that covers the tube wall. Once the film is present it will have a shape as shown in figure 1. Due to gravity the liquid layer at the pipe wall will be very asymmetric: a thin film will be present for most of the upper part of the pipe circumference, while a relatively thick layer of liquid will accumulate at the bottom.

Drops will entrain from the liquid layer and disperse into the inhomogeneous turbulent gas core. Droplets that are small enough will be able to reach the top of the tube and contribute to the film formation by depositing on the tube wall. The question is what fraction of the droplets present in the turbulent gas stream will make it to the top?

At Delft University we have studied this problem by using three different models with increasing complexity: a macroscopic Turbulent Diffusion (TD)-model, a mesoscopic Probability Density Function (PDF)-model, and a microscopic Large Eddy Simulation (LES). The first model is computationally efficient and cheap, but requires a great number of simplifying assumptions, the second enables us to learn more about droplet statistics and the third is computationally intensive, can handle only a limited number of drops, but requires only limited assumptions. The models have been applied to the relatively simple channel flow configuration, the first two with one-dimensional versions, while the LES is 3D. Moreover, we have simplified the problem further by ignoring the presence of the liquid film and concentrating on drops dispersed in the turbulent gas.

A crucial finding with the more sophisticated models is that the diffusivity for particles in wall bounded flow decreases with increasing particle Stokes number.

This decrease is caused by the crossing trajectory effects due to relative velocity differences between particle and fluid in streamwise direction and due to gravity and by the fact that wall bounded flows reduce the length and time scales as compared to homogeneous flows. For water drops with a size of 200 µm in air flowing at an average velocity of 32 m/s the diffusivity is reduced by 10%. The PDF calculations moreover show that the free-flight velocity that is used in the TD-models close to the walls is not uniform over the cross-section and 70% too high.

Although it was possible to incorporate some qualitative improvements into the TD-model on the basis of this comparative study, quantitatively there are large differences for the three models. The relative deposition of droplets is plotted in figure 2 as function of the Peclet number, which is the ratio of the convection due to gravitational settling and the turbulent diffusion. From the LES results one can derive that at an air velocity of 62 m/s in a horizontal channel water drops up to 140 µm may reach the upper wall. For the PDF model the maximum drop size is 100 µm and for the TD-model 70 µm. A factor of 2 between the largest and smallest calculation. This means that wetting of the top wall according to LES will occur at lower gas velocities than with the other models.

Our study has shown how information obtained with more detailed models can be used to improve the physics in simpler models. Further research will have to reveal to what extent it will be possible to grasp the essential phenomena in simpler models. For this purpose the calculations with the three models will be performed for the more complex tube geometry and compared with experiments.

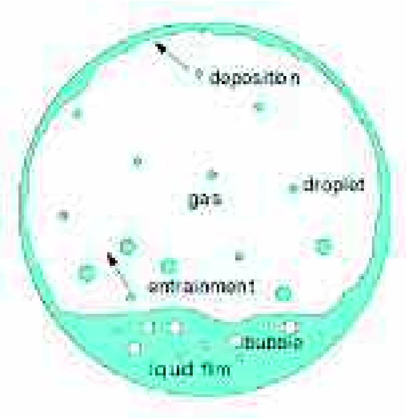

Figure 1 Gas/liquid annular dispersed flow configuration in a horizontal tube.

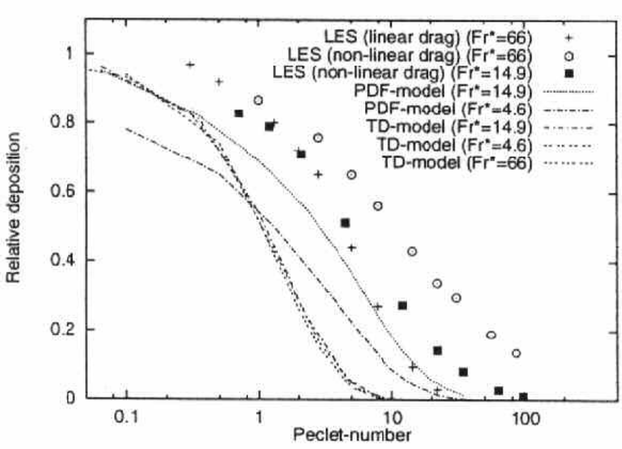

Figure 2 Relative deposition of drops in horizontal channel flow according to three models. The PDF and LES results strongly depend on gas velocity (Fr*-number).

J Mellema

Hydrodynamic diffusion

Introduction

As a result of thermal motion atoms and molecules are in perpetual motion. In the gas and liquid phases this motion is so strong that the particles can move freely and if on could follow the motion of an individual particle one would observe an apparently random trajectory in space. This random motion is called diffusion. On may think that diffusive behavior is a privilege of relatively small Brownian particles in thermal motion. It was a surprise when similar behavior was observed during the slow flow in a dispersion of relatively large particles. This diffusive motion which is flow induced and not caused by thermal motion is called hydrodynamic diffusion. This effect has practical as well as a theoretical implications. A practical consequence is that in viscosity measurements the possibility of apparent viscosity changes due to shear induced concentration changes should be taken into account. In flow phenomena like transport of sand and mud slurries, the flow of blood in arteria, and in processes in food industry unexpected concentration effects may occur and occasionally even phase separation. The theoretical challenge is to understand why random motion occurs as a result of intrinsically reversible Stokes equations which dictate the flow at the particle level. The solution of this appearent paradox is that in the many particle problem the environment of an individual particle is rapidly changing and these changes are essentially random. The dependence of the hydrodynamic diffusion coefficients upon parameters like the shear rate γ, the particle-radius and the volume fraction ϕ should be considered. From dimensional analysis one readily obtains that the diffusion constant should scale as $D = \gamma a^2 \hat{D}(\phi)$ where $\hat{D}$ is a dimensionless function of the volume fraction. The determination of this function is an important issue. Due to the anisotropy of the flow the diffusion is not equal in all directions.

So, in fact, a diffusion tensor is needed instead of a scalar quantity. In particular the components of this tensor, pertaining to the diffusivity in the velocity gradient and the vorticity direction are of interest.

Research in Twente

In the Rheology Group of the Faculty of Applied Physics of the University of Twente since 1996 a research project is performed on hydrodynamic diffusion.

Our research is focused on the self diffusion of individual particles.

Advanced measurement techniques are needed to detect and analyze the motion of individual particles under well defined flow conditions.

The experiment is based on spatial correlation of a sequence of video images of the sheared suspension of a refractive index and density matched acryl (PMMA) particles in water in which some (tracer) particles are colored. At a fixed position in the geometry images can be taken with a CCD camera and stored in a computer for further analysis. These images will only show the tracer particles and two consecutive images appear like the pictures in figure 1.

The positions of the tracer particles in the images are determined with image analysis software. Subsequently, the positions of the tracer particles in the second image are correlated with the positions of the tracers in the first image by calculating the displacement vectors. In a statistical analysis for a large ensemble of images the self-diffusion coefficients are determined.

Results

The available experimental data for shear-induced self-diffusion as a function of volume fraction ϕ and our results are combined in figure 2. Despite the significant experimental errors, there is fair agreement between the results of the various experimental methods with different systems and one can observe some trends. The dimensionless diffusion coefficient in the velocity gradient direction ($\hat{D}_{yy}$) is larger (about a factor 1.5) than in the vorticity direction ($\hat{D}_{zz}$). Both diffusion coefficients grow more than linearly with volume fraction up to circa 0.40. From the graphs it follows that the diffusion coefficients do not grow unlimitedly with ϕ, they leave open whether coefficients level off or go down above 0.40.

Currently we are investigating models at the particle level that can describe the observed behavior. Depending upon the volume fraction ϕ, two particle collision models, multi particle cluster models and models based upon global layers and strings of particles are considered.

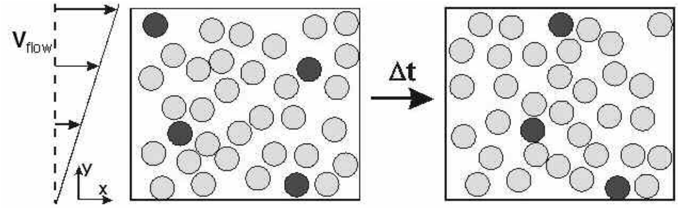

Figure 1 Images of tracer particles

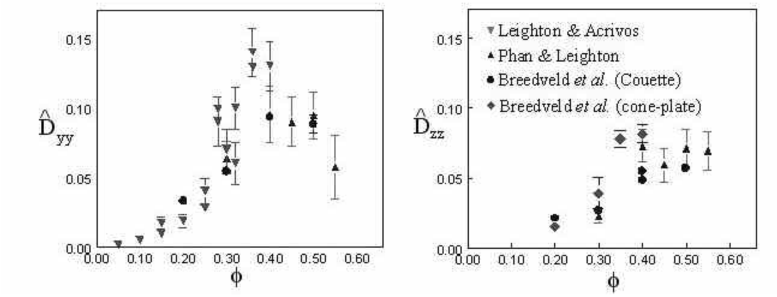

Figure 2 Experimental data for shear-induced self-diffusion

AEP Veldman
RWCP Verstappen

DNS of turbulent flow past bluff bodies

In view of the computational complexity of Direct Numerical Simulation (DNS) our first concern is to reduce the computational costs as far as we can get. This implies - among others - that the number of grid points has to be kept as small as possible. Therefore spatial discretization methods for the Navier-Stokes equations need to be strained to their limit.

On nonuniform grids various ways exist to discretize convective and diffusive operators. We propose to apply a high-order finite-volume discretization method that preserves the spectral properties of the convective and diffusive operators, i.e.convection : skew-symmetric; diffusion : symmetric positive definite. It is our experience that in this way the error of the convective discretization does not interfere with the diffusion on the smallest length scales. The energy of the discrete system is conserved, if the physical dissipation is turned off.

We have applied this numerical method to compute a fully developed flow in a channel, where a matrix of 25x10 cubes is placed regularly at one wall. The Reynolds number (based on the width of the channel and the bulk velocity) is equal to Re=13,000. Flow measurements by Meinders et al. have shown that the computational domain may be confined to the sub-channel unit shown below.

The flow through the sub-channel was one of the test cases at the 6th ERCOFTAC/ IAHR/COST Workshop on Refined Flow Modeling. Four groups have presented the results of their Reynolds-Averaged Navier-Stokes (RANS) computations.

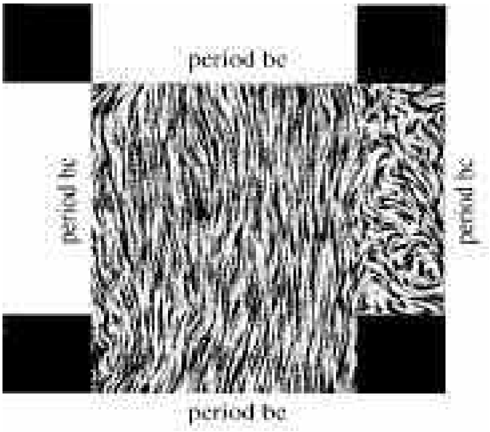

Figure 1 Top-view of a sub-channel unit. Shown is an instantaneous flow field at half the height of the cubes.

Both high- and low-Re-number RANS-models were applied. The RANS computation that agreed the best with the available experimental data used a 67x72x57 grid.

We have computed solutions of the incompressible Navier-Stokes equations (without using any turbulence model) on a number of grids. Figure 2 shows a comparison of the mean streamwise velocity of our 60^3 and the 100^3 Navier-Stokes computations, that of the best RANS computation and the available experimental data. On a corresponding grid, the mean velocities computed from the Reynolds-averaged Navier-Stokes equations agree less with the experimental data than the results of the 60^3 Navier-Stokes computation.

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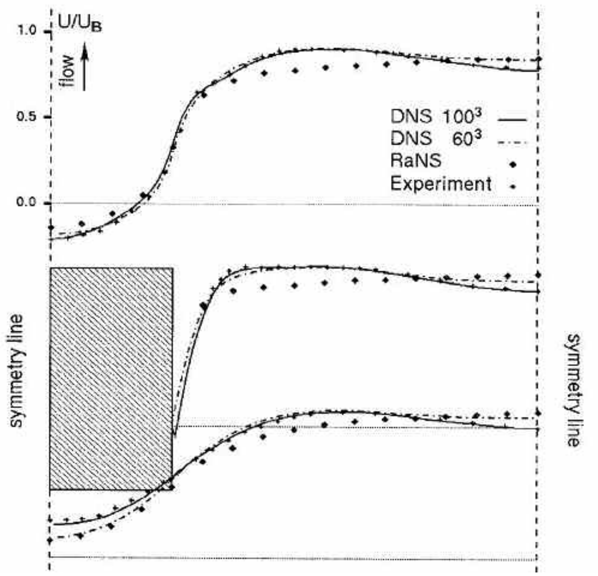


Figure 2 Comparison of the mean streamwise velocity at half cube height. The horizontal corresponds to the spanwise direction. The dashed vertical lines are lines of symmetry. The geometry is drawn to scale.

GJF van Heijst
M Beckers

Interacting vortex structures

The world of decaying 2D turbulence is a fascinating one: the inverse energy cascade leads to selforganisation of the flow, which can be observed in the emergence of large-scale vortex structures. In the earlier evolution stages of a randomly initialised 2D turbulent flow field on an infinite (or doubly-periodic) domain, the flow domain is densely populated by vortices, and intense mutual interactions occur. In this stage, a vortex generally experiences strong strain or shear induced by the ambient motion: only the stronger vortices survive, while the weaker ones are torn apart, giving birth to thin vorticity filaments. Somewhat later in the flow evolution the small-scale vorticity has to a large deal been removed by viscous effects, and the flow has the appearance of a dilute cloud of vortices, consisting of mainly monopolar and dipolar structures, while in rare cases even tripoles have been observed. At this stage the vortices still interact, but in a much better defined way: the interactions mainly occur between only two neighbouring vortex structures.

For example, when close enough two like-signed monopolar vortices show merger into one larger monopolar structure (accompanied by spiral-shaped vorticity filaments, which, however, quickly disappear owing to diffusion). Also monopole-dipole interactions can be observed, either leading to the formation of a single, larger monopolar or dipolar structure or showing so-called ‘partner exchange’ (one half of the dipole pairs with the monopole thus forming a new dipole, while the other half of the original dipole is left behind as a monopolar vortex).

Within the framework of the study on interacting vortex structures in a stratified fluid, some interesting experiments have been performed at the Fluid Dynamics Laboratory in Eindhoven: two oppositely-signed shielded vortices were generated close to each other by tangential injection of a small volume of fluid into two open cylinders immersed in the stratified ambient fluid (see Figure 1).

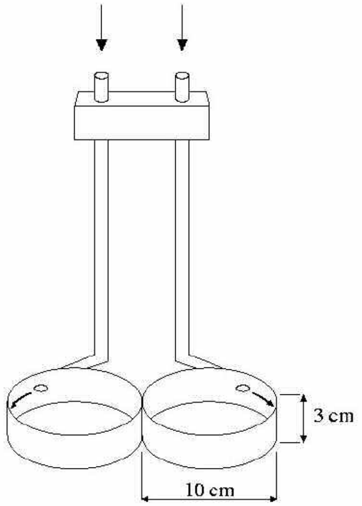


Figure 1 Sketch of the vortex generators. Some fluid is injected from above through the tubes and flows tangentially into the cylinders, along the inner walls, in opposite directions.

After the cylinders were carefully lifted, the released vortices were allowed to start interacting.

Even for relatively small separation distances (comparable to their sizes) these vortices hardly interact, because the ring of oppositely-signed vorticity surrounding each vortex core effectively ‘shields’ the vortex core. When the vortices are generated at the closest possible distance - the generating cylinders are touching, see Figure 1 - the opposite-vorticity shields are seen to roll up, and both vortex cores combine into a strong single dipole that propagates away along a straight path. This is nicely shown by the dye visualisation pictures presented in Figure 2. In this particular experiment the initial monopolar vortices were dyed with different colours (orange and green), and the emerging dipole consists of one orange and one green core. Somewhat later in the evolution, the vorticity originally contained in the shields is observed to become organised into a dipolar structure as well: again, this dipole is partially orange and partially green and it propagates away along a straight line, but now in the opposite direction.

In addition to the dye visualisation, which provides qualitative information, the vortex interaction process has also been studied quantitatively in laboratory experiments by applying a PTV technique and by performing numerical simulations with a spectral method (for more detailed information, see Phys. Fluids 10, 3099-3110 (1998)).

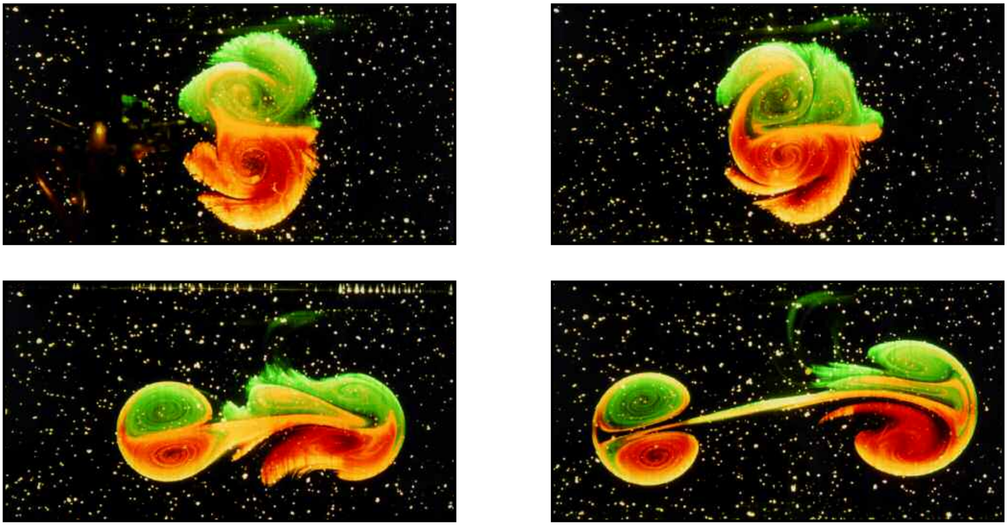


Figure 2 Sequence of photographs of the dye-visualised vortex interaction. The pictures are taken at 90 s, 134 s, 221 s and 387 s after the injection was stopped and the cylinders removed. The bright spots are tracer particles, which were still present in the flow.

FTM Nieuwstadt

Afscheid professor Hoogendoorn als wetenschappelijk directeur van het JMBC

Op 13 januari j.l. vond traditiegetrouw, de zogenaamde Burgersdag plaats, genoemd naar de grondlegger van de stromingsleer in Nederland en de naamgever van het JM Burgers Centre. Dit keer stond de dag in het teken van Prof.ir. CJ Hoogendoorn. Nam hij ruim twee jaar geleden al afscheid van zijn groep Warmtetransport bij de faculteit Technische Natuurkunde van de TU Delft, ditmaal nam hij afscheid als wetenschappelijk directeur van het Burgerscentrum. Vanaf de oprichting van deze onderzoekschool voor stromingsleer heeft Hoogendoorn, zo werd deze dag nog eens uitgebreid en terecht gememoreerd, veel werk verzet voor de totstandkoming en de bloei van het centrum. En ook al is zijn opvolger, Prof.dr.ir. G Ooms, inmiddels al aangetreden, de Burgersdag was bij uitstek de gelegenheid om Hoogendoorn te eren, alleen al gezien het feit dat hij een directe leerling van Jan Burgers genoemd kan worden. Na een openingswoord van Prof. RWJ Kouffeld, voorzitter van het bestuur van het Burgerscentrum, leidde Prof. Ooms het ochtendprogramma in. Dit besrond uit vier lezingen over onderwerpen die niet alleen een beeld gaven van het brede scala aan onderwerpen waaraan Hoogendoorn en zijn groep in de loop der jaren gewerkt hebben, maar ook van de fraaie combinatie van de “praktische” toepassing van fundamenteel onderzoek en de kracht van numeriek onderzoek.

Prof.dr. DJEM Roekaerts gaf een overzicht van het onderzoek naar verbranding binnen het Burgerscentrum. Ir. AJ Dalhuijsen van TNO liet een fraaie en zeer instructieve computeranimatie zien van de fysische processen in een glasoven. Dr. J Bruining sprak over een zeer actueel, en ook verontrustend onderwerp: de ondergrondse kolenbranden, die vooral in China op grote schaal voorkomen. Hij besprak de analogie van deze branden met het vergassen van kolen onder de grond. De spreker zette uiteen, hoe dit proces dat door de huidige lage olieprijzen weer wat uit de aandacht is verdwenen, bij de faculteit Technische Aardwetenschappen wordt onderzocht. Tenslotte hield Prof.dr.ir. AA van Steenhoven een voordracht over twee “apparaten”: een vat voor de opslag van koude of warmte en een zonnecollector die zowel met pv cellen electriciteit levert als met een absorber wamte opslaat.

Na de lunch sprak Prof. Hoogendoorn voor een goed gevulde collegezaal zijn afscheidsrede uit, getiteld “Met warmte en energie”. Voor de tweede maal, zo merkte hij op, trok hij nu de deur van het laboratorium van het JM Burgers Centre achter zich dicht: eerst als student in de jaren ‘50, nu als wetenschappelijk directeur. Als leidraad voor zijn voordracht nam hij zijn intreerede uit 1971, de tijd van de onheilstijdingen van de Club van Rome. Hoogendoorn merkte op dat de uitspraken die hij toen over het thema “energie en maatschappij” deed, eigenlijk nog altijd geldig zijn. Alleen staat het thema nu voortdurend in de belangstelling, dankzij de olieprijzen. Je zou kunnen zeggen dat Hoogendoorn’s groep in die tijd met de neus in de boter viel en veel pionierswerk op energiegebied kon verrichten.

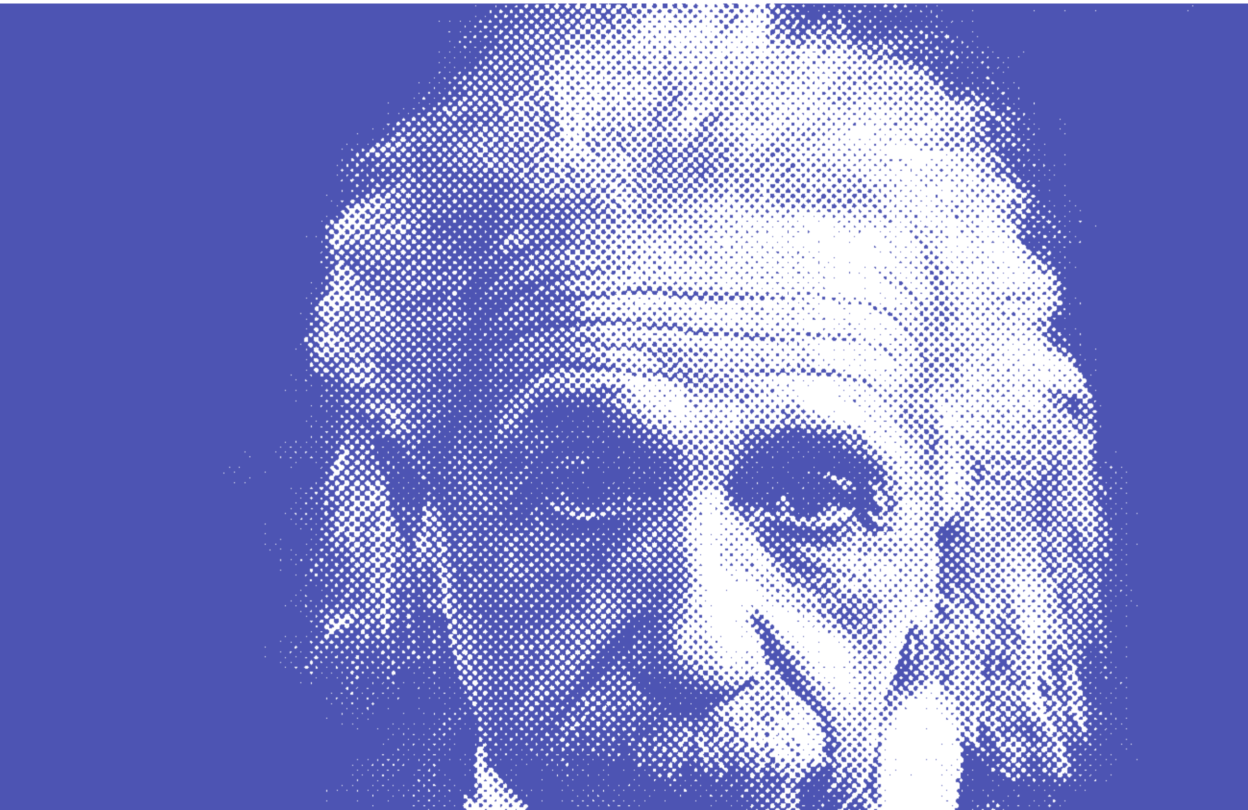
Over de toepassing van zonne-energie merkte de spreker op: als je zon wilt, zoek de zon dan op, daarbij enige aandacht bestedend aan de voortdurende behoefte van de mens om de uitputting van de olie- en gasvoorraden te voorspellen.

Hoogendoorn meende dat hier in feite geen zinnig woord over te zeggen is en liet zien dat de situatie eigenlijk alleen maar gunstiger is geworden. Over het huidige CO2 beleid merkte hij op dat dit eigenlijk zou moeten neerkomen op een bevolkingsbeleid, aangezien de statistieken laten zien dat de energieconsumptie per persoon per jaar vrijwel gelijk gebleven is gedurende de laatste 25 jaar. Voorlopig zag hij geen kans voor de grootschalige invoering van alternatieve energiebronnen, tenzij er (weer) een ernstige politieke of economische crisis zou uitbreken. De onlangs in Kyoto opgestelde doelstellingen zullen veel regelgeving opleveren en hoge kosten voor de burgers betekenen. En ondertussen groeit de autoproductie gewoon door. Alleen een belasting naar energieverbruik van auto's, en andere apparaten, kan zorgen dat mensen zuiniger omgaan met energie; een 'ecotax' werkt niet omdat deze slechts indirect werkt.
Daarna schetste Hoogendoorn het werk van zijn groep in de loop der jaren: zonneboilers, isolatie, efficiënte verbranding van aardgas, een wereldbekend simulatiemodel voor een vlam, enz. Als uitdaging voor zijn opvolgers zag hij vooral de modellering van turbulentie. Tenslotte sprak hij nog over het Burgerscentrum en wees daarbij op het belang van de numerieke groepen (waarbij hij opmerkte dat experimenten voor de validatie zeker nodig blijven). Hij toonde zich tevreden over de subsidies die de onderzoekschool in de loop der jaren had binnengehaald.
Het onderwijs loopt 'als een trein' maar wat betreft het onderzoek zou hij toch wat meer aandacht aan kwaliteitsbewaking en dergelijke willen zien. Na deze rede volgden een vijftal persoonlijke toespraken. Professor Kruit, decaan van Technische Natuurkunde, vroeg zich af hoe het voor Hoogendoorn geweest moest zijn toen hij in 1975 decaan werd, midden in de periode van 'democratisering'. Hij bood Hoogendoorn een klassieke serie boeken aan over 'government'. Professor van Heijst van de TU Eindhoven meende dat meer nog dan 'warmte' de term 'vuur' bij Hoogendoorn paste. Hierdoor kon hij structuur in het Burgerscentrum brengen en de KNAW-erkenning voor elkaar krijgen. De spreker memoreerde vooral de wijze waarop telefoongesprekken tussen beiden vaak verliepen. Dr. Van der Meer, al vele jaren verbonden aan de groep Warmtetransport, sprak zijn bewondering uit voor het feit dat Hoogendoorn vele deuren geopend kon krijgen (zodat van der Meer er achteraan kon glippen). Hij memoreerde de 29 'eigen' promovendi van de hoogleraar en diens goede geheugen en overredingskracht. Bovendien had hij altijd een goed oog voor de sfeer in de groep (die hij bewust klein hield). Professor van den Akker van Fysische Technologie vergeleek professor Hoogendoorn met de dodo (de leiding nemen) en de Kollumer kat (overzicht hebben) in het boek 'Alice in Wonderland', zichzelf met Alice en de rest van die wonderlijke wereld uit het boek met die van de Delftse professoren.

Dr. Dijksman van de Industriële Adviesraad van het JM Burgers Centre liet tot slot dia's van een apenrots zien. Naar aanleiding van de opmerkingen die af en toe gevallen waren over zijn wat autoritaire manier van leiding geven, merkte hij op dat hij inderdaad bij vergaderingen wel eens de voorzitter was, terwijl hij dat officieel niet was.

Raffiniert is der Herr Gott, aber boshaft ist er nicht

Albert Einstein



1999

K Hanjalic
S Kenjeres

Simulation of deterministic eddy structure by RANS

In many turbulent flows of industrial and environmental relevance, large-scale eddy structures are the major carrier of momentum, heat and species. In such flows the transport processes can be best controlled by affecting the coherent eddy structure, either by imposing an external force, or by control of boundary topology or its physical conditions. Both techniques have long been in use: rotation, buoyancy, electric or magnetic field, surface blowing and suction, riblets and grooves are only some of means used to control drag, heat and mass transfer, entrainment and mixing, combustion and noise. Major prerequisite for optimal control is the ability to identify the coherent structures and their role in controlling flow and transport processes. While DNS and LES methods can provide necessary information, their application in complex industrial flows at high Re, Ra, Ro numbers is still very limited.

We argue that for flows with dominant eddy structure, the application of time-dependent Reynolds-averaged Navier-Stokes ('TRANS') approach can be a powerful tool for identifying the organised motion and its response to the imposed external force or specific boundary conditions. The TRANS approach is based on the triple-decomposition where the large scale periodic-like motion is fully resolved in time and space, whereas the unresolved stochastic contribution is modelled by a conventional single-point eddy-viscosity or second-moment closure model.

In contrast to LES, in the TRANS approach the contribution of both modes (resolved and modelled) to the turbulence fluctuations are of the same order of magnitude. In wall boundary layers the TRANS model accounts almost fully for the turbulence statistics, with a marginal contribution of the resolved motion.

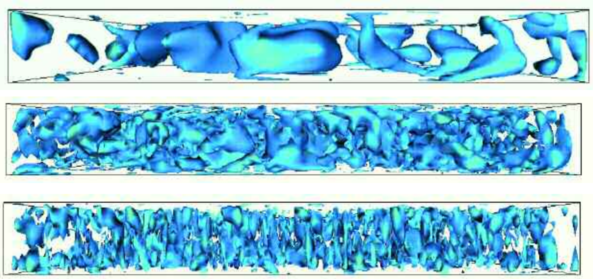


Figure 1 Effects of magnetic field ($B_i || g_i$, Ha=0,20,100) on the spatial reorganisation of coherent structures in RB convection, N_k=3, *Ra*=10^7

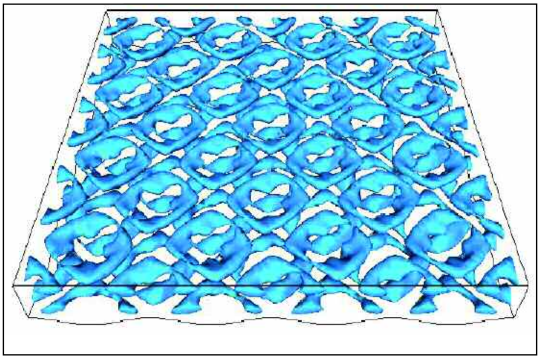


Figure 2 Spatial organisation of coherent structures defined by N_k=2 at T*=50 for a heated 3D wavy bottom wall; *Ra*=10^7, *Pr*=0.71

This proved to be the key of the success for accurate near-wall predictions (verified by DNS) of fluid velocity, temperature and wall heat transfer.

For the identification of structure morphology we used the classical vorticity/helicity approach and the critical point theory. Both the LES and TRANS capture only the large structure whereas the smaller ones are filtered out. Instead of grid size, as used in LES, the filter in the TRANS approach is defined by the specific length and time scales emerging from the subscale model.

As an illustration, the TRANS simulations of classical and magnetic Rayleigh-Benard convection is presented, the former with a wavy bottom wall. Figure 1 shows the damping and reorientation of coherent structure under the action of the Lorentz force in the horizontal plane for different strengths of magnetic field. Figure 2 illustrates the organised eddy pattern imposed by the 3-dimensional waviness of the bottom heated wall. Both results were obtained with the same TRANS method, using the model for subscale motion.

BHAA van den Brule
MA Hulsen
EAJF Peters
APG van Heel

From microscopic models to macroscopic complex flows

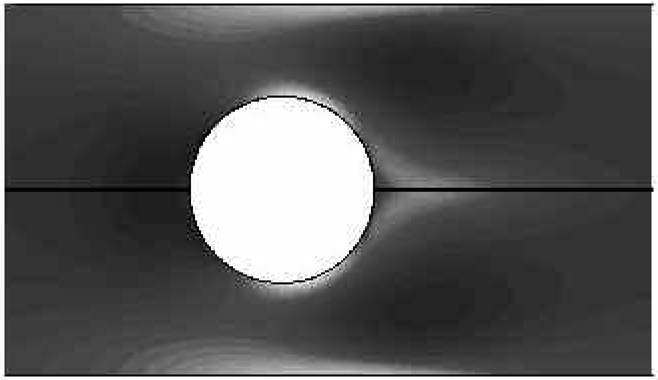
Polymers play a key role in the manufacturing of a huge and increasing number of consumer products. Since during processing conditions the polymers usually are in a liquid or dissolved state, good knowledge of their flow behaviour is of crucial importance for optimisation of both their processing conditions and the properties of the end products.

The flow behaviour of polymeric liquids can differ significantly from that of "ordinary" Newtonian liquids like water. This is because "polymeric liquids possess a memory".

Whereas the stress in a Newtonian liquid is completely determined by its momentary rate of deformation, in a polymeric liquid, the momentary stress is determined by the complete deformation history the fluid has experienced. This stress tensor is the crucial ingredient in the simulation of viscoelastic flows, and together with the material-independent conservation laws of mass and momentum it constitutes a complete set of equations to calculate the isothermal flow of the liquid.

In principle two approaches are possible to calculate the stress tensor: a macroscopic continuum-mechanical approach and a microscopic approach. In the traditional, macroscopic approach the flow behaviour of the material is modelled by a single equation, the so-called constitutive equation. Usually this constitutive equation is a postulated equation which contains several adjustable material-dependent parameters, which have to be determined experimentally.

In contrast to the macroscopic approach, in the microscopic approach, the flow behaviour of the material is regarded as the net effect of the dynamics of a large collection of polymer molecules. In this approach, polymer molecules are modelled as relatively simple mechanical objects and the stress in the fluid is determined directly from the configuration of these model polymers. The advantage of this microscopic approach to flow simulations is its generality: microscopic polymer models usually can not be described by a traditional constitutive equation.



Simulation of the flow of a polymer melt past a cylinder. The figure shows the yy-component of the stress tensor, which was calculated directly from the configuration of the polymers. The results were obtained using the Doi-Edwards polymer melt model, and were calculated using the deformation field approach.

In our group we have developed two new simulation techniques to combine a microscopic modelling of the polymers with the simulation of complex flows in macroscopic domains. These methods are the so-called Brownian configuration field method and the recently introduced deformation field approach.

The deformation field approach is ideally suited for the simulation of the flow of polymer melts. The idea of the method is to calculate the momentary configuration of the polymers, and consequently the stress, from their initial configuration and the deformation they have experienced afterwards. We have applied this method to the classical Doi-Edwards reptation model for a polymeric melt, and recently we generalised and applied the approach to more advanced polymer melt models which also include stretching of the polymers and loss of constraints.

AA van Steenhoven
HC de Lange

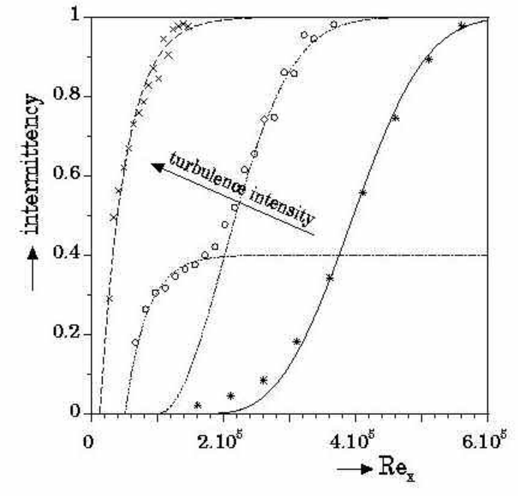
Bypass transition in a boundary layer at high main-stream turbulence levels

In natural boundary layer transition, unstable linear TS-waves are amplified until non-linear disturbances are formed. At a certain position these disturbances form the start of turbulent spots. These spots grow until the boundary layer is fully turbulent. At high free-stream turbulence levels disturbances in the free-stream intrude into the boundary layer.

They bypass the first stage of transition and result directly into the formation of turbulent spots. The spot formation process in bypass transition is a still uncomprehended phenomenon: are the spots caused by the amplification of intruding free-stream perturbations or are the spots formed by (near wall) laminar fluctuations induced by the main stream turbulence ?

It is clear that there are two main parameters of importance to the transition process: the intensity and the length scale of the turbulence. In our group experiments have been performed in a Ludwieg tube to obtain transitional data at high main stream velocities (of about 100 m/s). Main stream turbulence is induced by different meshes of variable diameter (1 till 4 mm) which produce a turbulence intensity of 1% to 4%. This leads to a large ratio of turbulent disturbance length scale to boundary layer thickness. In our experiments high performance hot films are used, which are able to measure the time-resolved heat flux at about 100kHz. This makes it possible to measure the influence of seperate turbulent spots. From these experiments intermittency distributions are derived.

At low turbulence levels the results agree very well with experiments performed in low speed wind tunnels. The intermittency distribution maintains the same shape as with natural transition.



Intermittency distributions as a function of the streamwise position for different levels of turbulence intensity.

This implies that the formation of turbulent spots is still due to the growth of laminar fluctuations, which turn into spots at a certain position. For higher turbulence levels, we find that the shape of the intermittency profile starts to change. Part of the profile still follows the low level curve, which corresponds to the growing spots.

However, the start of the curve follows a curve that can only be described by intruding turbulent spots which decrease in size. As the turbulence level is increased further the difference with the classical intermittency distributions becomes even more pronounced. The only way to account for this shape is by the assumption of spots which penetrate the boundary layer through the whole transition region.

Next, we have modified our experimental set-up to study the combination of steady turbulence and unsteady wake flow. Our results show that commenly used intermittency and superposition principles fail when these two flow phenomena are combined. Based on that, a model is being developed to describe the transitional flow under these conditions (which correspond to gas turbine conditions), which can be used in CFD-codes.

JAM Kuipers

Discrete particle simulation of fluidised beds

At Twente University, department of Chemical Engineering Hoomans [1] has developed a discrete particle model of a dense gas-fluidized bed. In this model the Newtonian equations of motion are solved for each individual particle in the system while taking into account the mutual interaction between the particles and between particles and the confining walls. The gas phase flow field is obtained from the volume-averaged Navier-Stokes equations taking into account two-way coupling.
In the figure shown below a typical result obtained from the discrete particle model is presented.

The snapshots were obtained from a discrete particle simulation of a two-dimensional gas-fluidized bed with homogeneous gas distribution at the bottom of the bed. The top portion of the figure shows the simulation results obtained for non-ideal particle collisions (e=0.9 and m=0.3) whereas the bottom portion of the figure shows the simulation results obtained for ideal particle collisions (e=1.0 and m=0.0). The results obtained by Hoomans indicate that dissipative mechanisms (i.e. non-ideal particle-particle collisions) have a decisive effect on the global dynamics of the fluid bed (i.e. the occurence of gas bubbles).

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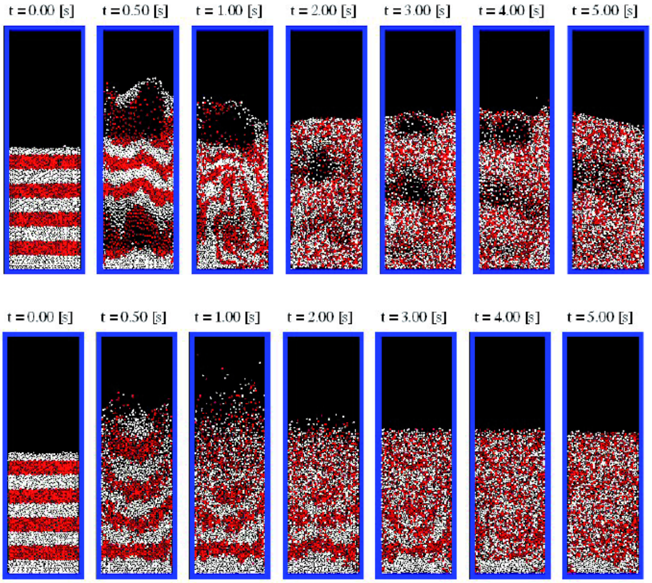


Snapshots of particle configurations for the simulation of bubble formation with homogeneous inflow conditions in a two-dimensional gas-fluidized bed. Top: non-ideal particles (e=0.9, m=0.3); bottom: ideal particles (e=1.0, m=0.0).

AERO- & HYDRODYNAMICA.

LANTAARNPLAATJE

KIST F Nr. 45

Het origineel van het plaatje is te vinden:

GROEP:

Meetinstrumenten

ONDERWERP:

6-voudige alcohol-manometer

BESCHRIJVING:

Negatief R 46

R I 113 - '24 - 1706

D Lohse

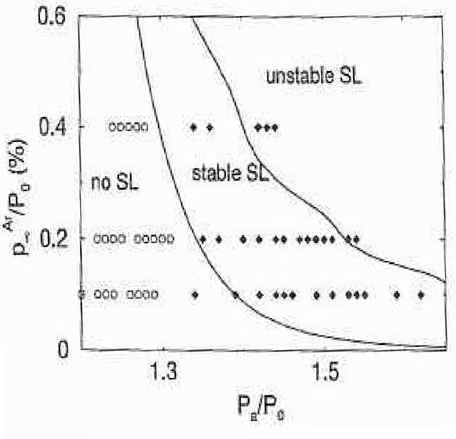
Sonoluminescence: when bubbles glow

When Felipe Gaitan was working on his PhD at the University of Mississippi in 1990, he hoped for new insights into the dynamics of a single, ultrasonically driven bubble. He was thrilled to discover that he could make the bubble emit a steady glow of bluish light. This phenomenon is now known as (single bubble) sonoluminescence (SL) [1-3]. Converting sound into light is so remarkable as the energy density in the emitted photons is about 12 orders of magnitude greater than in the driving sound field!

Sonoluminescence immediately became the target of the efforts of many research groups, but even several years after Gaitan's discovery the mechanism of light emission was still unknown, and a number of other unresolved puzzles had appeared. These included the extreme stability of the phenomenon (over hours or days) in a very narrow range of driving pressures or the increase of the light intensity with decreasing water temperature.

Meanwhile almost all of these open questions have been answered satisfactorily in the past few years, and the increased understanding of SL bubbles has finally lead to a plausible model for the light emission, too.

The starting point for the work in our group was the shape and diffusive stability of the bubbles [4,5]. Moreover, the bubble collapse must be violent enough so that the gas inside the bubble can adiabatically heat up [5]. However, also the chemical stability of the gas inside the bubble is crucial [6]. At the high temperatures achieved at bubble collapse all molecular gases (oxygen, nitrogen) in air dissociate, and the resulting radicals form products that dissolve in the surrounding water. The only constituent of air which cannot dissociate is argon, and therefore it is only the partial pressure of argon which is relevant for the bubble stability.



Theoretical phase diagramme and experimental data obtained at 33.4 kHz for air. Pa is the forcing pressure, P0= 1atm the ambient pressure, p{ar} the partial pressure of argon. The open circles are stable non-sonoluminescencing points, the closed diamonds denote light emitting bubbles. Good agreement between theory and experiment is found.

These criteria lead to phase diagrams of sonoluminescence in parameter space. One example is given in figure 1. There are three regimes: stable SL, unstable SL, and no SL. The theoretical results are in very good agreement with recent experiments conducted in the group of Robert Apfel in Yale [7], see figure 1.

The picture of light emission itself, the spectacular feature of sonoluminescing bubbles, has also cleared up recently, based on the outstanding measurements by Bruno Gompf, Wolfgang Eisenmenger and their collaborators at the University of Stuttgart [8,9].

They succeeded to time resolve the light pulse in different frequency regimes. There measurements prompted theoretical work which can quantitatively account for the light as thermal bremsstrahlung [10,11].

Are there applications of SL ? Here I will only mention one: In ultrasound diagnostics, bubbles are used as tracers because of their huge scattering cross sections for diagnostic ultrasound [12]. With the present understanding of bubble dynamics, largely due to sonoluminescence research, a deliberate "design" of bubbles seems now possible.

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G Fekken
J Gerrits
HW Hoogstraten
GE Loots
AEP Veldman

3D Free-surface flow simulation using Cartesian grid

A lot of CFD codes have in common that they use body-fitted coordinates. Although this has advantages in the field of boundary treatment and refinements, the construction of a new grid for each separate problem is often more costly than the simulation itself. Our approach is to use finite-volume discretization of the (incompressible) Navier-Stokes equations on a simple, rectilinear (Cartesian) grid, thus enabling the use of arbitrary complex (3D) geometries. The drawback of this approach is that measures have to be taken at the non-grid-aligned boundaries (for example, the introduction of several ghost velocity fields).

The development of this numerical method, called ComFlo, started in 1995 while free-surface flow was a feature included from the outset. The position of the fluid (and thus the free surface) is described by an improved Eulerian VOF function, which can be regarded as a discrete analogon of the indicator function of the fluid. Transportation of the free surface is achieved using a local level set method: a local height function. This advection method performs well on several standard volume-tracking tests, while still admitting all possible flow configurations like overturning waves.

New features which we are currently working on include elastic walls, in combination with fluid-structure interaction, and moving solid boundaries (while still only using one Cartesian grid).

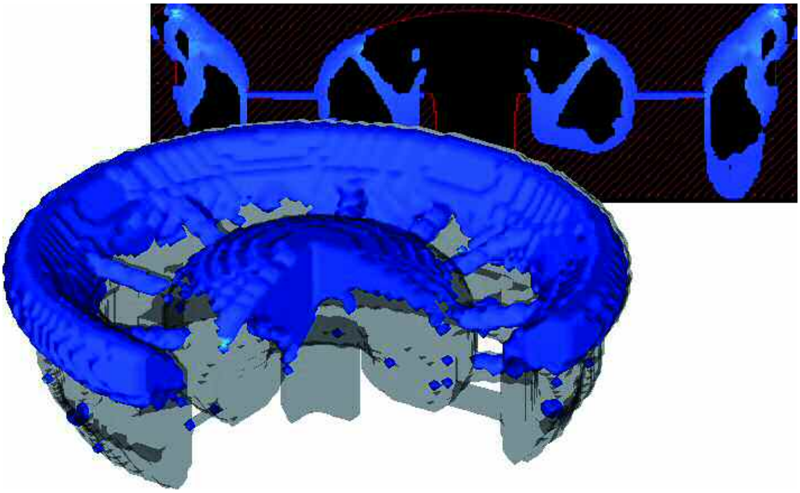

Figure 1 Snapshot of the sloshing flow in the piston crown of a diesel engine.

Because of the above described flexibilities and features, our method is capable of dealing with a wide variety of flows. It has already been used for several industrial applications; for example, piston engine cooling (Wartsila NSD, see Figure 1) and air curtains (Biddle BV).

A second example is the green water loading on the foredeck of a ship wrestling through heavy waves (see figure 2). Figure 3 shows our numerical results compared with the experimental data of the Maritime Research Institute Netherlands (MARIN). The results have been presented at the 7th International Conference on Numerical Ship Hydrodynamics (Nantes). Animations of these and other simulations can be found at : http://www.math.rug.nl/~veldman/cfd-gallery.html

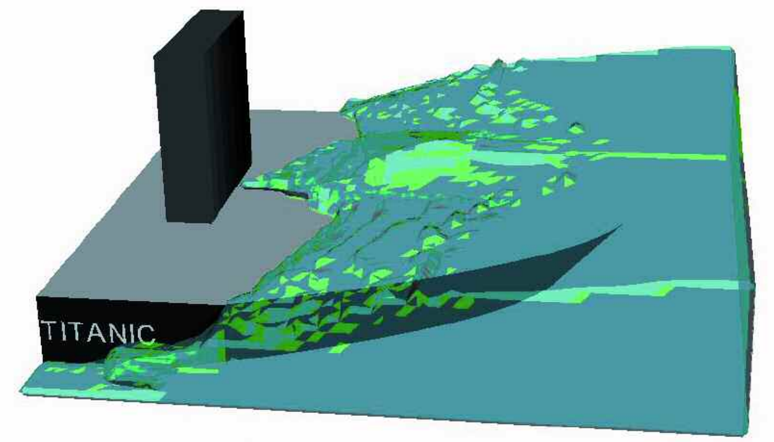

Figure 2 Green water loading: experiment by MARIN (left) and ComFlo simulation (right)

Figure 3 Comparison between numerical results and experiments

Only those who
dare to fail greatly
can ever achieve
greatly

Robert F Kennedy

2000

JR van Ommen
M-O Coppens
JC Schouten
CM van den Bleek

Early detection of misbehaviour in multiphase systems

In process industry, multiphase systems are used for all kind of purposes, like separation processes and chemical reactions. In several of these applications, the hydrodynamics can suddenly show an undesired change. For example, agglomeration of particles can lead to defluidization of fluidized-bed reactors, extensive foaming can disturb the smooth operation of bubble columns, and flooding can cause problems in countercurrently operated random packings for gas-liquid contacting. The measurement procedures currently used in industry often detect these problems when it is already too late: an easy return to normal operation has become impossible and an expensive shut-down of the system is forced. Up to now, these problems are often circumvented by operating the equipment with a certain safety margin from the hazardous conditions, often implying a lower efficiency.

We recently developed a monitoring method for the hydrodynamics of multiphase systems that can detect changes that are so small that they do not yet influence the yield of the process, but are a precursor of unwanted events that will have a large impact on the process [1]. This monitoring method uses a characteristic process variable (e.g., pressure) measured at high frequency (typically in the order of 100 Hz). The obtained time-series of some minutes length is transformed into an attractor [2], representing the collection of the successive states of the system during its evolution in time. Consecutive attractors obtained during the operation of the process are compared with a reference attractor reflecting the desired behaviour. This comparison is carried out using the statistical test of Disk et al. [3] and yields a dimensionless distance S between the attractors. If S is larger than 3, a significant change (confidence level > 95%) has taken place in the system.

Figure 1 shows a result for the monitoring of biomass gasification in a fluidized bed. The average pressure drop over the bed only indicates that defluidization has occurred.

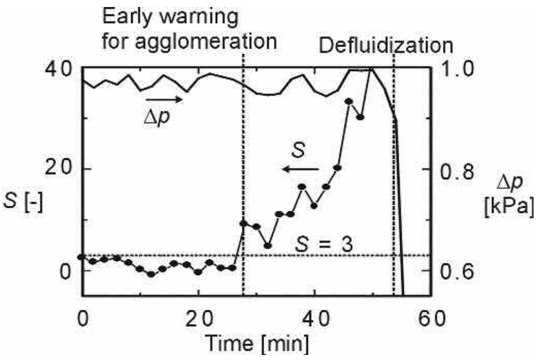

Figure 1 The early detection of agglomeration during the gasification of straw. At t = 28 min, the S-value exceeds 3 indicating the onset of agglomeration.
The pressure drop only shows defluidization when it is too late. Work in cooperation with W Lin and K Dam-Johansen (Technical University of Denmark).

The monitoring method gives an early warning 25 minutes before defluidization happens. In practice, this gives the opportunity to prevent the bed from becoming defluidized, e.g., by replacing part of the bed material.

Figure 2 shows the monitoring of a bubble column. Increasing amounts of ethanol are injected in the column to induce foaming. The monitoring method is able to detect the hydrodynamic change before a large foam layer is formed.

The proposed method can be used to detect the onset of misbehaviour in a wide variety of multiphase systems so that measures can be taken to prevent expensive production loss. This makes it possible to operate multiphase systems closer to their economic optimum.

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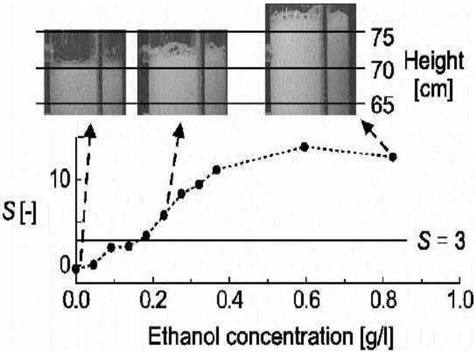
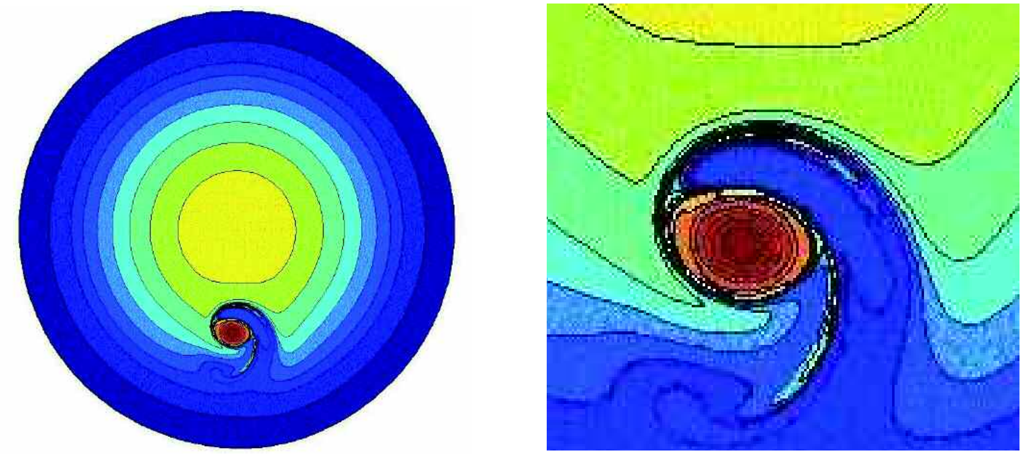


Figure 2 The early detection of foam formation in an air-water bubble column. Increasing amounts of ethanol are added to induce the foaming. The S-value indicates a change in the hydrodynamics before the foaming gives serious problems. Experimental work carried out by J Villa.

RM Schoemaker
PCA de Haas
HJH Clercx
RMM Mattheij
GJF van Heijst

Numerical methods for simulating vortices in 2D flows

Vortices are present everywhere and on all kinds of scales. Large-scale vortices can be found in the atmosphere and oceans, e.g. high and low-pressure areas, eddies in the ocean, and the huge polar vortex. The atmosphere and oceans are thin layers of fluid covering the Earth, and the motion of large-scale vortical structures are slow compared to the Earth's rotation. These vortices can therefore be modelled by the two-dimensional Euler equations and an ideal numerical approach for simulating the dynamics of this kind of vortices is the method of contour dynamics[1]. This method enables rather efficient numerical simulations of 2D incompressible inviscid vortex flows. Contour dynamics is based on the observation that the evolution of a patch of uniform vorticity is fully determined by the evolution of its bounding contour. Nested patches of uniform vorticity can approximate a continuous vorticity distribution. Contours are discretized into nodes and linear elements. The method does not make use of a grid, but the discretized contours need, however, a sufficient number of nodes. Highly curved filamentary structures need more nodes than long straight contours, i.e. during a simulation nodes are redistributed in an adaptive way. For investigating 2D vortex flows with non-uniform background vorticity (when the gradient in the background rotation of the Earth is included) and associated tracer transport, the computation time can be exceedingly large. For this purpose an acceleration of the method is appropriate. A hierarchical-element method[2] (HEM) has been developed for accelerating the conventional method from $O(N^2)$ to $O(N)$, with N the number of nodes.



The figure depicts a frame of a simulation of an isolated vortical structure evolving in a flow with non-uniform background vorticity as is valid near the pole of a rotating sphere. Left: The complete numerical domain with the pole in the center. Right: A closer inspection of the vortex.

The algorithmic structure of the HEM is on its turn suited for parallelisation. A parallel HEM is not only of O(N), but performs concurrent computations when simulating physically interesting complex flows and associated transport properties.

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CJ Wisse
MEH van Dongen
DMJ Smeulders

Shock-induced wave modes in poroelastic media

Borehole waves play a crucial role for the in-situ determination of the properties of a hydrocarbon reservoir. Exploration wells are probed by means of acoustic tools, and the measured signals are used to obtain information about the porosity, permeability, lithology, and hydrocarbon saturation.

We studied the propagation of guided wave modes in porous elastic cylinders, both experimentally and theoretically. In our experiments, a conventional shock tube is used to generate pressure wave impact on a porous sample [1,2]. The test section of the shock tube is shown in Figure 1.

Between the porous sample and the inner wall of the shock tube, an annulus is left. The position of the sample with respect to the pressure gauges can be adjusted by means of the screw gear unit and the piston. This allows us to record the annulus pressure at arbitrary position along the sample wall, which is a prerequisite for wave mode decomposition. Using Prony's technique [3], phase velocities and damping coefficients of the various wave modes could be measured in the 1-120 kHz frequency range [4]. Typical results for a Bentheim sandstone are plotted in Figure 2, where we compare our measurements with computations on the basis of Biot's theory [5].

These computations comprised the development of a Newton-Raphson solver in the complex wavenumber plane. Three wave modes (S,L1,L2) are predicted that are propagatory over the entire frequency range, whereas the higher-order modes (L3,L4, etc.) have cut-off frequencies.

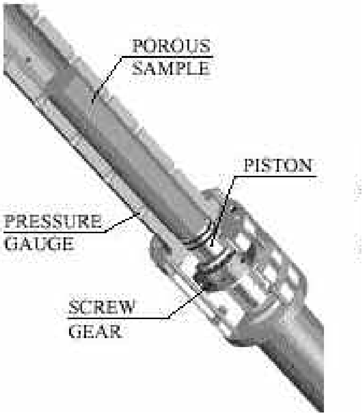

Figure 1 Experimental set-up. The screw gear unit allows adjustment for a of the porous sample with respect Bentheim sandstone.

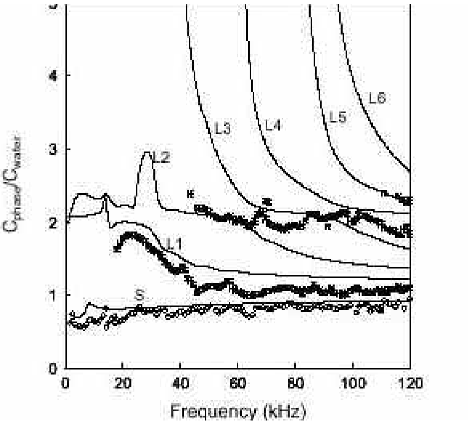

Figure 2 Phase velocity measurements (symbols) compared with theory (solid lines) for a Bentheim sandstone.

We notice that the experimental data represented by circles are in excellent agreement with the S-mode predictions. For the Bentheim sandstone, the S-mode represents a pseudo-Stoneley wave in the high-frequency limit, and a bulk wave in the low-frequency limit.

The other measured data form two different lines. The lower line corresponds to the L1-mode predictions. The upper line is more difficult to explain, but clearly can be attributed to higher-order phenomena. We found that the surface modes are sensitive to the permeability oftheporous sample, which can be understood from the fact that they represent a "breathing" mode, where fluid from the annulus is forced into the core, and vice versa. Obviously, this has important implications for the analysis of permeability estimation from acoustic logging data.

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R Steijl
HWM Hoeijmakers

The dynamics of vortex wakes in the atmosphere

The project "The dynamics of vortex wakes in the atmosphere" involves a theoretical and numerical study into the three-dimensional instabilities in a counter-rotating vortex pair, which models the vortex wake far downstream of an aircraft. Figure 1 shows the development of the long-wavelength instability, commonly known as 'Crow' instability.

The figure shows the condensed water vapour from the jet ex-hausts that is entrained in the trailing wake vortices. These patterns are commonly known as contrails. Linear stability theory is used to predict the most unstable wavelength, the exponential growth-rate, etc. This data is used to compute the initial conditions for numerical simulations. Numerical studies are performed using highly-accurate numerical simulation methods, speciffically developed for this project. Figure 2 shows iso-vorticity contours for the long-wavelength instability at two stages of the development: the initial phase of the reconnection of the two vortices and the end of the formation of vortex rings.

At present, results for the Crow instability have been obtained at various conditions and mesh resolutions. Furthermore, the short-wavelength instability has been studied. This instability is typically observed in vortex pairs with a smaller spacing than aircraft wake vortex pairs. Qualitatively, this instability mode is quite different from the Crow instability and ongoing (numerical) work studies the complex flow patterns at later stages of the development.

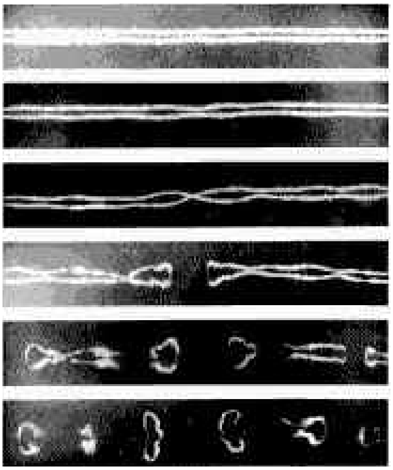

Figure 1 Contrails in atmosphere

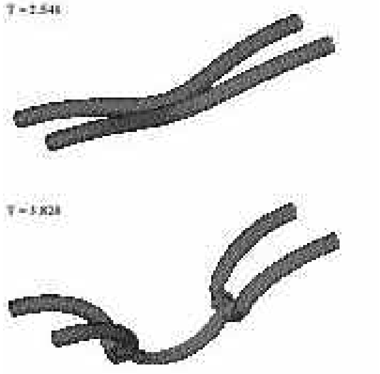

Figure 2 Numerical simulation

AERO- & HYDRODYNAMICA.

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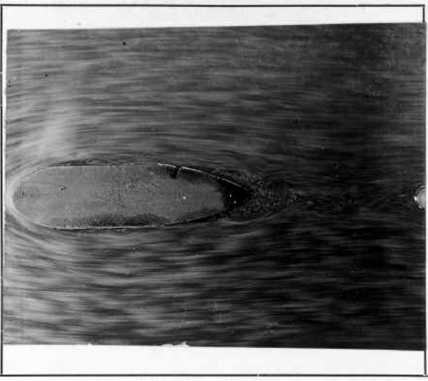

GROEP: Strooming willek. lichamen

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HB Levinsky

How well does GRI-Mech 3.0 predict NO formation in 1-D premixed flames ?

The use of numerical models has enhanced our understanding of flame structure and chemistry enormously. However, the quality of our understanding is only as good as the accuracy of the models used. During the last several years, a great deal of effort has been spent to construct chemically sound and accurate mechanisms to describe NO formation in natural gas flames. To assess the quality of the predictions of one of these mechanisms, GRI-Mech 3.0, we have simulated our previously measured profiles of temperature (using CARS) and NO mole fraction (determined by LIF) in a variety of 1-D, premixed natural gas and methane flames, using this mechanism. Typical profiles are shown in fig. 1 for a near-adiabatic flame at $\phi = 1.3$. Although the temperature is well predicted, the predicted NO mole fraction is 60% higher than the measurement.

Varying the equivalence ratio for near-adiabatic flames (fig. 2) indicates reasonable predictive power for stoichiometric and lean flames, with increasing disparity with increasing equivalence ratio for fuel-rich flames. The predicted response of NO formation to heat losses to the burner and flue-gas recirculation is also substantially poorer for fuel-rich flames. The mechanistic origin of these shortcomings in predictive power is the subject of our research in the next few years.

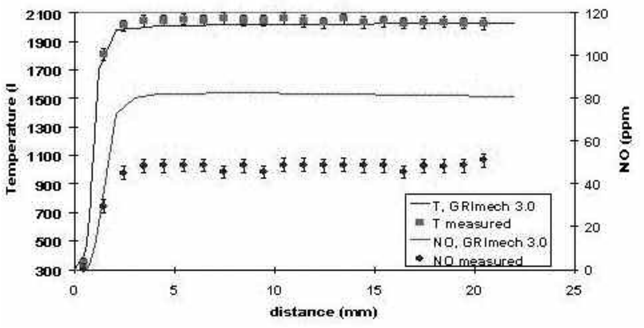

Figure 1 NO and temperature profiles in near adiabatic flame, phi=1.3,25 cm/s

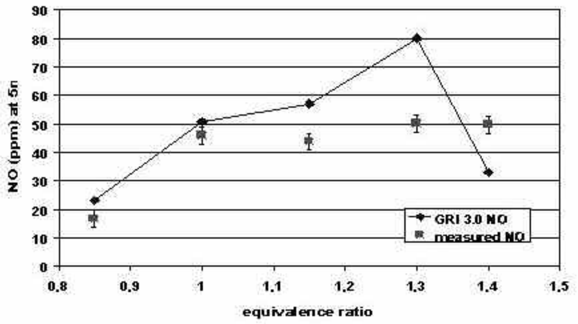

Figure 2 NO at 5 mm vs. equivalence ratio, adiabatic flames

AERO- & HYDRODYNAMICA.

LANTAARNPLAATJE

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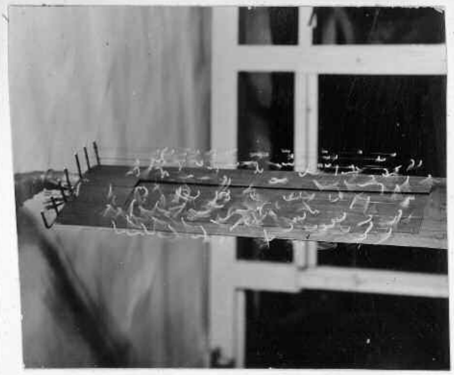
Opname in Lab. voor Aero- & Hydrodynamica op 11 Oct. 1925 in kleine tunnel



GROEP: Strooming draagvlakken

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BESCHRIJVING: Draagvlak (in vrijen straal) als gebruikt bij de grenslaag afzuigproeven van A. Th. Meijer (Amerikaansch profiel?); $\alpha = 16\frac{1}{2}^\circ$; tunnelsnelheid is 14.3 m/sec, zonder afzuiging. De boven het profiel gespannen wollen draadjes zijn zeer onrustig. Vergel. C 48

R 1 113 - '24 - 1766

JJ ter Meulen
N Dam

Development & application of laser diagnostic techniques for gas flow research

Molecular Tagging Velocimetry (MTV) is a relatively new technique for the measurement of velocity fields in liquid or gas flows. Velocity information is obtained by following tagged molecules in the flow. The technique does not require particle seeding of the flow and therefore, does not suffer from seeding-related limitations. This makes MTV a very suitable technique for applications where these limitations are of importance, like vortex cores, small-scale turbulence, and boundary layers. In MTV a laser pulse is used to 'write' a pattern of tagged molecules, by locally creating new molecules or exciting the flow molecules to a metastable state. After a delay time Dt the distribution of tagged molecules is 'read' back and from the displacement and distortion of the written pattern, a velocity field can be determined.

Recently, a new scheme for MTV in unseeded air flows was developed in the Applied Physics group in Nijmegen: Air Photolysis And Recombination Tracking (APART).

The APART technique is based on the local formation of Nitric Oxide (NO) molecules from N2 and O2 in air with a focussed excimer laser beam (193 nm). The NO distribution is measured with Planar Laser Induced Fluorescence with a pulsed dye laser (226 nm).

The lifetime of the formed NO molecules was measured and appeared to be more than 10 ms.

With APART velocities could be determined with an accuracy of 5 % in laminar and turbulent flows using single laser pulses for both the write and the read process. In figure 1 an APART image is presented of the NO distribution in a pulsed air flow, measured 100 μs after the excimer laser pulse. The method is also applicable in a premixed methane/air flame.

Another field of research in our group is the development and application of molecular light scattering techniques for compressible flow research. Two-dimensional density distributions can be obtained from Rayleigh and Raman images of the flow molecules.

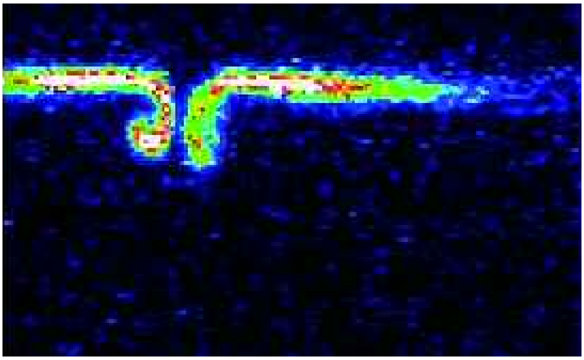


Figure 1 APART image in pulsed air flow. with delay time of 100 μs (single pulse of laser both 'write' and 'read' laser).

Rayleigh imaging is better suited for the investigation of unsteady flows, because density distributions can be frozen to a time scale of 20 ns, whereas Raman images have to be integrated during seconds to minutes to obtain comparable signal to noise levels.

The advantage of Raman imaging however, is that density information can be obtained from locations very close to strong scattering objects, because reflected laser light can be suppressed by filters that transmit the Raman scattered light.

Raman scattering images of the density field in a supersonic dry air flow around a sharp-edged wedge were measured with 248 nm KrF excimer laser light (Figure 2). The images were used to characterize the flow field in terms of density, Mach number and angle of attack. Density ratios were determined both from geometrical features (shock angles) as well as directly from the Raman intensity distribution. The two results show good agreement, lending credit to the quantitative interpretation of the Raman intensities.

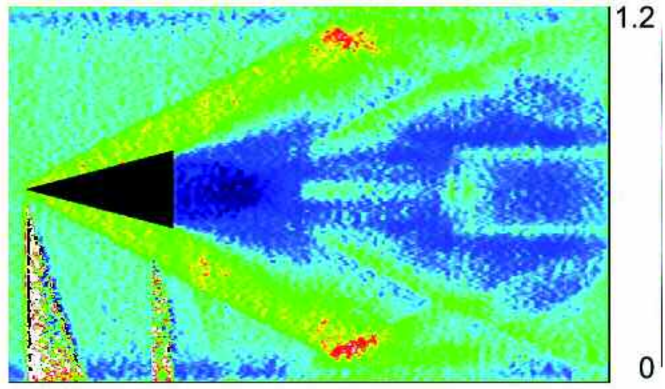


Figure 2 Raman image of supersonic flow around sharp-edged wedge (6000 pulses).
The scale indicates density relative to ambient air density.

FTM Nieuwstadt
G Ooms

Turbulence in the year 2000 : Looking back and ahead

(Panel discussion during the Burgersdag 2000)

Theme 1 : Turbulence experiment

Opening statement : Do you agree that all major discoveries in turbulence (except perhaps the theory of Kolmogorov) have been based on experimental data and in this light which experiments do you suggest (Lagrangian, high Reynolds number, transition) for future work?

The answer of the panel on this question was a clear No: experiments are not the only means that lead to new results in turbulence. First, it was noted that numerical simulations based on the full Navier-Stokes equations, i.e. without any modelling, can presently be considered to be at the same level as experiments and qualify perhaps for the term 'numerical experiment'. With the greater possibilities and capacity of the next generations of computers the role of the numerical experiment will continue to grow in the future. However, an additional advantage of laboratory experiments over numerical experiments is that a real experiment is never carried out in ideal circumstances (such as is usually the case in a numerical experiment). It are these non-ideal conditions which frequently lead to a new effect or insight. Second, while any experiment may provide useful data, experiments without underlying ideas or hypotheses do not advance the field very rapidly. The search for these ideas and hypotheses should be one of our principal concerns. Nevertheless, it has been strongly stressed that the role of the experiment either in the field or in the laboratory is far from being over. Apart from experiments in large facilities, e.g. to reach large Reynolds numbers, there are also many possibilities for small-scale experiments to illustrate or investigate certain aspects of turbulence dynamics.
Historically, serendipity is more likely in the laboratory than in front of a screen. Therefore, the future for experimental work is bright, particularly if we take into account the instrumental techniques that are available to us. These allow us to go from the 1-point data that has dominated turbulence research in the last century to multi-point data in the next century.

Theme 2 : Experimental techniques

Opening statement : Given the development of optical measurement techniques and their further development in the near future, where would you expect the breakthrough in experimental techniques or methods?

Without question the last few decades have seen a very strong development in experimental techniques to perform measurements in turbulent flow. The major accomplishment is that we can carry out multi-point spatial measurements and in the not too distant future it will be possible to routinely obtain data on the 3D-structure of turbulence even with a reasonable time resolution. The problem, which presents itself to us, is that these measuring techniques produce an enormous amount of data. Perhaps the most important problem where a future breakthrough is needed, is the development of methods of analysis for these large data sets.

To give an example: in a hologram of 1003 data points taken in a homogeneous turbulent velocity field, the two-point spatial correlation exists in a six-dimensional space of 1012 points. The computation of this spatial correlation can actually take more time than the processing of the original measurement data to compute the velocity vector fields and the two-point spatial correlation is the simplest multi-point statistics that we use to describe turbulence. We do not only need methods to compute such functions within a reasonable time but we also need the tools to extract the information that is buried in these data. One trend for the future may be to change from Eulerian measurements, which have dominated the past century to Lagrangian measurements and concepts. However, before such measurements are taken routinely we need to have a better interpretation of Lagrangian data. It is, for example, not always clear which Lagrangian property one should measure and where there is a moving frame of reference, in which frame one should obtain the data.

Finally, it should be emphasized that we have made great progress in measuring turbulence in standard fluids, i.e. air and water, under clear conditions. Observations in “dirty” flows, such as multiphase flow with a high particle loading, breaking waves, chemically reacting flows at high temperature, are much more difficult. These are frequently also the problems where a numerical simulation will not give a solution because the exact equations of motion are not always known. Therefore, the emphasis on future development of new experimental instrumentation should be on the techniques for non-ideal flow conditions.

Theme 3 : Turbulence simulation

Opening statement : Do you expect a solution for a universal subgrid-model (for instance valid near a wall or for complicated flow physics such as separation) without the use of empirical constants ? Which theoretical questions can be solved with Direct Numerical Simulation and/or which with Large-Eddy Simulation?

The general feeling of the panel, already mentioned above, is that Direct Numerical Simulation (DNS) can within its range of applicability provide results, that are at the same level of accuracy as experiments. One of the important contributions of DNS will be through novel numerical experiments where the choice of numerical parameters can lead to insightful observations on the mechanics of turbulence. Large-Eddy Simulation (LES) has at present not reached the same level of predictable accuracy as DNS. However, many areas and application have benefited in the past from studies using LES and will continue to do so, especially where the questions being asked depend on the large-scale structures in a turbulent flow. The main problem in LES is the subgrid model. Here, instead of looking for the correct subgrid model, one should perhaps spend more attention to find out why present subgrid models do or don’t work and study the reasons for their failures, especially near walls. Nevertheless, there are cases were LES seem to perform rather well, e.g. free shear flows, and separated flows where the turbulence is dominated by large scale structures.

However, whenever one considers effects depending on small-scale phenomena, such as the interface between turbulence and non-turbulent flow or near wall turbulence in attached boundary layers, the results of LES should be considered with caution. The prediction for the future is that LES will be mainly useful as an engineering model and as a qualitative research tool.

The performance of the so-called algorithmic subgrid scale models, where the subgrid scale motions are obtained from extrapolations from the large scales, is encouraging. LES has been found to produce reasonable results in a number of engineering flows such as the decay of isotropic turbulence, the backward facing step and a reacting jet.

However, there is some concern, especially in the atmospheric community, whether present LES models are capable to simulate all aspects of the high Reynolds-number turbulence as occurring in geophysical flows.

Theme 4 : Turbulence modelling

Opening statement : Given the fact that one-point closure models are the dominant turbulence models, when or whether at all in your opinion should we drastically change this strategy for turbulence modelling and should such change be guided by a quest for a universal turbulence model?

Over the past century it is undoubtedly true that substantial progress has been made in turbulence modelling especially for the case of single point turbulence closures. Further improvement is to be expected although this will be not as spectacular. An example of further progress will be a different treatment of the time response by considering the effect of various spectral scales. The panel considered that the use of zonal models, i.e. different models in different regions of the flow, as not feasible for engineering problems though its use has been recognised in geophysical flows. A better approach is the development of model which adjust themselves to the flow characteristic in certain flow regions, such as the dynamic procedure in LES. In some of the present turbulence closures this self-adjustment is already included. Nevertheless there have been many advances in various branches of turbulence research which have not been implemented in present day turbulence modelling. Examples are coherent structure and intermittency. Here, the disadvantage of single-point closures, which cannot easily incorporate spatial structure, is apparent. This would call for multi-point closures, which would also follow the line of the future experimental research. However, there may be many practical problems when multi-point statistics are needed. However, it will be difficult to embark on a fundamentally new strategy of turbulence modelling and achieve the same acceptance in the community as single point turbulence models presently have, even if this new route would lead theoretically to better results. Our user community and we ourselves are very much used to present turbulence models, especially for problems where only mean flows and fluxes are needed. We more or less know what to expect from them.

Perhaps the analogy with the reciprocating piston engine is appropriate. We know that it is not the most optimum engine that can be designed. Nevertheless, considering the effort that has gone into optimising this engine, it is next to impossible to change in practice to a theoretically better engine. On a longer time scale than the next decade, more striking new developments can be foreseen. Especially - but not exclusively - for two-and multi-phase flow, Lagrangian treatments, which enable a more comprehensive representation of the flow than Eulerian-based modelling, will, we foresee, be more widely employed.

We should also expect to see a general use of LES in a wide range of engineering applications but where the subgrid models themselves were rather similar to current generation 'turbulence models'. Indeed, where the Reynolds numbers were relatively low and the benefits of highaccuracy prediction appreciable, one can foresee that DNS will itself be employed directly: the case of heat transfer to the leading stages of a turbine blade is a case in print.

Theme 5 : Turbulence theory

Opening statement : Assuming that you agree that the Navier-Stokes equations contain all flow phenomena including turbulence, does this imply that any real theoretical progress is limited to an approach which make these equations their point of departure or are there alternatives?

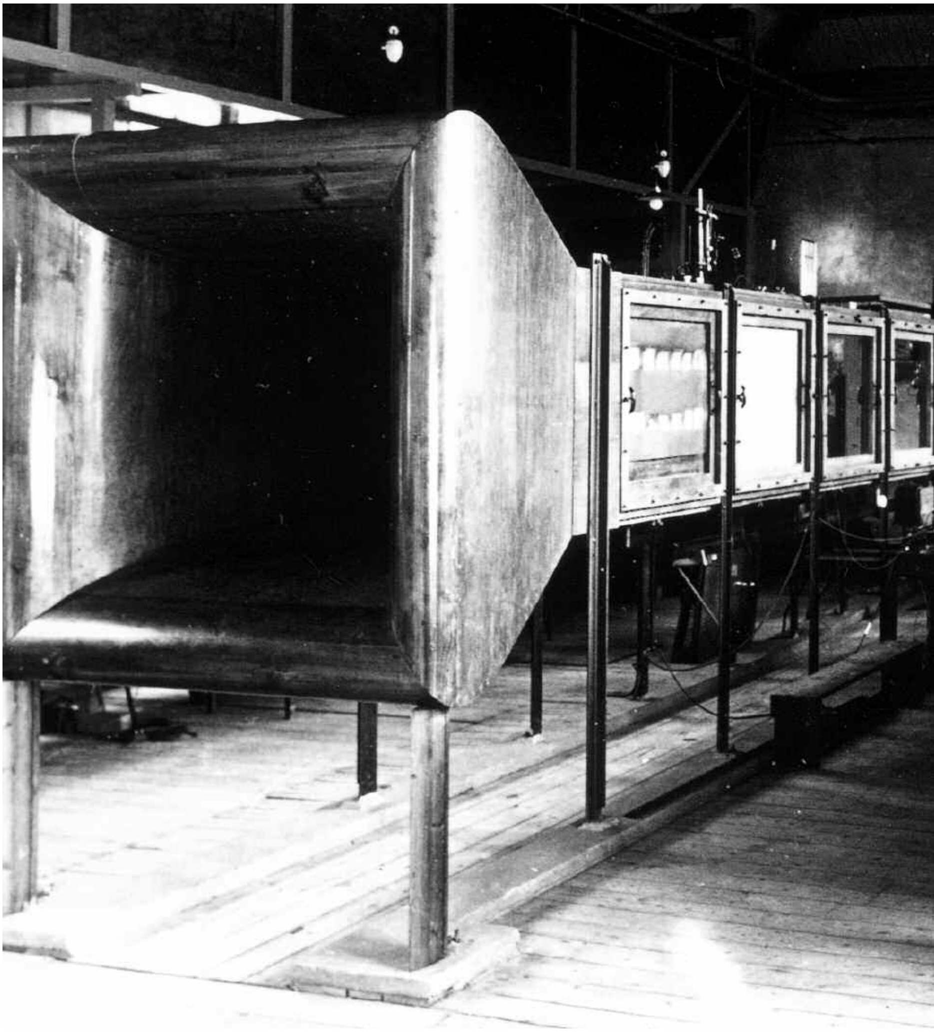
The answer of the panel on the question posed in the opening statement was a clear: No, Yes and Maybe. The main message is that there is presently no single theoretical route towards better understanding turbulence and for the future this seems unchanged. Research of idealised or simplified systems, e.g. using dynamical systems theory, stochastic and statistical theory, linear and non-linear transition theory and also numerical simulations of artificial flow systems can all teach us something about the theory of turbulence. The most important aim for theoretical work should be to provide concepts and ideas to guide the numerical and laboratory experiments.

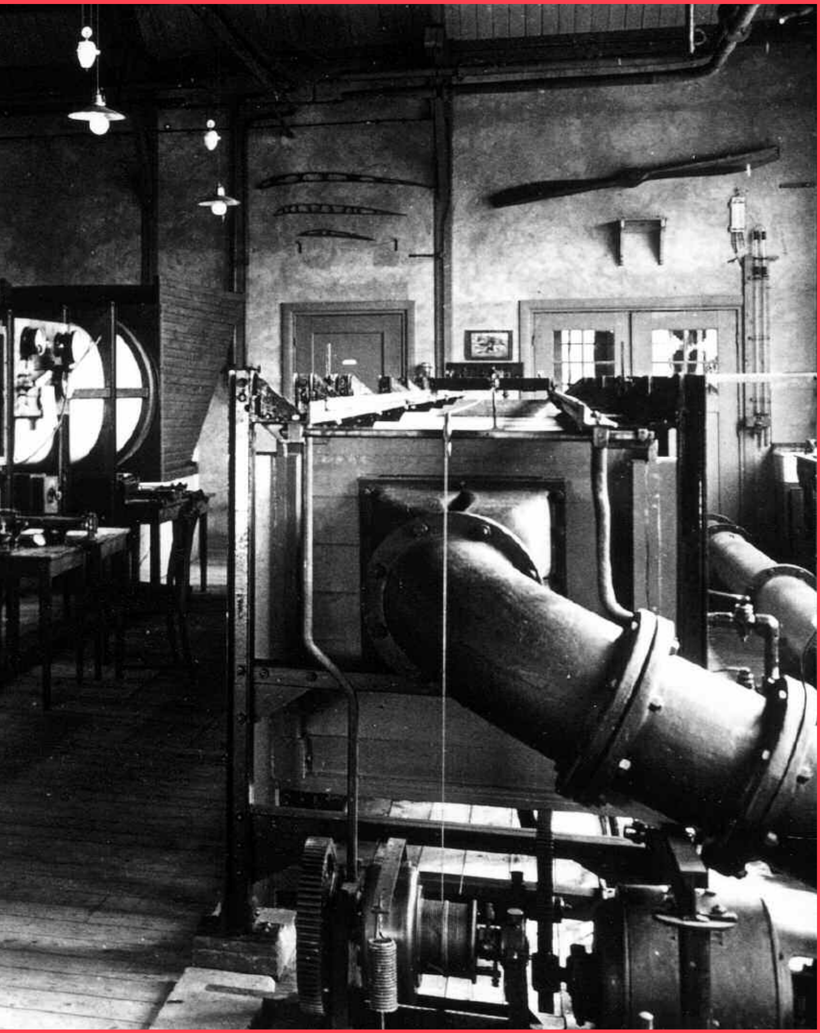
Theme 6 : Industrial and environmental applications

Opening statement : In view of the many industrial and environmental applications of turbulent flow, which priorities should in your opinion be set on the short-term and long-term research agenda for theory, experiment, simulation and/or modelling?

Although the turbulence problem has not been solved this century, we have nevertheless made great progress on a number of areas including redefining the turbulence problem as a series of problems. Surely, these improvements in understanding and modelling should be applied in solving practical problems. Turbulence modification and control based on our insight in structures is one of the areas where progress is to be expected in the near future. Practical problems in turbulence go from the individual flows in industrial applications toward problems on a larger scale such as global warming or the energy question, which are in part all turbulence problems.

Each problem should be considered on its own. As there is not a single theory of turbulence one should also not expect a universal turbulence model. Nevertheless, most of presently used applications of turbulence have been in terms of turbulence modelling based on the concept of a universal model. Not surprisingly industry finds that there are many limitations in the applications of turbulence models. Through Ercoftac there is presently an effort to categorise these limitations and to provide guidance to industry for an appropriate application of turbulence models. Such an effort is for the near future perhaps more beneficial for turbulence modelling in practice than the development of new models.

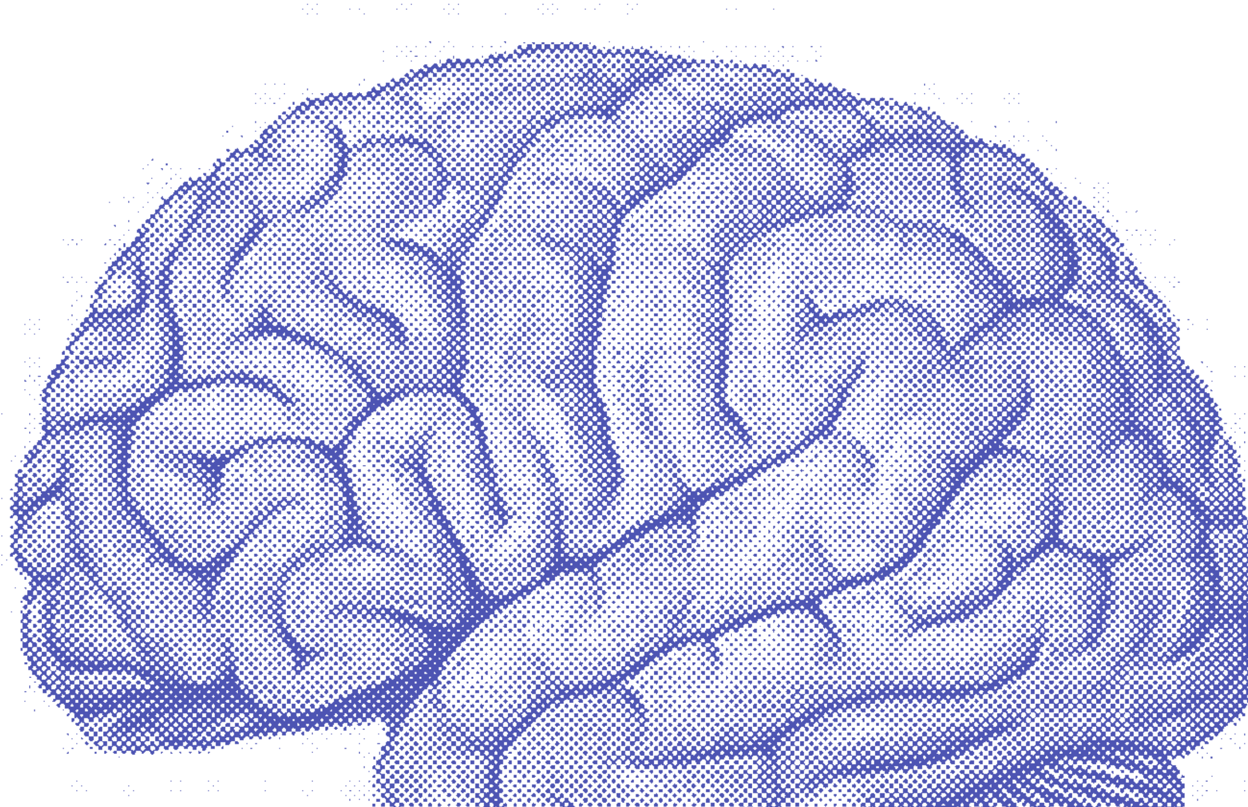




Windtunnel at the Laboratory for
Aero- and Hydrodynamics at the TU Delft

The only true
wisdom consists in
knowing that you
know nothing

Unknown



2001

ThC Treurniet
FTM Nieuwstadt

The interaction of a thin flame front with homogeneous turbulence

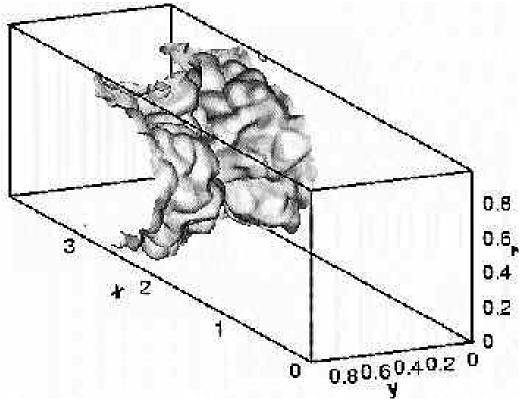
In a premixed combustion, such as a gas explosion, the flame propagates through the combustible mixture by means of deflagration. In deflagration the unburnt gas mixture in front of the flame is heated up by means of diffusion until the ignition temperature is reached. The actual combustion takes place in a thin surface, known as the flame sheet. The propagation speed of the flame sheet is proportional to the amount of mixture that is burnt or alternatively to the surface of the flame area where the combustion takes places. Thus the flame speed increases due to all processes, which increase the flame surface. One of these processes is known as Darrieus-Landau instability, which may be compared to the Rayleigh-Taylor instability of a heavier fluid on top of a lighter fluid. In this case it is the heavier (cold) gas, which is accelerated into the light (hot) gas that has been burnt. This gives rise to characteristic bulges on the flame front as shown in figure 1.

The results shown in figure 1 have been obtained with help of a direct numerical simulation in which the burning has been parameterized with help of the so-called G-equation, i.e. we define a scalar function G(x,t) and the flame position is given by the surface $G(x,t) = G_0$. At his position the fluid is heated from a temperature T_u to a temperature T_b and this defines the heat release parameter $t = (T_b - T_u)/ T_u$. In our computation we apply the low Mach number approximation, which implies that the density is only taken to be a function of temperature and not of pressure. With these assumptions we obtain a realistic description of the flame front dynamics and for more details we refer to Treurniet et al (2002)[1].

With help of this direct simulation we are able to study the interaction of the flame with a turbulent flow field. One of the results is that the kinetic energy of the turbulence can either decrease or increase after the flame front depending on the value of the heat release parameter t.

References

1. ThC Treurniet, FTM Nieuwstadt and BJ Boersma (2002). Direct numerical simulation of premixed combustion in homogeneous turbulence. Submitted to Journal of Fluid Mechanics.



An instantaneous picture of the flame front for t =3.

JM Burgers (right) and two of his co-workers

WSJ Uijttewaal

River flow with submerged and non-submerged groynes

The groynes in low-land rivers keep the navigation channel at the proper depth and prevent the river from meandering. In order to be able to optimise these constructions with respect to effectiveness and maintenance costs, it is important to understand the dynamics of the complex flow in a groyne field. Experiments using particle tracking velocimetry, have been performed on a physical model of a schematized river reach scaled 1:40, (figure 1). The experiments reveal the complexity of the flow in these shallow cavities where large-scale horizontal eddy structures determine the exchange of mass and momentum between the main stream and the groyne field.
With non-submerged groynes separation occurs at the groyne tip. Downstream of this point a mixing layer is formed and large vortices are regularly shed. The associated momentum exchange drives a recirculating flow in the groyne field. High turbulence intensities are found at the stagnation point and along the mixing layer, (figure 2).
When the water level is increased such that the groynes become submerged, a dramatic change is observed. The flow starts to oscillate with a large time scale, (figure 3). With a high streamwise velocity, the flow through the groyne field is parallel to the main stream and goes for the greater part over the groyne. With low velocities the system tends to a recirculating flow as in the non-submerged case,
with the dominant mass exchange via the main stream rather than over the groyne.
The strong fluctuations are associated with the alternation between both states and are observerd in a large part of the groyne field, (figure 4). It appears that the dynamics of this system are governed by the vortex shedding as it occurs even under submerged conditions. By adapting the groyne tip such that a stronger vertical mixing is established, the large scale fluctuations could be suppressed. The experimental data are also used for the development of numerical models suitable for the engineering practice.

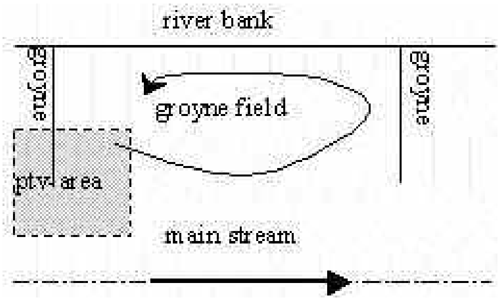


Figure 1 Top view of the experiment. Arrows indicate flow direction

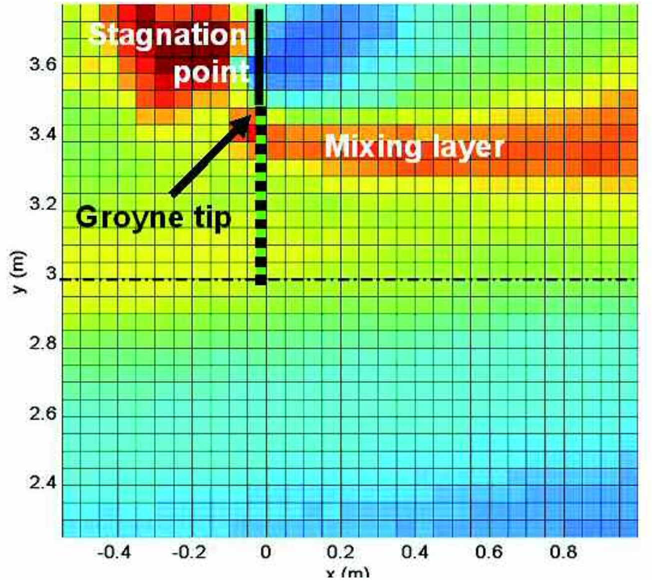


Figure 2 Magnitude of velocity fluctuations (m/s) around the groyne tip measured with PTV, non-submerged. High amplitudes are found at the stagnation point and in the mixing layer.

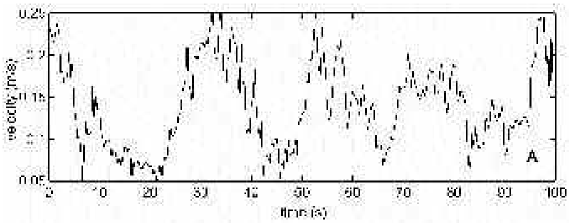


Figure 3 Velocity signal measured in the groyne field under submerged conditions.

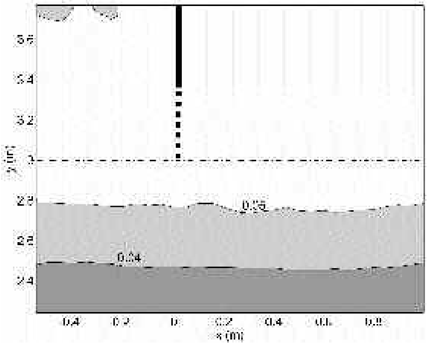


Figure 4 Magnitude of velocity fluctuations around the groyne tip for submerged conditions. High amplitudes are found in a large area, and are associated with the slowly varying mean motion of figure 3.

W van de Water
A Staicu

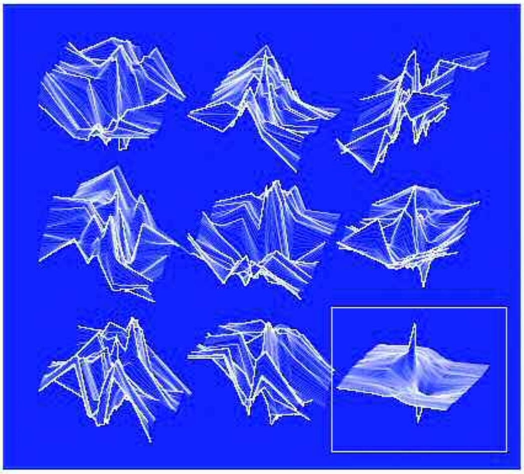
The rogue vortices of turbulence

What looks like crumpled pieces of unsuccessful origami are extremely strong vortical events in a turbulent windtunnel flow. Using a special grid to stir the turbulence, Reynolds numbers up to $Re_\lambda \approx 800$ were reached by us, and the velocity profiles were measured using arrays of hot wires. We can appreciate the strength of the vortices if we realize that the mean flow velocity is about 12 *m/s*, with the size of the turbulent fluctuations about 1.6 *m/s*. The shown vortices have a velocity difference of 5 *m/s* accross a mere 1.2 *mm*. That is, almost the mean flow velocity can be found accross a separation which is close to the dissipation scale.

Rogue vortices are rare. The ones of the figure occupy a mere fraction of 10^{-6} of a registered signal. Still, they severely upset Kolmogorov's well-known theory of fully developed turbulence. In fact, in self-similar turbulence we would have had absolutely no chance to observe rogue vortices. Further, the strength Δ_u of an eddy would have increased with its size r as $\Delta u \propto r^{1/3}$ (which underlies the well-known $k^{-5/3}$ scaling law of the energy spectrum). Instead, for our vortices $\Delta_u \propto r^{0.13}$. Rogue vortices signify small-scale intermittency, that is the tendency of strong turbulence to develop violent events. The vortices of the figure came with all sorts of random shapes, still they have a non-trivial average (the one in the lower right-hand corner). It is quite remarkable (and fitting our research school) that the average shape cannot be distinguished from a Burgers vortex. It agrees with direct numerical simulations, but at much smaller Reynolds numbers.

The measurements are done using arrays of hot-wires that collect extremely long time series of turbulence data along a line. Nowadays, hot-wire velocimetry may seem an unexciting technology, but in any other method (such as particle image velocimetry) our rogue vortices would have been disqualified as outliers.

The problem of intermittency has brought renewed interest from the physics community in turbulence. A current hot topic which we are focussing on is the persistence of large-scale anisotropy down to the smallest scales, both in the passive-scalar and the velocity field.



Airchannels ventilationbuilding Maastunnel

KRAM Schreel
R Rook
LPH de Goey

The response of burner-stabilized flat flames to acoustic perturbations

Since the introduction of low NOx premixed burners with a large modulation range, severe noise problems hamper further developments of modulating domestic heating boilers. In the past, the burner operated only at one or a few discrete thermal loads. Noise problems could be solved by trial and error methods.

Current developments, however, use designs where the burner load is allowed to vary continuously. The major drawback of this approach is that many different acoustic instabilities are now triggered and phenomena like high whistling noise and low vibrational excitations of the complete system occur. Instead of applying trial and error solutions after designing and building the boiler, an acoustical analysis is needed already in the early design stage. As a consequence, there is a strong demand for acoustical analysis tools.

A boiler can, for low frequencies (< 1000 Hz), be considered as a one dimensional tubular system. This allows the application of the so-called transfer matrix method [1], in which the system is divided into parts having the same acoustical properties, and in which these parts are connected via transfer matrices. At TNO-TPD, this method has been applied extensively on various systems. For burners/flames, however, no good description in the form of a transfer matrix was available.

The flames which are applied in boilers can be divided into two categories: (1) flat burner-stabilized flames and (2) irregularly shaped Bunsen-like flames. Our analysis started with category 1. These flames are one dimensional and it can be shown that the transfer matrix for these flames only contains a non-trivial value for the element coupling the acoustical velocity fluctuations at both sides of the flame.

When acoustical velocity variations occur, the stand-off distance of the flame starts to fluctuate. This leads to a fluctuating enthalpy at the flame holder, which is then transported by the flow as an enthalpy wave towards the flame. Since enthalpy fluctuations influence the mass burning rate of the flame, the motion of the flame, and hence the acoustics downstream of the flame are affected. When the phase of the enthalpy wave has the right relationship with the motion of the flame front, amplification or damping of the flame front motion can occur, and consequently a sound wave can be damped or even amplified. An illustration of the fluctuating enthalpy at the flame holder is given in figure 1.

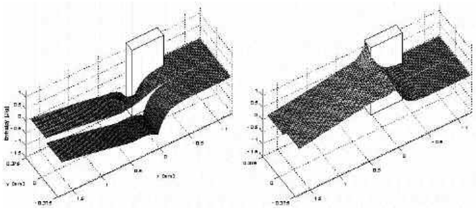


Figure 1 Fluctuating enthalpy at the flame holder (a perforated plate) for a 2D and a 1D calculation at two different time steps. In the 2D calculation the flame holder is represented as an array of slots. In the graphs the slot wall is represented by the white bar. The domain has symmetry planes as boundaries.

Large amplification of the acoustic velocity fluctuations over the flame front will occur when there is a 90 degree phase lag between the enthalpy wave and the motion of the flame front. The frequency of this resonance can be estimated by calculating the time it takes for an enthalpy wave to reach the flame front. The upstream flow velocity is of the order of 10 cm/s and the stand-off distance is typically 1 mm, yielding 100 Hz as an order of magnitude estimate for the position of the resonance. From this intuitive picture it can also be seen that one of the most important parameters is the surface temperature of the flameholder, since this determines the stand-off distance to a great extent.

Results of measurements, numerical modeling and an analytial model for the transmission coefficient can be seen in figure 2.

The correspondence between both models and the measurements is good in terms of the phase behavior and the position of the resonance. The experimentally observed magnitude of the resonance is somewhat larger, but that can be explained by some of the assumptions made in both models.

The correspondence between the experimental results and the analytical model [2] is that good, that this model is now successfully used by TNO-TPD in their acoustical description of boiler systems. In a recently granted STW project, this research will be extended to describe Bunsen-type flames as well. More information (including animations) can be found on: http://www.combustion.tue.nl/

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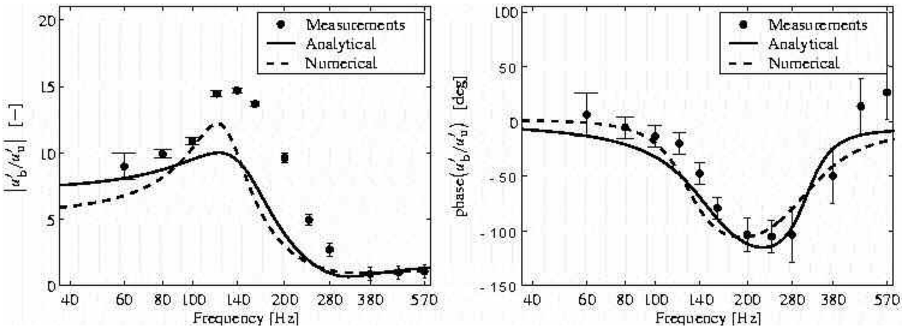

Figure 2 The frequency dependence of the magnitude and phase of the transmission coefficient for a 1D flame on a cooled brass flame holder. A strong resonance at 140 Hz is observed.

EWC van Groesen
Andonowati
R Huijsmans

MATHLAB : Mathematical support for hydrodynamic laboratories

The constantly increasing technical demands for testing ships and offshore structures in realistic sea conditions requires an increased capability of hydrodynamic laboratories to generate deterministic wave fields: at a specified area in the basin at a given time a specific wave/current pattern should be generated. The generation of deterministic wave fields was the main topic of an international collaboration project funded by KNAW (Royal Netherlands academy of Arts and Sciences) in the Scientific Programme Indonesia Netherlands, executed from 1997 till 2001 in collaboration between MARIN, University of Twente group Applied Analysis & Mathematical Physics, Center for Mathematics P4M Institut Teknologi Bandung and IHL, Indonesian Hydrodynamic Laboratory, Surabaya.

The project resulted in an increased insight in the non-linear deformations of wave groups, in a set of very accurate measurements of bi-chromatic waves and in efficient simulation tools. These results were published in various research papers and in theses of 4 PhD-projects. The successful execution leads to a continuation financed by STW (PhD and PD) and Indonesian research grants (2 PhD-projects, RUTI).

One simulation tool is a 'numerical wave tank', based on an 2D FEM/FD discretization scheme and includes wave generators and absorbing beaches. (At present the generalization to 3D calculations is under construction.) The theoretical investigations, restricted in the first instance to bi chromatic waves included a thorough investigation of the large amplitude increase, using various simplified model equations like (improved) KdV- and NLS-type of equations.

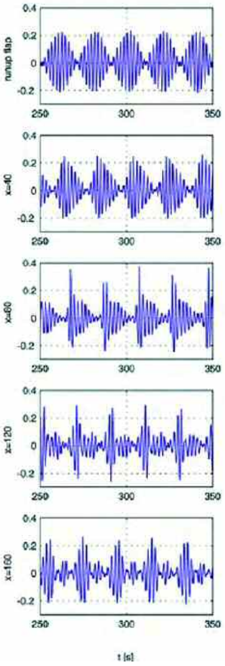

Figure 1 Time signals of an initially bi chromatic wave show large deformations while it evolves downstream in the tank (from top to down) . The deformations do not only depend on the wave amplitude, but also on the frequency difference.

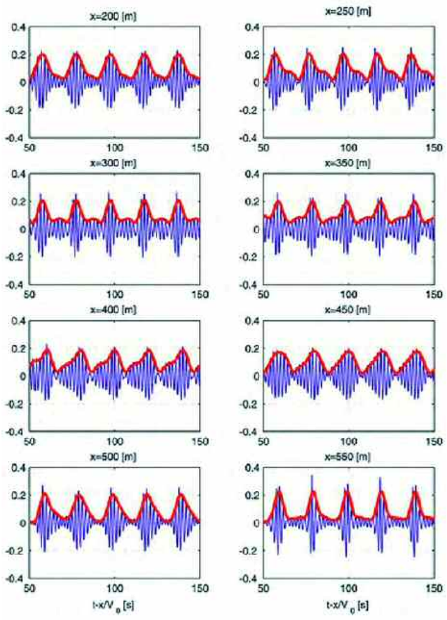

Figure 2 Accurate measurements in wave tanks up to 200 m were performed and efficient numerical and analytical simulation tools were designed. Accurate numerical simulations over long distances (up to 1200 m) revealed soliton type of interactions, well studied in simplified model equations like KdV and NLS.

Based on the insights, an Analytical Wave Code has been designed that calculates a unidirectional wave field at any position from a given point-measurement.

Time signals of an initially bi chromatic wave show (figure 1) large deformations while it evolves downstream in the tank (from top to down). The deformations do not only depend on the wave amplitude, but also on the frequency difference. Accurate measurements (figure 2) in wave tanks up to 200 m were performed and efficient numerical and analytical simulation tools were designed. Accurate numerical simulations over long distances (up to 1200 m) revealed soliton type of interactions, well studied in simplified model equations like KdV and NLS.

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D Lohse

A unifying theory for turbulent thermal convection

One of the classical systems in fluid dynamics is Rayleigh-Benard (RB) convection: A fluid heated from below and cooled from above. The control parameters are the Rayleigh number Ra, the Prandtl number Pr, and the aspect ratio Γ. The system responds with the Nusselt number Nu (the dimensionless heat transfer) and the Reynolds number Re (the dimensionless large scale velocity U). One of the key questions is to understand the dependences Nu (Ra; Pr; Γ) and Re (Ra; Pr; Γ).

About ten years ago, this problem had considered to be basically solved. In the famous high Rayleigh number helium (Pr= 0.7) experiments by Libchaber and collaborators in Chicago a scaling law $Nu \sim Ra^{2/7}$ had been found [1]. Various theories had then been developed, all of them giving the experimental scaling exponent 2/7 [2]. The situation changed when the Rayleigh-Benard experiments with mercury $Pr = 0.025$ by Ciliberto and coworkers [3] revealed a drastically different Pr number dependence of the Nusselt number than had been predicted by the various theories. Also experiments in Oregon revealed surprising results: With a 1m high helium gas cell Niemela et al. [4] achieved the remarkably high value of $Ra = 10^{18}$ and found that the Nu - Ra relation can be described by a scaling law $Nu \sim Ra^{0.309}$, very different from the 2/7 power law. Another recent milestone in the research on RB convection are the results by Ahlers and collaborators. They achieved such a precision in measuring the Nusselt number for two different aspect ratios Γ = 0.5 and 1, that they could distinguish between pure scaling laws and a sum of different scaling laws [5, 6]: The experiments favored the latter.

This had in fact been suggested before by Grossmann and Lohse [7, 8] who had developed a unifying theory of thermal convection. Hitherto theories were only valid in limited parameter ranges of the Ra - Pr parameter space. The new unifying theory claims to be applicable throughout.

The main idea of that theory is to decompose the energy dissipation rate ε_u and the thermal dissipation rate ε_θ into their boundary layer (BL) and bulk contributions,

$$\varepsilon_u = \varepsilon_{u,BL} + \varepsilon_{u,bulk} \quad (1)$$

$$\varepsilon_\theta = \varepsilon_{\theta,BL} + \varepsilon_{\theta,bulk} \quad (2)$$

For the left-hand sides the exact relations $\varepsilon_\mu = \upsilon^3 L^{-4}(Nu-1)\, RaPr^{-2}$ and $\varepsilon_\theta = k\, \Delta^2 / L^2$ are employed, where k is the thermal diffusivity, υ the kinetic viscosity, and Δ the temperature difference between the bottom and the top plates.

The individual contributions on the right-hand sides of eqs. (1) and (2) are modelled in terms of the large scale velocity U, the temperature difference Δ, the height L, and the widths λ_u and λ_θ of the kinetic and thermal boundary layers, see refs. [7, 8].

The result from this procedure are two implicit equations for the two unknown function $Nu(Ra; Pr)$ and $Re(Ra; Pr)$. They contain four fit parameters, representing the relative weight of the dissipation rates in the boundaries and in the bulk. These parameters are adopted to 151 data points for $Nu(Ra; Pr)$ obtained by Ahlers [6].

The resulting parameters space is shown in figure 1. Figure 2 shows the dependence of Nu from Ra for various Pr. The most important conclusion is that there indeed is no simple power law $Nu \sim Ra^{\beta_1} Pr^{\beta_2}$ as hitherto assumed. This immediately follows from the different physcial properties of bulk and boundary layer flow.

Of course one can always locally fit power laws. E.g., within our theory the famous $Nu \sim Ra^{2/7}$ power law follows as effective power in the regime $10^6 < Ra < 10^{11}$ as interpolation between the regimes I_l,, II_l, IV_l, and IV_u in the parameter space figure 1. If Ra gets larger, the contribution from regime IV_μ gets more important and the effective power law exponent larger, just as observed in ref. [4].

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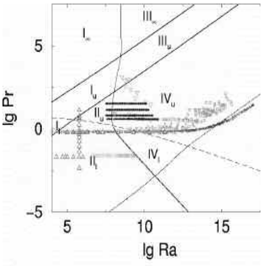

Figure 1 Phase diagram in the Ra - Pr plane according to the theory of ref. [8]: The upper solid line means $Re = Re_c$, the lower nearly parallel solid line $\varepsilon_{u,BL} = \varepsilon_{u,bulk}$, the curved solid line is $\varepsilon_{\theta,BL} = \varepsilon_{\theta,bulk}$ and the long-dashed line is the line $\lambda_u = \lambda_\theta$. The dotted line indicates where the laminar kinetic BL becomes turbulent, based on a critical shear Reynolds number of the kinetic BL Re_s of 420. Data points where Nu has been measured or numerically calculated have been included (for several aspect ratios): squares: Chavanne et al. [9], diamonds: Cioni et al. [3], circles: Niemela et al. [4], stars: Ahlers et al. [6], triangles down: Xia et al. [10], triangles up: Verzicco & Camussi (numerical simulations) [11].

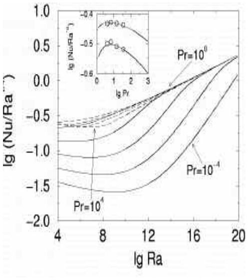

Figure 2 Nu as function of Ra for various fixed $Pr = 10^{-4}, \ldots Pr = 10^0$ (solid line) and $Pr = 10^1, \ldots Pr^4$ (dashed line). The inset shows how well the data [12] can be fitted within our theory. Here $Ra = 5.62 \cdot 10^7$ (lower) and $Ra = 1.78 \cdot 10^9$ (upper). As Nu is changing by 16 orders of magnitude in the given Ra range, we compensated it by $Ra^{1/4}$. The plot reveals that there are no clean power laws.

The beautiful thing
about learning is
that no one can take
it away from you

BB King

2002

S Gheorghiu
JR van Ommen
M-O Coppens

Power-law pressure fluctuations in fluidized beds

Local pressure measurements are a convenient and relatively cheap way to assess the hydrodynamics of gas-solid fluidization. While pressure is a quantity of limited interest in turbulence research due to its non-local nature, it proves to be a very valuable measurement in the study of fluidization. Recently, we discovered that the statistics of temporal pressure fluctuations $\Delta P=P(t+\Delta t)-P(t)$ encode information about quantities that are of major importance for fluidization engineering, such as the bubble size distribution within the bed.

The probability density function (PDF) of pressure fluctuations in a freely bubbling fluidized bed is found to have distinctive power-law tails, thus departing significantly from a normal distribution. The PDF is fitted very well by a so-called “Tsallis distribution”

$$\rho(\Delta P)=\frac{1}{Z_q}\left[1+(q-1)\beta(\Delta P)^2\right]^{\frac{1}{1-q}}$$

a parametrized form which converges to the normal distribution when $q \longrightarrow 1$ is related to the variance, and Z_q is the normalization constant. This particular shape of distribution is associated with the incoherent component of the pressure, i.e., the pressure disturbance produced by individual bubbles passing by the detector, and reflects the broad nature of the bubble size distribution (BSD) of the bed. Since bubbles typically grow via coalescence and breakup, one can expect that the main trend of the BSD to be an inverse power law, a description which seems to fit various data and models quite well. Meanwhile, the pressure fluctuations corresponding to bubbles of a certain size can be shown to be a stochastic variable with a variance proportional to the bubble size. By weighing this size-dependent bubble PSD with the frequency of occurrence of the respective bubble size (the power law BSD), one obtains the required Tsallis distribution of pressure fluctuations.

Beside shedding new light on the shape of the BSD of fluidized beds, this analysis holds a promise for potential applications in the area of monitoring the quality of fluidization. Since the PDF of pressure fluctuations is intimately related to the bubble size distribution, any changes in the latter due to e.g., agglomeration of the bed, would be reflected in the PDF, providing a valuable non-intrusive early warning of misbehavior. Detection of changes in the PDF can be achieved using information-theoretical tools commonly known as information- or “complexity” measures.

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AERO- & HYDRODYNAMICA.

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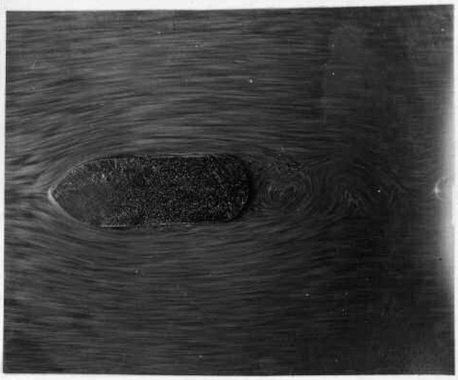

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F Scarano
BW van Oudheusden

PIV measurements of coherent structures in a compressible wake

Particle Image Velocimetry (PIV) has been applied to measure the compressible wake behind a blunt-based two-dimensional body in a supersonic freestream (Mach 2). Figure 1 shows the typical flow features by means of Schlieren visualization of the general flow pattern around the complete two-dimensional model under study. The two free shear layers that are formed at the base corners enclose a separated flow region where the flow recirculates at subsonic speed. At the downstream reattachment the flow undergoes a gradual compression and the two shear layers merge to form the redeveloping wake.

PIV has been employed for the measurement of the instantaneous velocity distribution over the vertical symmetry plane of the model. The unsteady turbulent structure of the redeveloping wake was analyzed in terms of instantaneous velocity and vorticity. Coherent structures were detected downstream of the reattachment through inspection of the instantaneous vorticity pattern. The instantaneous velocity and vorticity snapshots return the direct evidence of large-scale motion in the turbulent wake. Figure 2 describes the flow organization at two different time instants. It is necessary to enlarge the view and to subtract the estimated mean convective velocity in order to visualize the swirling motion corresponding to the vorticity peaks. From the top picture it can be clearly seen that the large-scale fluctuations exhibit a roughly symmetrical arrangement with respect to the wake axis. Counter-rotating structures oppose to each other, in most cases organizing themselves as double-rollers. The bottom picture reveals similar flow structures with the double-roller structures dominating the velocity fluctuations. In addition it is possible to see that also the whole wake axis exhibits large fluctuations in a flapping-like motion with an amplitude comparable to the wake width.

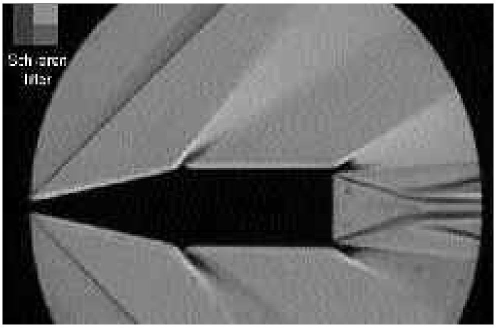

Figure 1 Schlieren image of the supersonic flow around the wedge-plate model.

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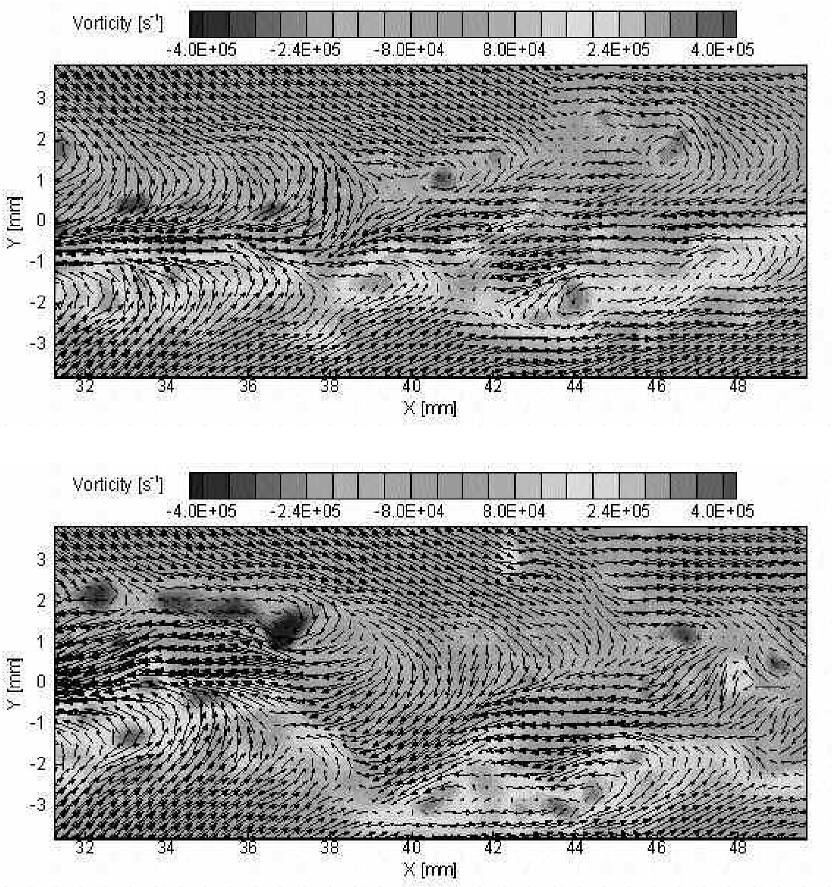

Figure 2 Two measurements of the instantaneous velocity and vorticity pattern in the redeveloping wake. Remark: a constant value is subtracted from the velocity field.

JJH Brouwers
CWM van der Geld
JGM Kuerten
R Smit
MPB Veenman

Investigation in statistical turbulence

As almost all flows in nature and industrial applications are turbulent, understanding of turbulence and turbulent transport is of great importance. However, until now an asymptotic theory of turbulence has not been found and turbulence models in presently used CFD software packages are largely based on empirical relations and in one or the other way on diffusion theory. However, as has recently been shown[1], diffusion theory or, equivalently, the Markov approximation for the velocity of a marked fluid particle, does not hold for turbulent flow.
The approximation gives an error of order unity irrespective of the Reynolds number. More promising is the Markov approximation for fluid particle acceleration. This approach seems to be consistent with the limiting behaviour of the flow for infinite Reynolds number. The resulting Langevin equation can be matched with the Lagrangian versions of the Kolmogorov hypotheses. What is left is the determination of the remaining coefficients in the equation. Only if these are known a model capable of predicting particle trajectories results.

A fundamental problem in the determination of the coefficients is the fact that the equation describes Lagrangian properties, which are difficult to measure. At the same time DNS simulations are restricted to limited Reynolds number, whereas the theory holds asymptotically for infinite Reynolds number. Therefore, theoretical efforts are aimed at the derivation of relations between Lagrangian and measurable Eulerian statistical properties.

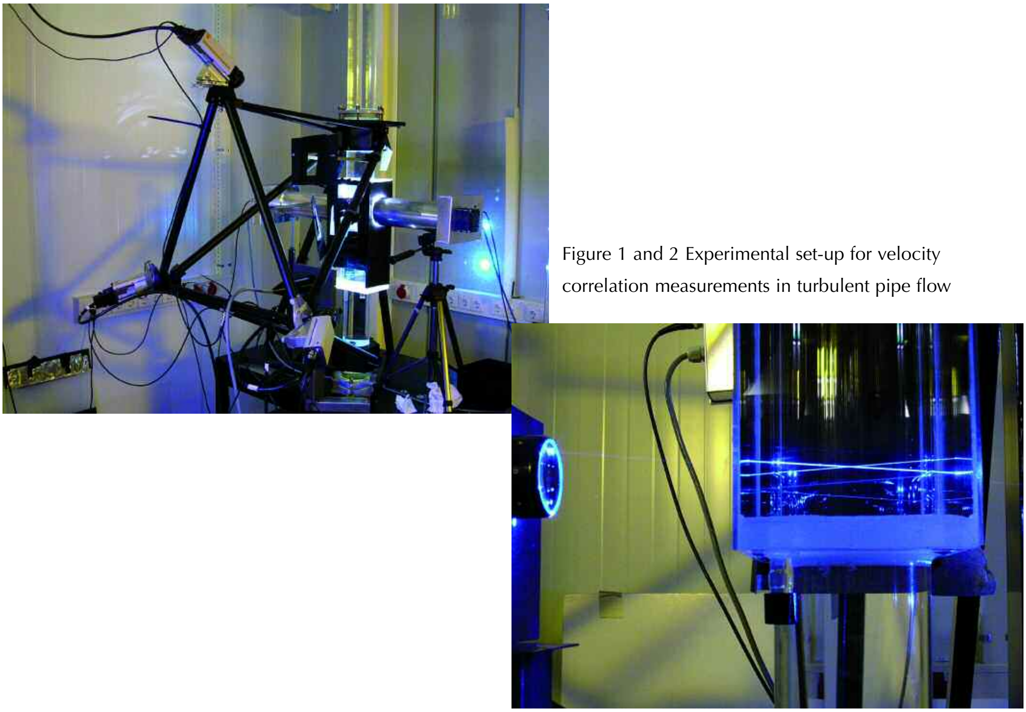

Figure 1 and 2 Experimental set-up for velocity correlation measurements in turbulent pipe flow

In order to investigate these relations, we study turbulent pipe flow in two complementary ways: numerically by direct numerical simulation at rather low Reynolds numbers and experimentally by two-probe LDA measurements at low and higher Reynolds numbers (see Fig. 1-2). The numerical method used in the DNS is based on a pseudo-spectral Fourier-Chebyshev expansion. Passive and real particles are tracked in order to obtain Lagrangian statistical properties^2. Concerning the measurements, the two laser probes are separated in axial direction and correlations are measured with a time interval between the two probes corresponding to their distance and the mean velocity. First results show a good agreement between the DNS and LDA results at low Reynolds numbers (see Fig. 3). At high Reynolds number (68000), the axial velocity correlation is still close to that at lower Reynolds number (13000).

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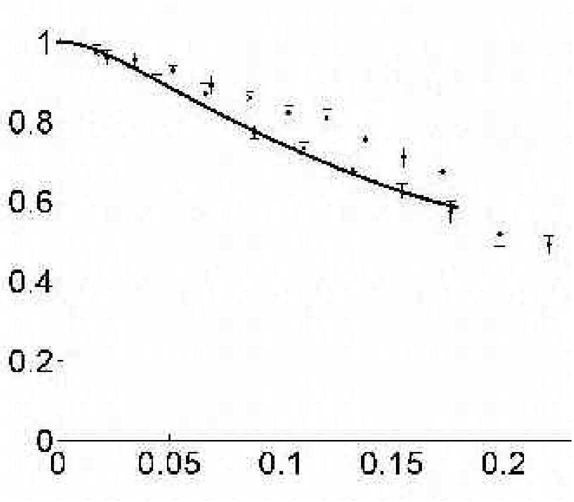


Figure 3 Axial velocity correlation in a moving frame; solid: DNS (Re=13000), o: LDA (Re=13000), *: LDA (Re=68000)

JJW van der Vegt
JJ Sudirham
HK Kuiken
RMJ van Damme

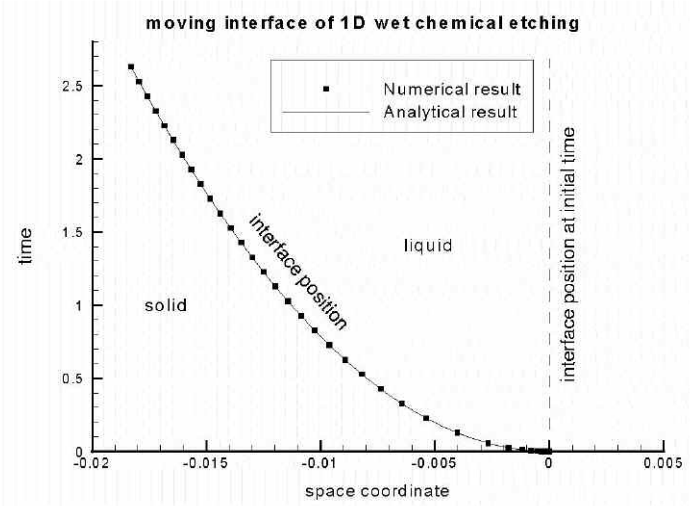
Analysis of wet-chemical etching processes

Wet-chemical etching is a manufacturing technique which is ideally suited for the machining of complicated small devices. In this production technique a mask is used which protects the material from the etchant, whereas the unprotected parts are dissolved by the etching fluid. Wet-chemical etching is attractive because after the design of a proper mask the production process is independent of the complexity of the design and etching is a fast room-temperature process. The etching process is also tension-free and the etched objects are free of burrs. This makes etching an important technique in industry for the mass production of complicated objects with small features, such as biochemical analysis systems, micro-pumps and sieves, shadow masks for color TV-screens, lasers, and printed circuit boards.

In order to improve the control of wet-chemical etching more insight into the transport phenomena is necessary, since the desired shape (partly) depends on the details of the transport of the etching fluid to and the etching products from the solid. The transport phenomena in wet-chemical etching are governed by a number of physical properties which have a large disparity in length scales. This presents serious challenges for the accurate and efficient numerical simulation of wet-chemical etching.

In order to accomplish this, a new space-time discontinuous Galerkin finite element method (DGFEM) for the solution of the convection-diffusion equation, combined with the computation of the boundary of the etching cavity due to chemical reactions, has been developed.

This method uses h-p adaptation, which is a combination of mesh refinement (h-adaptation) and increase in the order of the polynomial basis functions (p-adaptation), to capture the detailed local structures near sharp corners and in the diffusion boundary layer.



This numerical technique is an extension of the space-time DG method discussed in [3,4] using the DGFEM for elliptic partial differential equations in [1]. The research on etching is supported with matched asymptotic expansion techniques [2] and detailed experiments in the group of Prof. M Elwenspoek, MESA+ Institute, University of Twente.

The algorithm has been tested on a number of model problems, including the etching of a two-dimensional slit. Here we consider only one active species in the etching fluid. These computations required locally a relatively fine computational mesh near the mask edges to capture the corner singularities. The motion of the surface depends on the etching rate and is part of the computation. Presently, the extension to three-dimensional problems is under development in order to be able to etch more complicated structures.

This research is supported by STW, project TWI 5453, which support is gratefully acknowledged.

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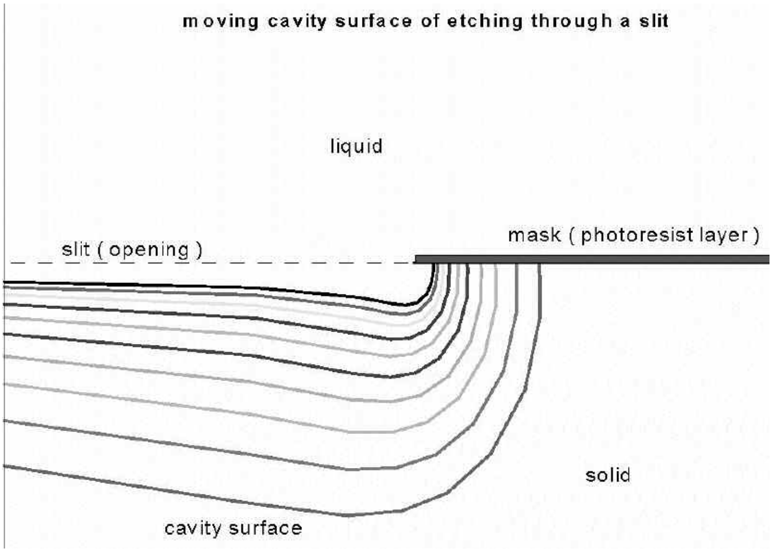

If I have seen
further than others,
it is by standing
upon the shoulders
of giants

Isaac Newton

2003

DR van der Heul
SP van der Pijl
A Segal
C Vuik
P Wesseling

Computation of moving interfaces in fluids

Moving interfaces occur for example in bubbly flows, or as phase boundaries in crystal growth or in optical recording. Our work in solids is not part of the research program of the JMBC, and is not reviewed here. Our aim is to develop computing methods with a nice balance between computing time and accuracy. Fig. 1 shows a snapshot of cyclic sheet cavitation in flow around a hydrofoil.

Mathematical models of interface dynamics in cavitating flow are very cumbersome. Instead, we use the so-called homogeneous equilibrium model, in which the physical fluid is replaced by a hypothetical homogeneous medium with an artificial equation of state. This makes computing the bubble interface superfluous; instead, it is captured automatically as a zone of high density gradient. The density is taken to be function of pressure p only, and equals the vapor density for $p < p1$ and water density for $p > p2$, with p1,2 clustered closely around the critical pressure pc, at which cavitation sets in. Usually, engineers can make a pretty good a-priori guess of pc . In this way, the difficulty of interface tracking is replaced by the challenge of solving the barotropic Euler equations with a strongly nonlinear nonconvex equation of state, with density varying by a factor 1000. The Mach number in the flow depicted in Fig.1 ranges from 0.001 to 25, so a unified computing method for compressible and incompressible flows is called for. We have developed a suitable method; see for example Refs.1,2. Fortunately, the homogeneous equilibrium model, despite its bold simplification, gives realistic results. Our unified method also has astrophysical applications; see Ref.2.

Figure 1 Density plot; dark: low density (vapor); bright: high density (water). An animation can be found at http://ta.twi.tudelft.nl/nw/users/wesseling

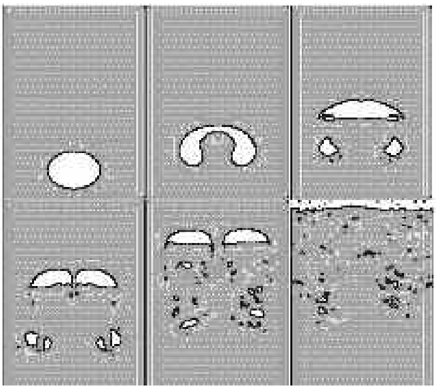

Figure 2 Rising air bubble; two-dimensional computation

Of course, there are many applications where interfaces between different phases need to be tracked, for instance, when surface tension cannot be neglected.
The volume-of-fluid method conserves mass, but the shape of the interface is not well represented. The level-set method gives a good approximation of the interface, but mass is not conserved exactly. We have devised an effective combination of these two methods, combining their good properties. A result is shown in Fig.2. Animations in two and three dimensions can be found at http://ta.twi.tudelft.nl/nw/users/vdpijl. This work is part of a joint NWO project with the Laboratory for Aero- and Hydrodynamics and the Computer Graphics and Human-Machine Interaction unit of TUD. Animations in two and three dimensions can be found at http://ta.twi.tudelft.nl/nw/users/vdpijl.

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S Guet
G Ooms
RVA Oliemans
RF Mudde

Bubble size effect on the gas-lift technique

The gas-lift technique is a gravity-driven pumping process applied in the oil industry. It enhances oil production by injecting gas in the production pipe to decrease the hydrostatic weight of the oil column. The decreased bottom-hole pressure results in an increased pressure drop from the reservoir to the pipe and increases the oil flow rate into the well bore. In the present investigation we study the effects of the size of the injected bubbles on the efficiency of the gas-lift technique. The most important bubble size effects are due to: the changes of bubble relative velocity, the radial distribution of bubbles and of phase velocities, and the flow pattern transition.

To predict the efficiency of gas-lift systems, the drift-flux model is commonly used. The main advantage of this approach is the possibility of taking into account the above-mentioned effects in a simplified, one-dimensional model. This model uses a distribution parameter C_0 and a weighted mean drift velocity $|U_{drift}|$ to take into account the effects of the radial distribution and relative velocity on the area average void fraction. To investigate the bubble size effects on the radial profiles of void fraction and phase velocities, measurements are carried out on a vertical bubbly pipe flow of 18m height and 72 mm diameter. Laser Doppler Anemometry is used for the liquid velocity. Single and four-point optical fibre probes are applied for the bubble fraction and velocity determination. These techniques are combined in a measurement section on the pipe flow (figure 1).

The bubble size is varied for given input flow conditions, and the profiles of void fraction and phase velocities are measured. The phase velocity profiles associated with small and large bubbles are presented in figure 2 and 3, corresponding to small bubbles (Db ~4mm) and large bubbles (Db ~10 mm) respectively. It is clear from these measurements, that the bubble size has a significant impact on the phase velocity radial profiles.

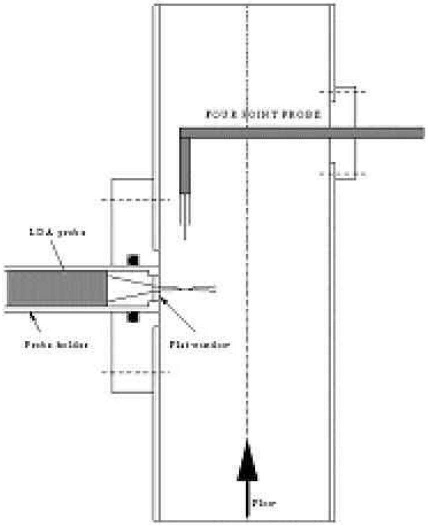

Figure 1 Measurementsection.

Based on the phase flux measurements, the drift-flux distribution parameter C_0 is determined as a function of the bubble size and liquid input conditions by applying its definition. Provided the liquid input is large enough to prevent a returning liquid flow at the wall, the distribution parameter is found to vary from $C_0 = 0.95$ for small bubbles associated with a wall peaking radial distribution of void fraction, to $C_0 = 1.1$ for large bubbles corresponding to a centerline peaking void fraction distribution (figure 4), and up to $C_0 = 1.2$ for the slug flow regime. Based on these measurements models are developed to quantify the gas-lift efficiency changes with bubble size.

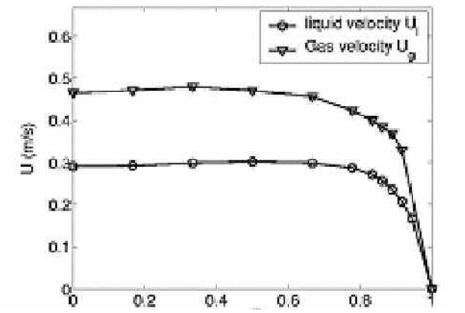

Figure 2 Phase velocity radial profiles associated with small bubbles.

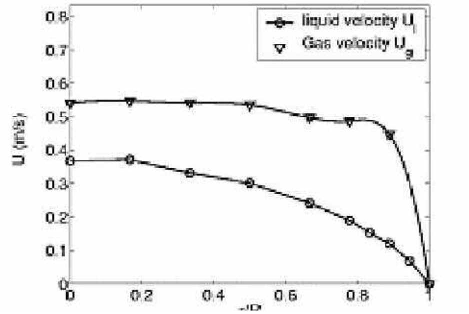

Figure 3 Phase velocity radial profiles associated with large bubbles.

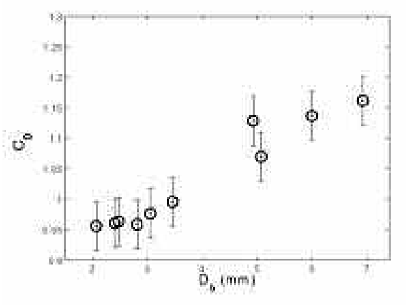

Figure 4 Distribution parameter changes with bubble size.

M Ren
CCM Rindt
AA van Steenhoven

The influence of a heat input on the wake dynamics behind a heated cylinder

The effect of heat input on the coherent vortex structures shed from a cylinder is studied in a combined experimental-numerical approach. For the experiments High Resolution Particle Velocimetry is applied in a towing tank configuration and Laser Induced Fluorescence measurements are performed for the temperature fields. For the numerical investigation the Spectral Element Method is used. The Reynolds number was always around Re = 100 and the Richardson number (a measure of the heat input) was varied between Ri = 0 (forced convection) and Ri = 1:5 (mixed convection).

This research is supported by FOM, which support is gratefully acknowledged.

The following important observations were made:

1. The vortex street undergoes a negative deflection, i.e. downwards, for Ri < 1 in contradiction to what one would expect when heat is added. The remarkable downward deflection of the vortex street for small heat input (Ri < 1) is caused by a strength difference between the upper and lower vortices. Besides this negative deflection, the strength difference also leads to a relative motion of two subsequently shed structures. The strong linking between the shed structures as observed in the 'unheated' vortex street is now entirely damaged. This rotation and linking can be clearly seen in the side-view visualization as presented in figure 1. The reason for the strength difference between the upper and lower vortex row lies in the baroclinic vorticity production due to occurring temperature gradients [1].

Figure 1 Side-view visualization of the flow around a heated cylinder for *Re* = 117 and *Ri* = 1 [2]. The flow is from left to right, the cylinder is positioned at the left.

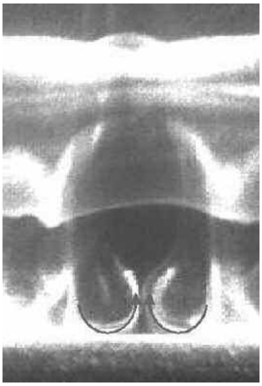

Figure 2-3 Top-view of the vortex shedding process for *Re* = 117 and *Ri* = 1 [2]. The flow is from bottom to top, the cylinder is positioned at the bottom. Left: escape of mushroom-type structures, right: a detail of the flow at the rear end of the cylinder showing a pair of counter-rotating vortices.

2. 3D structures are observed at the rear end of the cylinder for Ri > 0:3 pointing at an early transition towards 3D compared to the forced convection case [3]. From figure 2:left, which gives a top-view of the vortex shedding process, it can be concluded that this span-wise distance is determined by instability processes taking place in the vicinity of the cylinder. A more closer look reveals that pairs of counterrotating vortices occur at the rear end of the cylinder, see figure 2:right. The distance between these counter-rotating structures is around 2 times the cylinder diameter. Also the results of 3D calculations show the same features, see figure 3. A frontal view is displayed of a small downstream region in the vicinity of the cylinder. In the center, one area with positive and one area with negative vorticity can be seen, forming one pair of counter-rotating vortices [4]. The span-wise distance between two pairs of counter-rotating vortices is found to be 2 cylinder diameters. As can be seen, the counter-rotating vortices are separated by a high-temperature region suggesting that baroclinic vorticity production plays a crucial role. In a running PhD-study the near-wake and far-wake instability mechanisms are studied in more detail.

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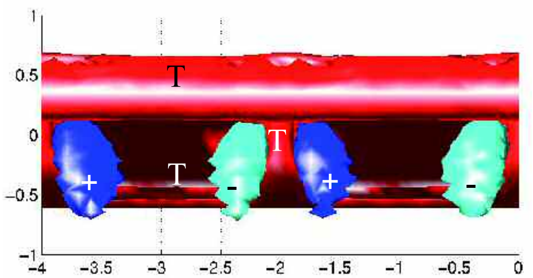


Figure 4 Calculated iso-vorticity surface (of the component in gravity direction and indicated with the +=¡ signes) and iso-temperature surface (indicated with T) for *Re* = 85 and *Ri* =1 [4]. On the horizontal and vertical axes the dimensionless span-wise and vertical coordinates are indicated.

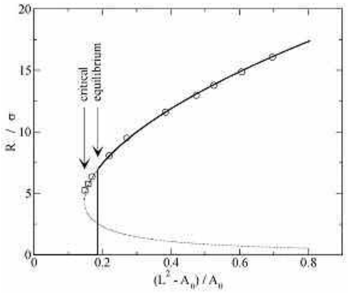
TV Tolpekina
WK den Otter
WJ Briels

Simulating a hole in an amphiphilic bilayer

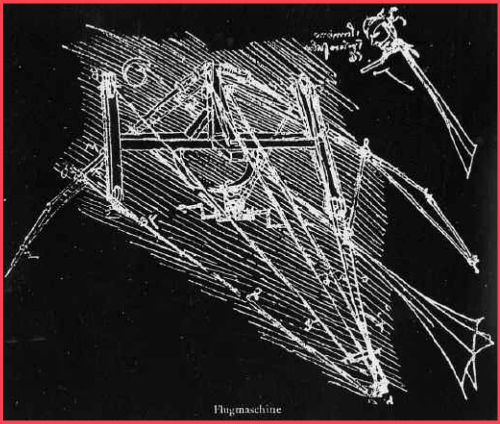
An amphiphilic molecule combines a polar or charged hydrophilic ‘head’ group with one or two apolar hydrophobic ‘tail’ groups. Because of these conflicting interests, amphiphiles dissolved in water form aggregates with the tails on the inside, shielded from the water by a layer of heads. The shape of the aggregates, e.g. spherical micelles, worm-like micelles or bilayers, is determined by the chemical composition of the molecule. Their best-known application is as the active ingredient in soaps and detergents. In the oil recovery industry they are used as designer fluids: the relative easy with which aggregates break up and unite provides very interesting flow characteristics (see the item by Shkulipa et al.). In biology, amphiphilic bilayers form the membranes surrounding living cells. The formation of a hole in this membrane has dire consequences for the cell, its contents can leak out and infective agents can sneak in, and could ultimately prove fatal. We have performed coarse-grained simulations of bilayers with a hole. The amphiphiles are modeled as chains of one head particle and four tail particles, and the solvent as lose particles. For a snap shot of the system, we refer to the item by Tolpekina. The plot below shows the average radius of the near-circular hole as a function of the length L of the periodic simulation box. We were able to explain all data with the following simple free energy expression,

$$F = \frac{K_A}{2A_0}\left(L^2 - \pi R^2 - A_0\right)^2 + 2\pi R k_c$$

where the first term accounts for elastic stretching of the membrane, and the second term results from the edge of the hole. The average radius predicted by this expression was fitted to the simulation data, see the plot, using only the edge energy k_c as a fit parameter, the other two material constants, K_A and A_0, having been determined previously from simulations with an intact bilayer. The numerical values compare very well with experimental results. In agreement with theory, the simulations show that holes are stable beyond the equilibrium elongation, unstable below the critical elongation, and metastable in the intermediate region. An important consequence of the theory is that these two elongations scale inversely proportional to the cubic root of the number of amphiphiles. This explains why simulations of stable holes typically require elongations of the order of 15 to 20%, while in experiments (which use much larger patches) an elongation of 2% suffices.



Average hole radius versus the elongation of the simulation box.
The thick solid line corresponds to the absolute free energy minimum, the dashed line to a local minimum, and the dotted line to a maximum (i.e. an activation barrier).



Airplane by Leonardo da Vinci (picture from Fokker-factory)

Vision is not enough,
it must be combined
with venture. It is
not enough to stare
up the steps,
we must step up
the stairs

Vaclav Havel

2004

EH van Veen
DJEM Roekaerts

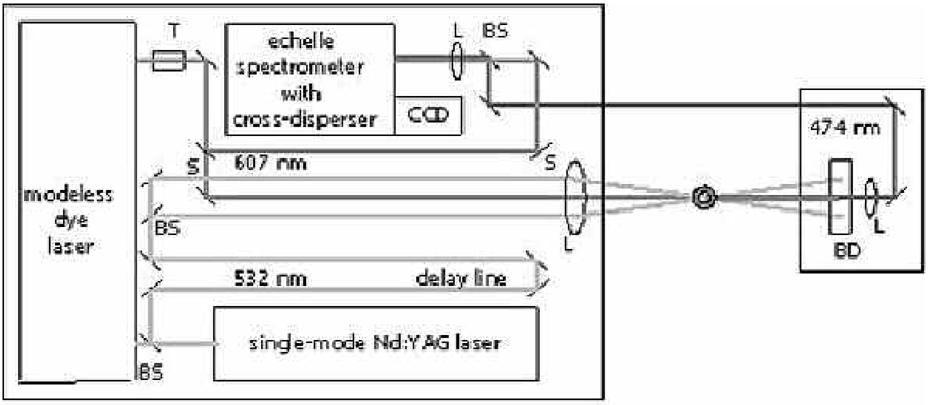
Thermometry for turbulent flames using coherent anti-Stokes Raman spectroscopy

Temperature is a key variable in both heat release and product and pollutant formation processes in combustion and the search for accurate ways to measure it with high spatial and temporal ac-curacy remains an important research area.

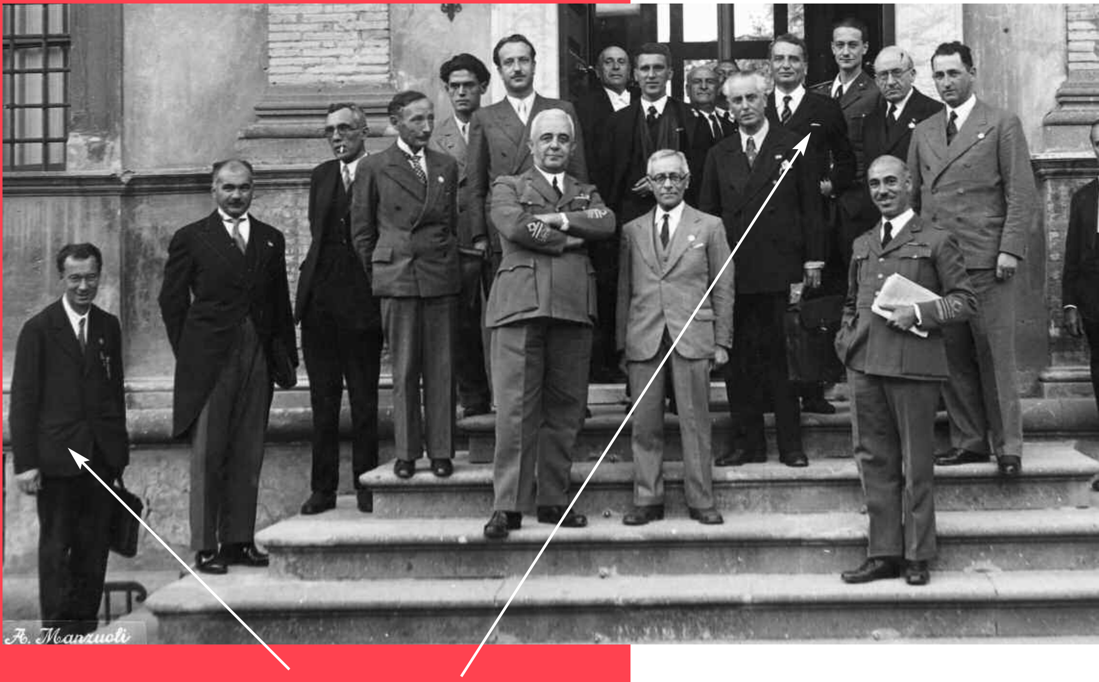
Coherent anti-Stokes Raman spectroscopy (CARS) on the nitrogen molecule is broadly accepted as the method of choice for performing non-intrusive and instantaneous temperature measurements in flames. It has also been applied in in-dustrial conditions. The single shot precision of a CARS temperature measurement is limited by the shot to shot variation of the dye laser profile. To overcome this limitation a new system for CARS temperature measurement has been developed. It combines three special pieces of equip-ment: a single-mode pump laser, a modeless dye laser, and an echelle spectrometer with cross-disperser (See Figure 1). The key feature of the method is the simultaneous measurement of the N2-CARS spectrum and the broadband dye laser profile, in combination with a procedure to transform the dye laser profile in software to the excitation profile, needed to reference (or nor-malize) the N2-CARS spectrum. Using the unique shot-to-shot excitation profiles, simultaneous referencing eliminates systematic errors. At 2000 K and 300 K, the 95% confidence intervals are estimated to be approx. 20 K and approx. 10 K, respectively.

The new system will be applied in studies on the influence of hydrogen in laminar natural gas flames and on turbulence-chemistry interaction in turbulent gaseous flames.

The setup described in this article was realized using an investment grant from the FOM program on “Turbulence and its role in energy conversion processes” for laser diagnostic facilities for combustion research (joint project of U Twente, TU Delft and TU Eindhoven).



Experimental setup of the rovibrational CARS system. BS, beam splitter; T, telescope; S, sampler; L, lens; BD, beam dump. The measurement volume is where the two green beams and the red beam meet and the blue beam (CARS signal) is generated.



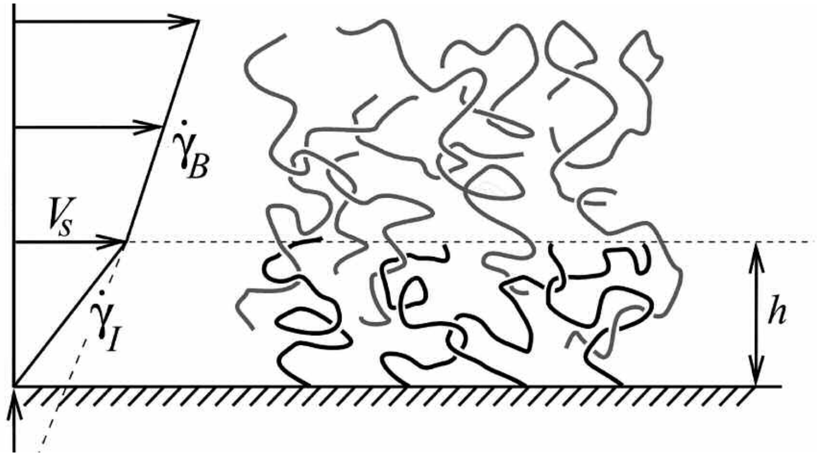
Volta Congres 1935. Burgers and Von Karman

R Stepanyan
JJM Slot
J Molenaar
M Tchesnokov

Constitutive modeling of a polymer flow near a polymer-grafted wall

Recently, there has been a lot of attention paid to the role surface anchored polymer chains play in the friction between a flowing polymer melt and a solid interface (see [1] and references therein). The roots of such an interest lie mainly in the practical importance of the issue: an opportunity to manipulate the flow behavior via surface modification could be of great industrial importance, e.g., in extrusion. Moreover, it is believed that the interaction between the adsorbed polymer layer and the bulk material should be held responsible for various flow instabilities in constant speed polymer extrusion (for an excellent review see [2]). Though the origin of some instabilities still remains poorly understood, it is generally admitted that the so-called "stick-slip" transition plays a prominent role in the understanding of the phenomena. In this respect, a deeper insight in the processes that take place in a near-wall polymer flow is essential. In the system under consideration, different friction regimes were identified with a clear transition between them ("stickslip"). For low shear rates the flow is stable ("stick" regime), however at a certain critical rate the slip velocity Vs, Fig. 1, makes a dramatic jump and the polymer melt starts "slipping" on the surface. The prediction of the critical rate based on a microscopic view of the phenomenon is one of our main goals.

The proposed constitutive model is based on a generalization of a so-called Rolie-Poly equation [3] in a combination with an accurate microscopic picture of the relaxation of the grafted chains. It is shown that beyond a certain threshold shear rate value, the grafted chains become extremely stretched by the flow and disentangle from the bulk ones resulting in reduced bulk-wall friction and a jump in Vs. The main advantage of the model proposed is its simplicity, which gives one the opportunity to use it in numerical simulation of complex flows.



A sketch of the near-wall region: bulk polymer (gray) is entangled with grafted chains (black) forming a layer of a height h (typically, about 10nm). The slip velocity Vs is defined as the one on the interface between the grafted layer and the bulk. The picture is not on scale.

Despite its simplicity, the model allows one to mimic all the generic features of a near-wall flow observed in experiments [1]. For instance, the flow rate dependence of the slip velocity shows the typical behavior in Fig. 2.

The scaling relations extracted from the model are in accordance with earlier theoretical studies and experiments: e.g., the critical shear rate is predicted to scale as the molecular weight of the bulk polymer in power –3.4. Different grafting regimes, varying from nonoverlapping to strongly interacting grafted chains, are successfully reproduced, Fig. 2.

The results obtained can be used to manipulate the friction between a solid substrate and a polymer melt via surface modification. The quantitative predictions made show that the surface grafting density allows to tune the friction in the most effective way. One of the further applications of the model is the consideration of polydispersity of the grafted layer as well as of the bulk melt. E.g., adding a very small amount of shorter or longer material to the melt, one retains its mechanical and aesthetical properties but influence strongly the critical rate at which a “stick-slip” transition occurs.

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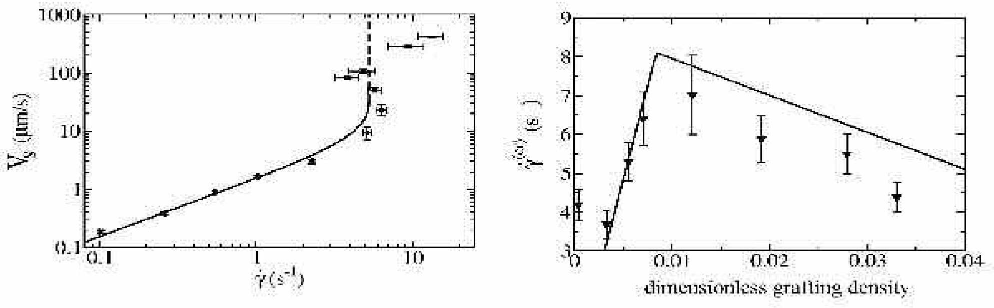

Left: Slip velocity vs bulk shear rate: comparison of the theoretical prediction (line) to the experiment [1] (points). Right: Critical shear rate as a function of the grafting density (line – theory, points – experiment). Dimensionless grafting density of 0.04 corresponds to strongly overlapping grafted chains. The experimental data [1] are for a PDMS melt (970 kg/mol) near a silica wall grafted by PDMS chains with molecular weight of 96 kg/mol.

J-C Baret
F Mugele

Electrowetting-induced self excited droplet oscillations

Electrowetting is one of the most versatile and promising actuation techniques for various microfluidic applications, such as droplet-based Digital Microfluidic Devices (see Ref.1). Electrowetting amounts to the fact that the contact angle of conductive liquids on an insulating surface in an immiscible non-conductive environment (e.g. water droplets in oil) can be controlled by applying a voltage between the conductive liquid and an electrode embedded into the substrate surface. Using several suitably patterned electrodes, it becomes possible to move droplets along pre-defined paths on a surface, to control the morphology of liquid microstructures, to generate small droplets, and to control two-phase flows in microchannels. In a recent experiment we studied self-excited oscillations in which droplets periodically detach from a wire (through which a voltage is applied) and reattach to it: a wire is placed on top of a sessile droplet such that it is barely immersed at zero voltage. Upon applying a voltage, the contact angle decreases and the droplet spreads. This leads to the formation of a thin capillary neck, which becomes unstable and brakes beyond a certain threshold voltage. Once the droplet is detached, the contact angle increases again because the voltage is no longer applied. As a result, the droplet reattaches to the wire and the cycle starts all over again (see Ref. 2). If this experiment is performed at DC voltage (or at low AC frequency f), the dynamics are determined by charge relaxation: immediately after detaching, the droplet is charged and the contact angle remains low. Only as the charge disappears via some leakage currents, the droplet relaxes slowly (time scale: several seconds) and eventually reattaches to the wire. For sufficiently high AC frequency, however, the contact angle switches back to Young's angle during the pinch off process (time scale: O(1ms)). Under these conditions, the dynamics are determined by the hydrodynamic response of the droplet to this abrupt change of the boundary condition. The oscillations are then much faster with a typical frequency of 10 ... 100Hz. Depending on the dimensionless number $Oh=\eta/(\rho\gamma r)^{1/2}$, the oscillation dynamics are dominated either by viscosity (Oh>1; Fig. 1a) or inertia (Oh<1; Fig. 1b). These fast oscillations can be used to promote mixing within the droplets (Fig. 2) which is of considerable interest for microfluidic applications.

The sudden appearance of Young's angle during the fast oscillations implies that the droplets are discharged during the pinch off process at high AC frequency: as the capillary neck breaks its electrical resistance R diverges algebraically with $R=R_0(t/t_0)^{-\mu}$ (where t_0 and μ are determined by the hydrodynamics). Electrical modeling shows that the residual charge on the droplet after the pinch off depends on a dimensionless number $\alpha=2\pi f\,(R_0 C t_0^{\mu})^{1/(\mu+1)}$ (C: droplet-electrode capacitance). For $\alpha >> 1$, the charge after the breakup is negligible (giving rise to fast oscillations) while for $\alpha < 1$, a significant amount of charge remains on the drop (leading to slow oscillations).

Thus the interplay between the pinch off dynamics and the applied frequency determines the charge of the detached droplets. This detachment controlled discharge (DCD) mechanism is very general. It should be applicable in any situation where droplets detach from a reservoir (or from a nozzle) in the presence of electric fields.

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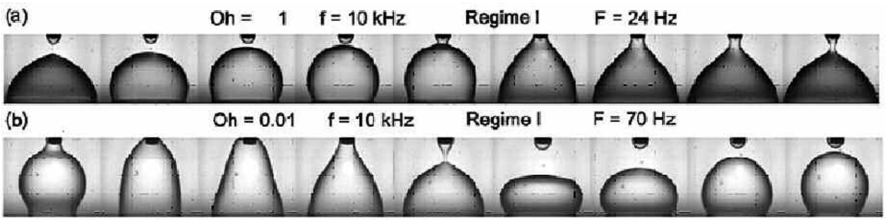

Figure 1 The oscillation process: viscosity (a) and capillarity (b) dominated droplet oscillations.

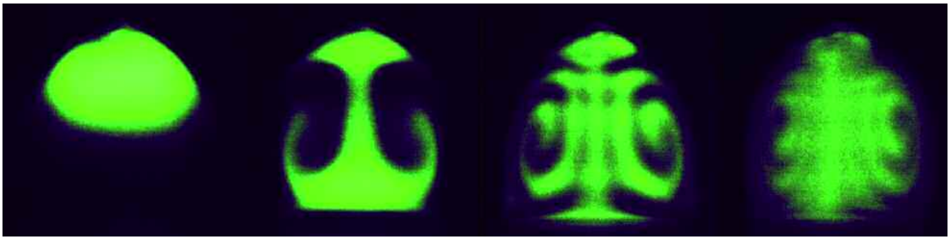

Figure 2 Oscillation-induced mixing. Water droplet, initially dye-stained in the top part, oscillating at ?80Hz between the two morphologies indicated in the left picture. Droplet diameter: 1mm. Time between consecutive images: 1s.

P Stoltenkamp
J Willems
A Hirschberg

Dynamic behaviour of volume flow meters

Volume flow measurements are essential in the industry. For example The Netherlands produces 1011 m3 natural gas per year. Turbine flow meters allow measurement of such quantities with accuracies of the order of 0.2% under ideal flow conditions. Acoustical perturbations can however induce spectacular errors.

Some turbine meters can even rotate when exposed to a purely oscillatory fluid flow. These spurious volume flow measurements are due to asymmetry in wing profiles of turbines. As illustrated by the flow visualisations (see figure 1), the sharp downstream edge displays vortex shedding, which does not appear at the rounded front edge. This results into a net time averaged force driving the rotation.

When acoustical velocity fluctuations are superposed on a main flow, the rotor will display errors due to non-linear behaviour. Following a simple quasi-steady theory for an ideal frictionless flow the relative error is equal to the square of the relative amplitude of velocity fluctuations. A theoretical prediction of these errors allows the correction of volume flow measurements. It is therefore essential to test theories in a wide range of experimental conditions. In the new set-up of TU/e, developed within the framework of the STW project ‘Flow-Induced Pulsations in Gas Transport Systems: prediction, prevention and influence on volume flow measurements’, we can measure this behaviour for volume flows up to 1 kg/s of air and frequencies from 5 Hz to 2 kHz (see figure 2).

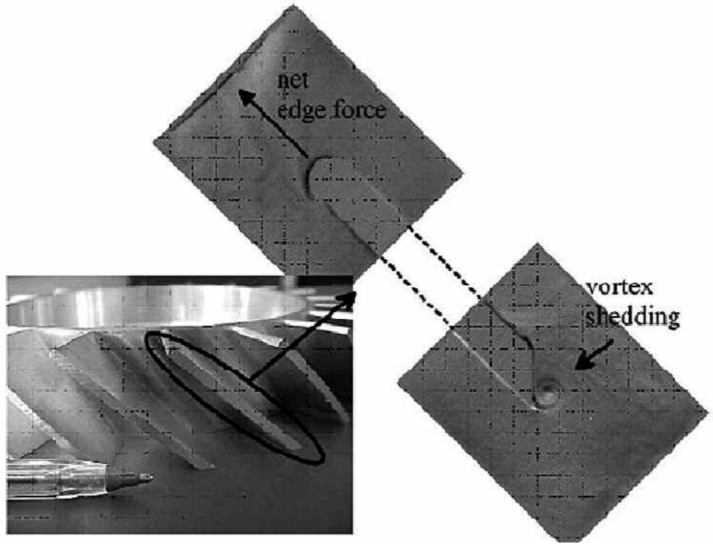

Figure 1Vortex shedding at the sharp trailing edge of a rotor blade,

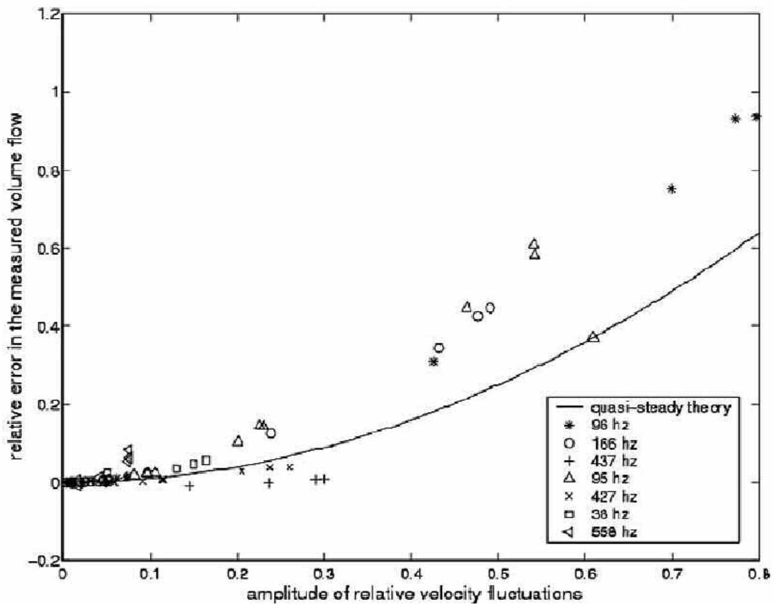

Figure 2 Comparison of observed error with prediction of a quasi-steady model.

AEP Veldman

Numerical simulation of free-surface flow

One of the main research themes of our group is the numerical simulation of free-surface flow. This line of research actually started at NLR in the late 1970s, with a study towards the influence of liquid sloshing onboard IRAS. With the moderate computers of those days only limited, two-dimensional models of liquid motion under microgravity could be studied. A major boost took place in 1995 with the development of Sloshsat FLEVO (Facility for Liquid Experimentation and Verification in Orbit): a mini-satellite designed and built by NLR (with support from ESA and NIVR) to experimentally study liquid dynamics onboard spacecraft (Figure 1). In our group we then started the development of ComFlo: a simulation method for fully three-dimensional free-surface flow.

With capillary forces being a main driving mechanism under microgravity, it is essential to achieve an accurate description of the location and evolution of the free liquid surface (including contact line dynamics). Thus sharp interface methodology is used, based on a piecewise linear reconstruction of the surface (SLIC, PLIC). Moreover, special attention is paid to discrete mass conservation. Another key ingredient is the use of Cartesian grids with cut-cell discretization. This allows the study of flow past (and inside) objects of arbitrary geometrical complexity.

Figure 1Sloshsat FLEVO.

The liquid dynamics is coupled to the spacecraft motion, thus free-flying spacecraft can be simulated (Ref. 1). In February 2005, Sloshsat has been successfully launched, and we are currently evaluating the outcome of the experiments carried out during its one-week mission. Figure 2 shows some computational snapshots during a so-called 'flat spin' maneuver, where the spacecraft rotation transfers from the axis of intermediate m.o.i. (moment of inertia) to the axis of maximum m.o.i.

This 'extra-terrestrial' research has lead to a more 'down-to-earth' spin-off in cooperation with MARIN. Since 1998, ComFlo is also used in several maritime applications, such as hydrodynamic wave loading on offshore platforms, sloshing in LNG cargo tanks, and ship anti-rolling devices. With the main interest lying in an accurate prediction of the peak pressure loads during wave impact, again the mass-conserving sharp interface methodology is an essential ingredient (Ref. 2).

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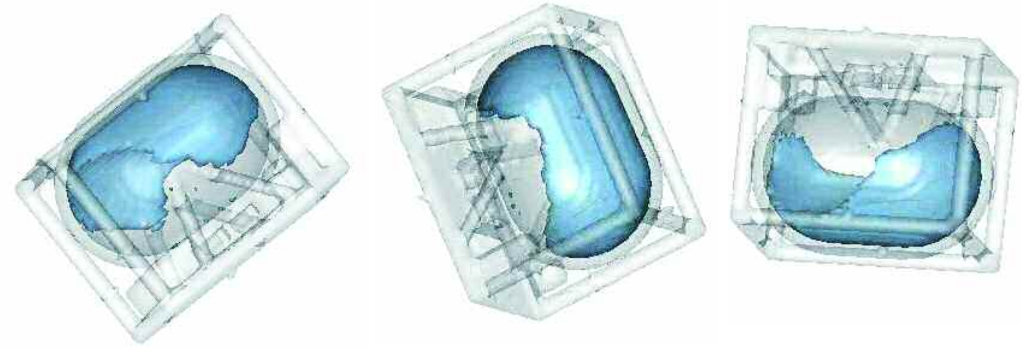


Figure 2 Snapshots from a simulated free-tumbling maneuver of Sloshsat FLEVO.

AA van Steenhoven

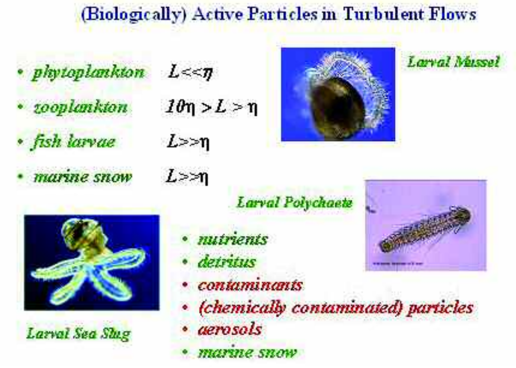
Bio-Fluid Mechanics in The Netherlands

Bio-fluid mechanics is a rapidly increasing area of research within the JMBC. Many groups have established good research contacts with medical and biological partners and got grants for their research from FOM, STW or NWO. The purpose of this Burgersdag-presentation is to show that this research area is indeed a vivid one and to sketch some aspects for the future. To that end, first three research directions are illustrated.

The first one is the trend from physical models to computer models and is illustrated by the Eindhoven Heart valve research project. It started in the 1970's by physical models to explain the early closure of the aortic valve during flow deceleration by visualisation experiments and potential-flow models. In the 1980's in-vitro and in-vivo experiments were performed to investigate the influence of non-modelled parameters, like aortic wall movement and porcine leaflet stiffness. This led to the development of fluid-structure interaction models in the 1990's and resulted in a three-dimensional completely coupled analysis of wall and leaflet motion and fluid flow. These results, obtained by De Hart and Baaijens (TUE), also clearly demonstrated the Kelvin-Helmholtz instability in the leaflet (due to the velocity difference across it) as earlier observed in the in-vivo experiments. Next, using the predicted stress distribution, Bouten (TUE) develops artificial leaflets using biodegradable polymers on which natural cells are seeded and adapt them to carry the load. A similar nice topic of current research is the analysis of the vocal volds as investigated by Hirschberg (TUE) and Veldman (RUG).

A second trend is the direct application of the bio-fluid mechanics to medical and biological problems. A nice example is the analysis of the deposition of aerosols in the lungs of small babies and the improvement of the deposition method in the clinic (de Jongh, UT/AMC). Another application is the analysis of the swimming behaviour of fish larves, the oxygen uptake and the development of muscles and backbone as a function of external parameters (van Leeuwen, WUR).

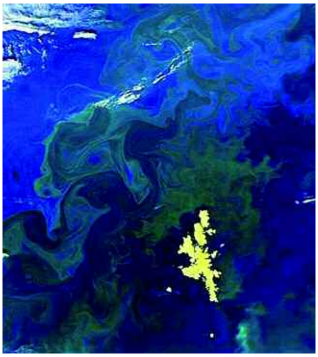
Finally, the trend to smaller scales is also evident. Although the processes within the cells are not really a topic of research within the JMBC, the cell behaviour in response to fluid mechanic parameters, like pressure or wall shear stresses, is an intriguing area of research. The embryonal development in the chicken heart



(Biologically) Active Particles in Turbulent Flows

- *phytoplankton* $L<<\eta$
- *zooplankton* $10\eta > L > \eta$
- *fish larvae* $L>>\eta$
- *marine snow* $L>>\eta$

- *nutrients*
- *detritus*
- *contaminants*
- *(chemically contaminated) particles*
- *aerosols*
- *marine snow*



(Nieuwstadt/Westerweel ,TUD) and the micro-bubble behaviour due to high-frequent ultra-sound and the possibilities for local drug supply (Versluis/Lohse, UT) are very characteristic examples of this line of research. For the interaction of very small biological active particles with the turbulent flow field in oceans Clercx (TUE) recently was awarded a VICI-grant.

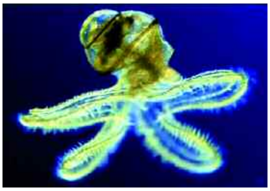
As illustrated above, the bio-fluid mechanics theme is an excellent area for collaboration between several research groups from inside and outside the fluid-mechanic community. Therefore, the researchers within the JM BurgersCentre in close collaboration with their medical and biological partners strive for a NWO-granted research program on Bio-Fluid Mechanics. Two categories of projects can be distinguished:

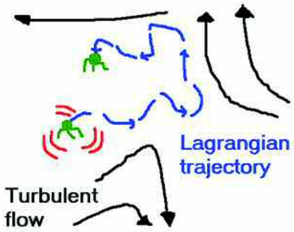
1. Old physics in a new biological context

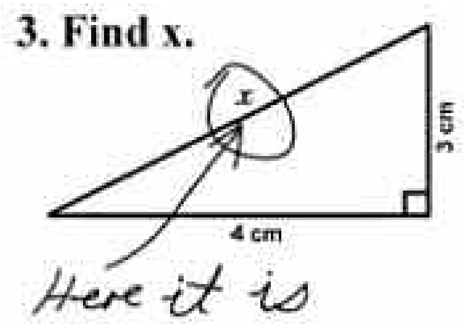
Flow in living systems occurs mostly within flexible walls or around deformable bodies so that flow-structure interaction cannot be neglected. Besides, our intuition in general is not helpful as the flow processes in living systems occur frequently near the end of the parameter range in which they are usually studied and the structure is strongly linked to its surroundings. Therefore the challenge here is to integrate the well-known principles from classical fluid mechanics in an unfamiliar environment.

2. Biologically inspired new physics

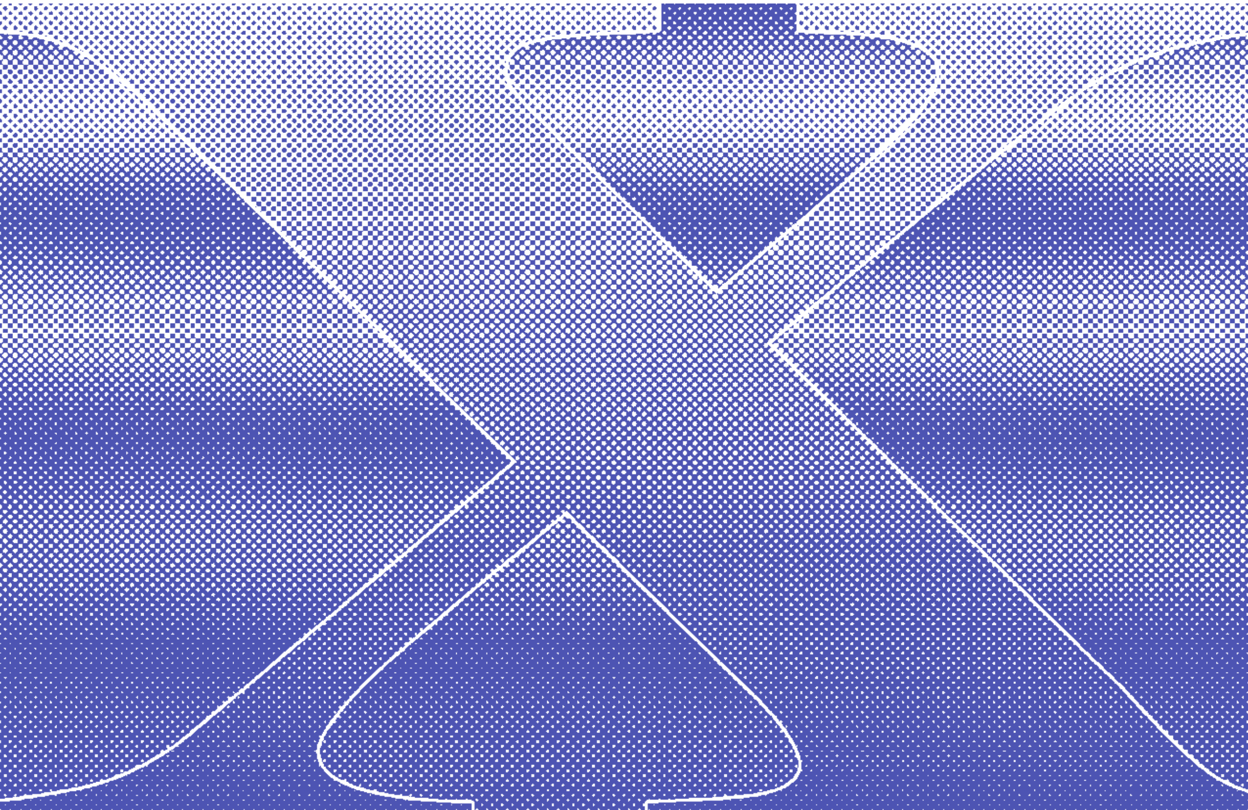
In other biomedical and biological problems, primarily in the processes occurring on the micro-scale, new flow physics may occur with which we are as yet not familiar. For instance instead of inertia, electrostatic forces and temperature effects may dominate the flow. At the small scales also the properties of the fluid, i.e. the rheology, are increasingly important. Another important question to be considered in this context is to which scale the continuum approach of fluid mechanics can be used. The boards of the NWO-daughters ALW, FOM and ZonMW are now investigating whether they will support this kind of research. As another illustration of the growing contacts between the fluid-mechanics/ biological and medical partners next autumn a JM Burgers Centre AIO-course on Bio-Fluid Mechanics will be organized by Van de Vosse and Van Dongen (TUE), in which all major research groups in The Netherlands will participate and to which PhD students from both communities are invited to participate.







A humorous answer to a math question



2005

MP Sobera
CR Kleijn
HEA van den Akker

Subcritical flow and heat transfer past a circular cylinder surrounded by a porous layer

The flow through thin layers of fibrous material is relevant to applications in e.g. filtering and separation, and air flow through garments. An important parameter is the permeability of the layer. Various models relating permeability to porosity and fiber diameter have been proposed, none of which is accurate over athe entire range of porosities. Moreover, it has been observed that randomness in the fiber-to-fiber distance increases the permeability, but no systematic study of this effect has been performed yet.

Through 3-dimensional numerical solution of the Stokes equations for cross flow through fibrous layers, we studied the influence on permeability of porosity, fiber radius and non-uniformity. We found that for this purpose the latter can be characterized by a single parameter, based on the standard deviation in the hydraulic diameters of the rectangles spanned by the fibers. We proposed a novel model correlation, predicting the permeability for a wide range of fiber radii, porosities and non-uniformities [1].

For testing textile materials, a widely used experimental setup consists of a solid cylinder in cross flow, surrounded at some fixed distance by the textile material [2]. The outer flow is expected to resemble the well known oscillating flow around a solid cylinder. However, the flow underneath the porous cylinder, its interaction with the outer flow, and the influence of the porous layer on heat and mass transfer, have hardly been studied.

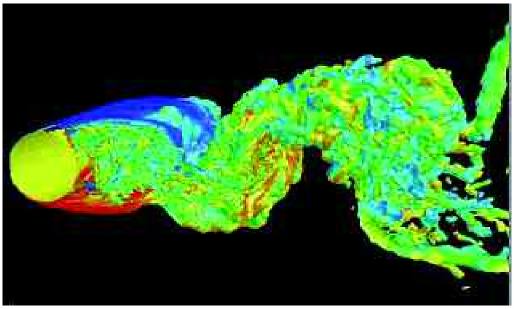


Figure 1 DNS simulations of the flow around a solid cylinder at Re=3,900.

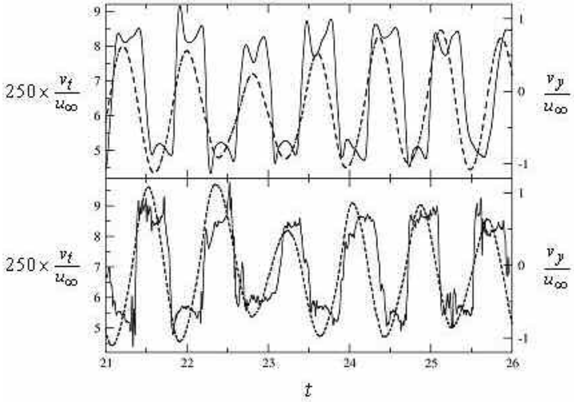


Figure 2 Time history of the tangential velocity vt in the fluid gap (dashed lines) and the transverse velocity vy in the wake (solid line). Upper: Results from T-RANS. Lower: results from DNS.

To elucidate these issues, we have performed: (i) 3-dimensional DNS simulations [2,3], (ii) 3-d transient RANS (T-RANS) simulations; (iii) 2-d steady-state RANS simulations [4] and (iv) Laser Doppler Anemometry measurements of time-averaged tangential velocities in the fluid gap [4].

DNS simulations at Re=3,900 were performed with the commercial CFD code Fluent, and with the T-Rex code, developed in our department by Niceno and Hanjalic. For flow around a solid cylinder only (see Figure 1), both codes were validated - with very good agreement - against each other and against experimental and DNS data from literature. For the cylinder covered by a porous layer, the flow underneath the porous layer was found to be laminar and periodic, with a frequency locked to that of the vortex shedding in the wake behind the cylinder (see Figure 2) [3]. However, only the low Strouhal frequency is pronouncedly present inside the fluid gap, whereas higher frequencies are filtered out. Therefore, accurate results of the flow inside the gap, and of the heat transfer to the solid cylinder, can also be obtained using a transient RANS (T-RANS) approach, as also shown in Figure 2.

By applying 3-d T-RANS and 2-d RANS simulations, the influence of the porous cover layer on the heat transfer was studied at a wide range of Reynolds numbers, porous layer hydraulic resistances, and geometric ratios. All results could be summarized in a single empirical correlation [4].

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P Vennemann
M Pourquie
R Lindken
J Westerweel

Blood velocity measurements in microvessels

The spatially resolved measurement of blood velocity distributions can contribute to a deeper comprehension of numerous biomedical questions: the identication of instantaneous flow patterns helps to understand the function of heart valves and atherosclerotic plaque formation, the derivation of shear stress distributions adds to the understanding of shear responsive gene expression, the accurate estimation of volume flow rates verifies the effectiveness of perfusion affecting substances, monitoring skin perfusion reveals information about burn depth.

Established measurement methods like nuclear resonance imaging or ultrasound Doppler velocimetry suffer from limited spatial resolution due to relatively long utilized wavelengths. Other methods like laser Doppler imaging and time varying speckle velocimetry depend on scanning and therefore imply a temporal resolution longer than typical heart rates. Particle image velocimetry (PIV) can overcome these limitations. The method allows for the determination of the velocity magnitude, and direction. The wavelength of visible light allows a spatial resolution that is high enough for accurate wall shear stress derivations. Video rate or high speed imaging enables the resolution of typical heart rate frequencies.

In this research project, PIV is used to study the questions whether extraembryonic flow influences the heart development. It is speculated that the heart development is linked to the wall shear stress patterns within the forming heart. The wall shear stress acts on the endothelium, that is a thin layer of cells lining the whole vasculature including the heart. From in vitro flow studies on these cells, it is known that flow induced shear stress modulates gene expression [1]. By combining the fluorescent visualization of gene expression with a quantitative measurement of the instantaneous flow field in vivo using PIV, a relationship between placental blood flow and cardiogenesis might be found.

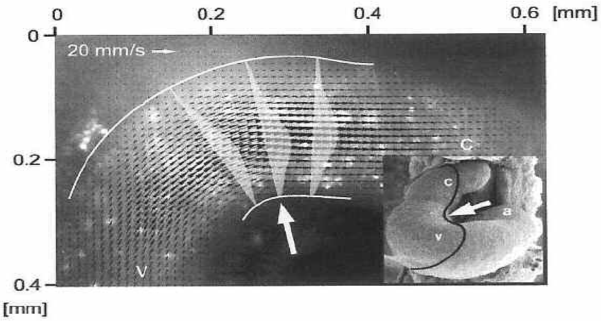

Figure 1 PIV measurement in the ventricle of a chicken embryo. The inset shows an electron micrograph of the heart [4] to illustrate the position of the measurement plane.

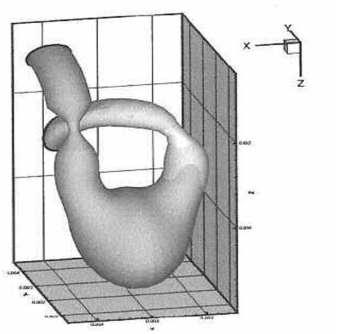

Figure 2 Numerical model of the embryonic chicken heart

Chicken embryos are used as a model for human embryos in this research. Due to the small dimensions of the embryonic heart (about 200 m maximum inner diameter) a PIV system is utilized. The measurement plane is defined by the limited depth of focus of a microscope objective [2]. Fluorescent liposomes with a nominal diameter of 500 nm are used as tracer particles. The liposome surface is coated with polyethylene glycol (PEG) molecules to prevent wall adhesion [3]. The use of fluorescent tracer particles enables the distinction between the light that is emitted by the tracer particles and background light that is scattered by the surrounding tissue.

Figure 1 shows the average of fifty phase-locked vector fields in the fully expanded ventricle1. From the velocity distributions at different points in the cardiac cycle velocity profiles are extracted. From the derivative of the velocity profile, low and high shear stress domains can be identified. The maximum velocity of the velocity profile in figure 1 is shifted into the direction of the inner curvature wall.

For the measurement plane of figure 1 the inner curvature wall is thus identified as a high shear stress region, relative to the outer curvature wall. Additional work is done on the numerical simulation of the embryonic chicken heart. A preliminary result using a strongly simplified geometry is shown in figure 2. It shows the heart during the phase in which the cushions near the outlet are fully closed, and the cushions near the inlet are closing, giving shear stress near the inlet cushion. Light color indicates higher wall shear stress, dark indicates lower wall shear stress. The heart has the form of a distorted tube, the cushions are at the places which are constricted. The cushions near the outlet are fully closed, the cushions near the outlet (light color, high stress) are closing. This project is funded by the Dutch technology foundation STW (DSF 5695).

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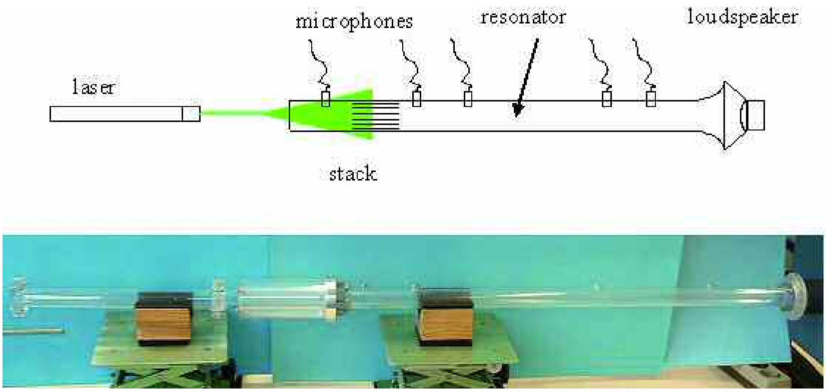
PCH Aben
A Hirschberg
J Molenaar
PHMW in 't Panhuis
SW Rienstra
ATAM de Waele
JCH Zeegers

High amplitude oscillatory gas flow in interaction with solid boundaries

Thermoacoustics is a field in physics in which the interaction between sound and heat plays a key role. On the one hand a sound wave interacting with a wall generates heat transport. On the other hand a sufficiently large temperature difference along a wall can generate and sustain sound. In recent years this technology has been applied to develop cooling engines and natural gas liquefiers in the USA. Two new developments in The Netherlands are the generation of electric power in natural gas wells for the oil industry (Shell), and thermoacoustic heat pumps for upgrading waste heat (ECN). In the first case the characteristic power is on the order of a few watts; in the last case the magnitude is of mega-watts. All this technology is still in a developing stage and offers interesting market opportunities. Two key references for thermoacoustics are [1,2].

The transport of energy in this equipment can be understood from the principles of acoustic wave propagation and interaction with obstacles in the waveguide.
At low acoustic pressures linear one-dimensional theory can be used to describe the propagation. A one-dimensional model that describes the acoustic propagation accurately is DeltaE, from Los Alamos National Laboratories. However at high acoustic pressures (>10% of the mean pressure) it is not possible to use linear theory to describe the acoustics. At high sound intensities the theoretical energy balance, is not in agreement with measurements. The full energy balance involves terms like vortex energy, viscous dissipation, non-linear wave steepening, and turbulence. In order to develop the best design, it is important to understand these phenomena theoretically as well as experimentally. The goal of the current project is on the one hand to develop computational software to model the energy balance of high amplitude waves in acoustic cavities. Furthermore the sound wave's behavior will also be investigated experimentally in order to validate the theoretical results.



In the upper diagram a schematic impression is given of the acoustic set-up by which resonant acoustic waves are generated. The interaction of the acoustic sound field with a stack will be studied with PIV techniques. The photo shows the first test set-up that was developed. Only the resonator is shown with the stack and on the right hand side the loudspeaker section The experience with this set-up will help us to develop a more professional set-up in 2006.

Finally the development of these tools can lead to the design of new and novel apparatus.

In much (standing wave) thermoacoustic equipment, the sound wave interacts with a stack, which simply is a set-of parallel plates that are the medium by which the acoustic field pumps the heat. But this can also be a wire gauze (Rijke's tube acoustics) or regenerator like material (traveling wave heat-pump). The project is first aiming to understand the interaction of high intensity oscillatory gas flow with stack like geometries. By starting from this, the mathematical analysis can also be made in parallel to the experiments. In the future more emphasis will be placed on real thermoacoustic heat pumps, in agreement with the sponsors of the project.
The preliminary experimental set-up that we use now is shown in the figure. Acoustic microphone measurements as well as PIV are made to understand the phenomena in the resonator.

In the upper diagram a schematic impression is given of the acoustic set-up by which resonant acoustic waves are generated. The interaction of the acoustic sound field with a stack will be studied with PIV techniques. The photo shows the first test set-up that was developed. Only the resonator is shown with the stack and on the right hand side the loudspeaker section The experience with this set-up will help us to develop a more professional set-up in 2006.

The project is a 2-PhD project that is granted by STW and is in cooperation with Shell, ECN and Aster-Thermoakoestische systemen. The work is performed as a joint project between the Fluid Dynamics Group of Faculty of Physics, and the Centre for Analysis, Scientific Computing and Applications of the Faculty of Mathematics and Informatics, both of Eindhoven University of Technology. The project started in July 2005.

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JJ van der Werf
JS Ribberink
SJMH Hulscher

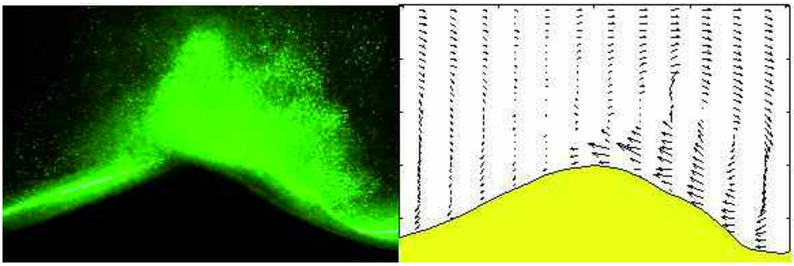
Sand transport over rippled beds in oscillatory flow

1. Introduction

Sand transport by waves over rippled beds is one of the largest knowledge gaps in the modelling of sand transport in coastal seas. Wave-induced ripples typically have heights of 0.01-0.1 m and lengths of 0.1-1 m. They strongly influence the boundary layer structure and turbulence intensity near the bed and have a great influence on the sand transport (see Fig. 1). This recently completed PhD research was aimed at a better understanding and modelling of the interaction processes between the wave-induced oscillatory flow, the ripples and the suspended sand. To that end, new full-scale experiments were carried out in two large oscillatory flow tunnels. Measurements were made of the ripple dimensions, the intra-wave flow (see Figure 1), suspended sand concentration and sand flux field around ripples and the net sand transport rates covering a wide range of flow and sand conditions. The new experimental data were combined with existing data to make a large data set of sand transport processes over rippled beds for oscillatory flows with field-scale amplitudes and periods. The insights and data obtained from the experiments were used to validate and improve various types of models to predict ripple dimensions, suspended concentration profiles and net sand transport rates.

2. Sand transport processes

The new data show that the sand transport over rippled beds in asymmetric oscillatory flows (where the onshore orbital velocity peaks are larger than the offshore orbital velocity peaks) is concentrated in a lower layer with a thickness of about one ripple height (Van der Werf et al., 2005). The net sand transport is determined by two competing mechanisms: wave-related bedload transport in onshore direction and wave- and current-related suspended load transport in offshore direction. It is found that the relative importance of these two mechanisms is controlled by the vortex suspension parameter P, which is the ratio of the ripple height and the median grain-size. The ripple height represents the vertical mixing intensity of the flow and the grain-size represents the downward settling of the sand. For large P (corresponding to high ripples and fine sand) suspended transport is dominant, resulting in offshore-directed net sand transport, while net sand transport is onshore-directed for small P where bedload is the dominant transport mode.



Laser illumination of suspended sand particles (left) and measured flow field (right) at approximately the moment of flow reversal (flow direction reverses from right to left).

3. Sand transport modelling

The transport over rippled beds in oscillatory flow cannot be modelled in a quasi-steady way, because of unsteady phase lag effects that are very important in the case of ripple regime transport. The practical models of Nielsen (1988) and Dibajnia and Watanabe (1996) include these unsteady effects but have been calibrated against data from small-scale experiments and do not perform well for the data from full-scale experiments. A new sand transport model (Van der Werf et al, accepted) is proposed based on a modified half wave-cycle concept. The magnitudes of four half wave-cycle transport contributions are related to the grain-related Shields parameter, the degree of flow asymmetry and a newly-defined vortex suspension parameter P. The new model has been calibrated using net transport data from regular flow experiments and has subsequently been validated using other data, including measurements from irregular flow experiments. The new model performs better overall than the existing practical transport models. We conclude that it is possible to describe the general sand transport phenomena over rippled beds in regular oscillatory flow with the 1DV boundary layer model of Davies and Thorne (2005). In the important near-bed layer of one ripple height, the model predicts the timing and magnitude of the sand flux peaks well. Furthermore, it shows reasonable agreement with measured net transport rates. However, the model is not able to reproduce the measured time- and bed-averaged velocity profile. This is probably related to differences in parameter ranges between the experimental data used for model development and the new experiments used for model assessment. Except for a lower layer with a thickness of half a ripple height, the predicted upward propagation of concentration peaks lags behind the data. This is caused by the fact that the mixing above rippled beds is a convective process that cannot be modelled adequately with the gradient diffusion approach applied in the model. We propose three model adjustments, which result in improved predictions of the sand transport processes.

Acknowledgements

This PhD work has been carried out within the EU project SANDPIT (‘Sand transport and morphology of offshore sand mining pits’), contract number EVK3-2001-00056.

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A Staicu
F Mugele

Electrowetting-induced oil film entrapment and destabilization

Electrowetting on dielectric (EWOD) is increasingly becoming the driving mechanism of choice for droplet-based digital microfluidic devices [1]. While the electrowetting effect is essentially a classic example of interaction between fluids and electric fields, its efficiency, reproducibility and ease of use make it preferable over other methods of manipulating small drops, such as Marangoni effects or thermo-capillary stresses [2].

In order to prevent evaporation of the (usually aqueous) droplets and in order to minimize contact angle hysteresis, digital microfluidic chips are usually operated in a two-phase configuration, i.e. droplets are surrounded by an ambient oil that wets the substrate completely. As a voltage U is applied between the droplet (typical size) and the electrode(s) on the substrate the contact angle decreases following the well-known electrowetting equation [1], implying automatically a motion of the contact line.
As the contact line moves, a film of the ambient oil is entrapped under the drop, depending on the speed and on the viscosity contrast between the drop and the oil. While the formation of such thin oil layers was known (e.g. [3]) the dynamics of their formation and their subsequent fate under the action of surface tension, electric Maxwell stresses and - provided their thickness is small enough - van der Waals forces remained elusive.

We performed a standard electrowetting experiment with a water drop spreading on a teflon-coated ITO glass substrate in ambient silicone oil. The contact area between the droplet and the substrate was imaged with DIC microscopy from the substrate side (see Figure 1). Interference fringes appear during the spreading, indicating the presence of a trapped oil layer with a thickness of the order of the wavelength of light. However, the entrapped film is unstable and breaks up into a radially symmetric pattern of microscopic oil droplets (within less than 1s in the example in Fig.1).

To understand this behavior we performed a linear stability analysis of the thin film similar to that of [4], but with an effective interface potential that includes the Maxwell stress. Modulations $u(r, t) = e + u_0 e^{iqr} e^{t/\tau}$ of the oil film thickness e are considered and one solves for their viscosity-mediated time evolution in the approximation of small amplitudes and slopes $\mu_0 << e, |\nabla\mu| << 1$[5]. From this analysis we find the wavelength of the fastest growing unstable mode for a given initial film thickness e:

$$1/\lambda_m = q_M/2\pi = 1/(2\sqrt{2}\pi)\left(-\frac{A}{2e^4\pi} + \frac{\varepsilon_0 \varepsilon_d^3 U^2}{d^3 \left(1+\frac{e\varepsilon_d}{d\varepsilon_{oil}}\right)^3 \varepsilon_{oil}^2}\right)^{1/2}$$

which is reflected in the drop size. If we assume a constant initial oil film thickness $e(r) = ct.$, we find $\lambda_m \sim r^{-1}$, since the only radial dependence left is due to the externally controlled linear voltage ramp $U(t)$. This is indeed in agreement with the experimentally measured drop size distribution (Fig. 2).

The assumption of a constant initial film thickness, however, is somewhat counterintuitive.

The speed of the contact line decreases during spreading due to volume conservation, suggesting that the entrapped film thickness is smaller close to the edge of the drop-surface interface.

This is indeed confirmed by an independent measurement of the oil film based on the interference patterns seen prior to the film break-up. A direct comparison between λ_m *(e(r))* and the droplet diameters extracted by image processing is shown in Fig. 2. Despite a radial variation of the initial film thickness by about one order of magnitude, the droplet size varies only by a factor of two. This weak dependence is in fact implicit in the expression for λ_m *(e)*, which displays a plateau behavior within the experimental range of *e*. These results emphasize that, in general, the droplet landscape observed at the interface between an electrowetting-actuated droplet in oil and the substrate is strongly influenced by dynamic wetting effects. The thickness of entrapped layers, which can be as low as 10nm, is crucial for the long-term performance of lab-on-a-chip devices, where oil layers can contribute to the protection of substrates from fouling.

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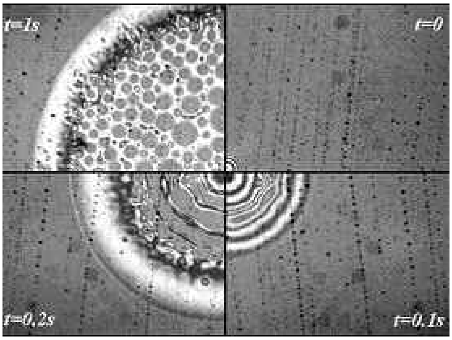

Figure 1 DIC microscope images taken at the substrate-droplet interface during the application of a fast voltage ramp *U=25V /s*. The thin oil film trapped under the water droplet destabilizes progressively and breaks-up into microscopic droplets.

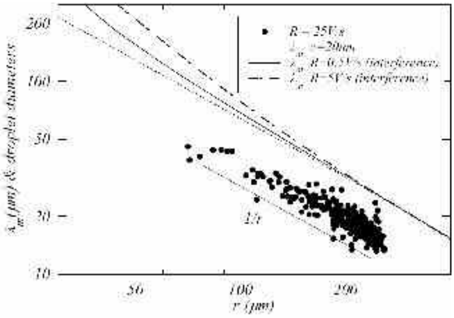

Figure 2 Measured radial dependence of oil droplet diameters for U=25V /s and predictions of linear stability analysis that use interference measurements of the unperturbed oil film thickness. The dotted line corresponds to e = ct. *($\lambda m \sim 1/r$)*.

M Depken
M van Hecke
W van Saarloos

Continuum approach to wide shear zones in quasi-static granular matter

Granular flows show a very wide variety of behaviors, and even though the microscopic dynamics of dry cohesion-less grains is simple and well understood, there is no general theory describing their emergent macroscopic properties.

This is especially true for very slow flows, where inertial effects are negligible. In this regime the grains form enduring contacts, leading to highly complex contact and force networks. This renders approaches based on kinetic theories unapplicable. For this reason we have recently developed a different approach [1].

For concreteness we focus on a recently introduced experimental setup consisting of a modified Taylor-Couette cell with split bottom [2{4] (see Figure 1). It is well established that slow and dense grain flows exhibit rate independence [6], and we therefor aim construct an explicitly rate independent theory. We further assume the stress fluctuations to be fast enough, so that if in a certain plane the strain rate is zero then there will be no residual shear stress in this plane. This implies that the principal-strain and stress directions are the same.

Many flows are such that they can be considered as comprised of a collection of sheets, with no internal shear, sliding past each other. We refer to these sheets as shear-free sheets (SFS) (illustrated for the modified Couette geometry in Figure 1), and the corresponding flows as SFS flows. The assumption of a fast stress relaxation in SFS flows gives a very simple form of the stress tensor (see Figure 2), which has recently been confirmed by numerical simulations [5].

Another upshot of the theory is that, in order to account for the shape of the shear zones, the effective-friction coefficient between he SFS must retain a dependence on the local orientation of the flow relative to the local body force (gravity). This has also recently been supported by numerics [5]. Though the origin of such an effect is unclear, we speculate that it is due to the competition between the organizational tendencies of the flow and the gravitational pull.

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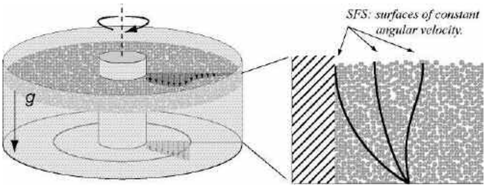

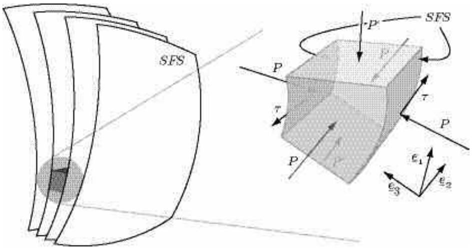

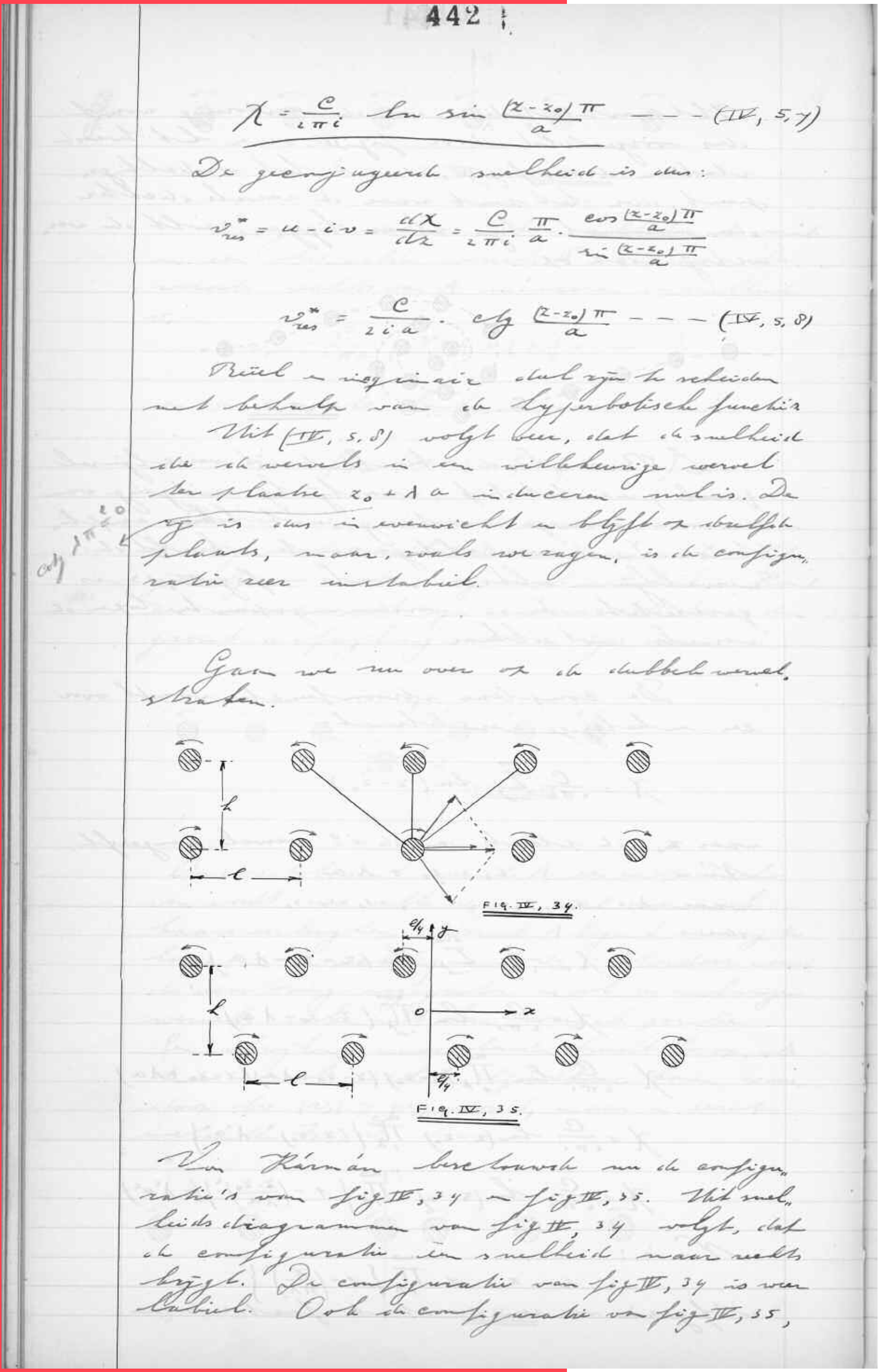

442

$$\chi = \frac{C}{2\pi i} \ln \sin \frac{(z-z_0)\pi}{a} \quad - - - (\mathrm{IV}, 5, 7)$$

De geconjugeerde snelheid is dus:

$$v^*_{res} = u - iv = \frac{d\chi}{dz} = \frac{C}{2\pi i} \frac{\pi}{a} \cdot \frac{\cos\frac{(z-z_0)\pi}{a}}{\sin\frac{(z-z_0)\pi}{a}}$$

$$v^*_{res} = \frac{C}{2ia} \cdot \mathrm{ctg} \frac{(z-z_0)\pi}{a} \quad - - - (\mathrm{IV}, 5, 8)$$

Reëel en imaginair deel zijn te scheiden met behulp van de hyperbolische functies

Uit (IV, 5, 8) volgt weer, dat de snelheid die de wervels in een willekeurige wervel ter plaatse $z_0 + \lambda a$ induceren nul is. De rij is dus in evenwicht en blijft op dezelfde plaats, maar, zoals we zagen, is de configuratie zeer instabiel.

ctg $\lambda\pi$

Gaan we nu over op de dubbele wervelstraten.

Fig. IV, 34.

Fig. IV, 35.

Von Kármán beschouwde nu de configuraties van fig IV, 34 en fig IV, 35. Uit snelheidsdiagrammen van fig IV, 34 volgt, dat de configuratie een snelheid naar rechts krijgt. De configuratie van fig IV, 34 is weer labiel. Ook de configuratie van fig IV, 35,

Page out of a "Collegedictaat Aerodynamica 3" from Burgers' lectures

M Pashtrapanska
N Dam
H ter Meulen
W van de Water

Writing the capital letter H in turbulent air

This poorly calligraphed capital letter H is a small (6 mm size) structure that was written in a turbulent air flow. Just after writing, the H was still neat, but now, 30 μs later, it has been deformed by the turbulent velocity fluctuations. This pattern was written by fusing the O_2 and N_2 molecules of air into *NO* molecules in the focus of a strong UV laser beam. By crossing these beams several times through a turbulent jet flow, a letter H was made which has both small and large length scales. Following it provides a microscopic view on turbulent mixing. The *NO* molecules were made visible by making them fluoresce using a second UV laser.

The width (100 μm) of the lines that make the pattern is a few times the Kolmogorov length, so that these lines embrace several small eddies. The distance Δ between the crosses encompasses the inertial range. The time *t*. since writing is a few times the small-eddy turnover time and all sorts of eddies have had their chance to wrinkle the written pattern. Since the small eddies are coherent, the width of the lines increases exponentially in time.

The inertial-range eddies cause the distance Δ between the crosses to increase linearly with time, $<\Delta^2(t)> = <\Delta^2(0)> + Ct^2$; this is the Batchelor regime. Very long times *t* will lead us into the Richardson regime, $<\Delta^2(t)> \alpha\ t^{3},$ which is believed to control the dispersion of pollutants on atmospheric scale (but which has never been observed directly).

The surprise is that the distance between the nodes of the H, which are extended clouds themselves, increases very accurately according to the Batchelor law, although Batchelor devised his formula for mathematical points. These results are obtained by a collaboration between the Laser Spectroscopy group at the Radboud University Nijmegen and the Fluid Dynamics Laboratory of the Eindhoven University of Technology, in a quest for new optical methods for flow diagnostics.

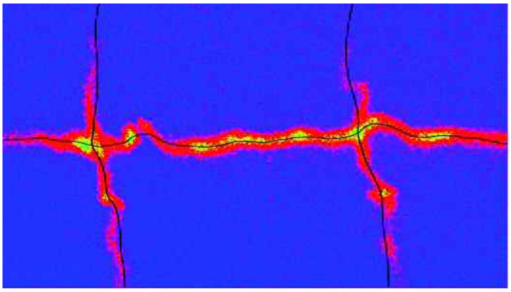

Figure 1 Pattern of *NO* molecules written in a strongly turbulent jet flow, made visible by laser-induced fluorescence, 30 µs after it was written. The thin line is a fit for finding the intersections. The horizontal extent of the figure is 6 mm.

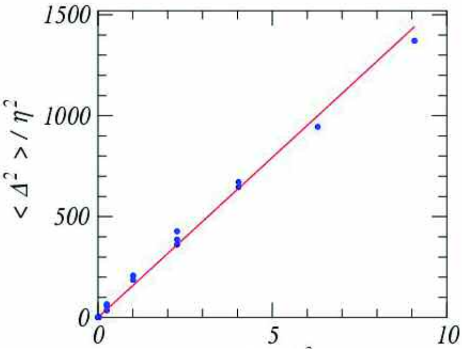

Figure 2 The increase of the root-mean-squared separation of the nodes of the H with time very accurately follows the Batchelor prediction (full time). This is a surprise because the nodes are physical clouds that span several Kolmogorov lengths.

AERO- & HYDRODYNAMICA.

LANTAARNPLAATJE

KIST A Nr. 19

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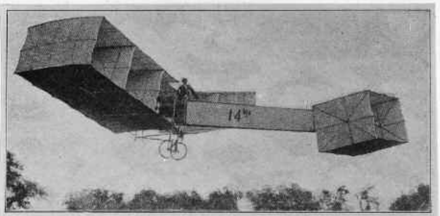

Fig. 173. Drachenflieger von Santos-Dumont (1906). Doppeldecker mit Kastensteuer an der Stirnseite. Antrieb durch eine Luftschraube an der Rückseite der Tragflächen. Tragflächen gekielt und mit lotrechten Querwänden versehen.

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All that we are is
the result of what
we have thought

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H Bijl

Numerical simulations of fluid-structure interactions

Over the past decades numerical simulation tools have matured into useful design and analysis tools. Most of these tools available today deal with mono-disciplinary, deterministic systems, e.g. only fluid flow or only structure mechanics with predetermined properties and boundary conditions. However, many research areas, such as aeroelasticity, require the simulation of multi-physics problems and can be subject to uncertainty in e.g. material properties or boundary conditions. For practical applications the ideal fluid-structure interaction solver is accurate, fast and capable of quantifying uncertainties in the solution. Developing a deterministic multi-physics solver from scratch is already a cumbersome and time-consuming task, let alone developing a multi-physics stochastic solver. A different approach is the coupling of existing mono-disciplinary solvers, shifting the main effort to developing a suitable coupling algorithm for modelling the interaction between flow and structure. For engineering applications, efficiency of the coupling of flow and structure as well as of the uncertainty quantification techniques is of the utmost importance.

Efficient Coupling

When a computational fluid dynamics (CFD) code and a computational structure dynamics (CSD) code are spatially and temporally coupled through a coupling interface a partitioned fluid-structure interaction (FSI) solver is obtained (see Fig. 1). Coupling in space is required since the spatial meshes on which the fluid and structure dynamics equations are discretized generally do not match at their mutual interface. An incorrect transfer of data from one mesh to the other may result in unphysical solutions and a loss of accuracy. We found that a radial basis function interpolation is an accurate and fast method to transfer data between non-matching flow and structure meshes. In addition a temporal coupling is necessary since the flow and structure are advanced asynchronously in time. Temporal accuracy and numerical stability can be lost when data are not transferred at the correct time levels. High order accuracy in time is preserved when a combination of implicit and explicit (IMEX) multi-stage Runge-Kutta schemes is used. Therefore less time steps are necessary to simulate the same time interval, decreasing the computational time spent.

Uncertainty quantification

Uncertainty can be quantified straight-forwardly with the Monte-Carlo method, which requires a large number of deterministic solves. For practical engineering problems - where a deterministic solver is already computationally expensive - the resulting computing time is too large. A more sophisticated approach is to use a polynomial chaos expansion to describe the uncertainty.

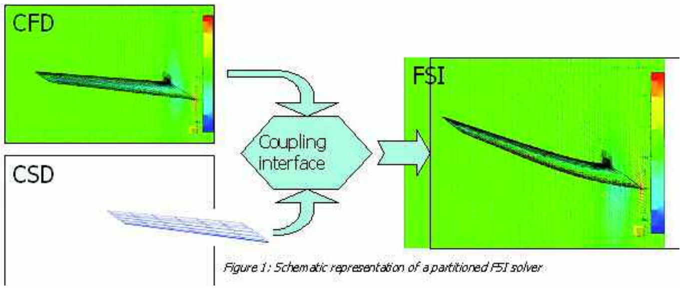


Figure 1 Schematic representation of a partitioned FSI solver

However, the common Galerkin polynomial chaos method is intrusive, because the solver needs to be changed to solve a coupled set of the original deterministic systems of equations. We are developing a non-intrusive alternative, the probabilistic collocation method, which can reuse the deterministic solver as a black-box, but does not require the large number of samples as the Monte Carlo method.

Results

Efficiency of the coupling and uncertainty quantification method are demonstrated for a vertically spring-mounted circular cylinder in a uniform flow, see Fig. 2. After an initial start-up a periodic order staggered scheme and our third to fifth order IMEX schemes. For a given required accuracy in the structural displacement we find that the higher order IMEX schemes greatly reduce the computational time required, see Fig. 3. When the flow velocity is uncertain, the response of the cylinder is uncertain as well. In Fig. 4 the probability distribution for the frequency of the oscillation is shown for the polynomial chaos expansion by probabilistic collocation. This method requires just 3 samples (deterministic runs) to obtain an accurate result. As a comparison the Monte-Carlo approach would require at least 100 samples. By quantifying the probability distribution, the reliability of the computational prediction is increased. The potential of uncertainty quantification is demonstrated for a NACA 0012 airfoil in uniform flow. The Mach number of the incoming flow is uncertain. With just 5 samples, the polynomial chaos expansion by probabilistic collocation can provide the mean (Fig. 5) and variance (Fig. 6) in the pressure field around the airfoil. With these data the pressure distribution on the structure can be determined with additional information about the possible variations. This helps to identify the regions that are most sensitive to an uncertainty such as, in this particular case, the Mach number.

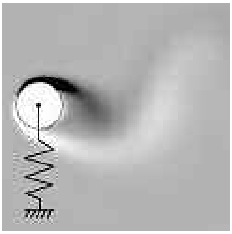


Figure 2 Vertically spring mounted circular cylinder.

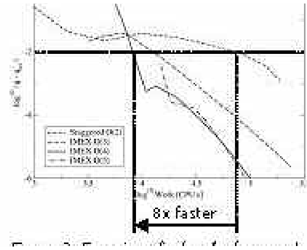


Figure 3 Error in cylinder displacement versus computing time.

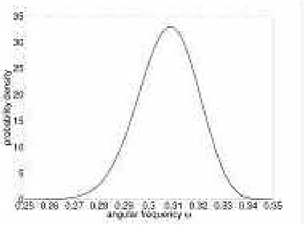


Figure 4 Probability distribution of the oscillation frequency.

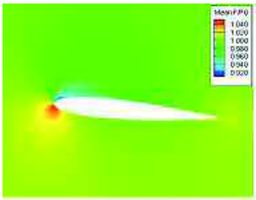


Figure 5 Mean pressure field.

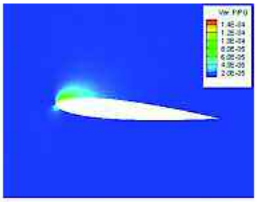


Figure 6 Variance in pressure field.

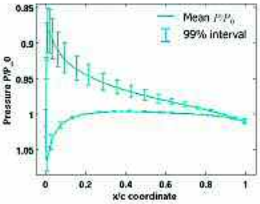


Figure 7 Pressure distribution around the airfoil.

GS Stelling

Harbour siltation in turbid waters

Harbour siltation in estuaries causes expensive dredging. An important example of this is the Port of Rotterdam (Fig. 1). This study concerns the exchange of fine sediments between a tidal river and a harbour basin. Presently, our knowledge of the complex estuarine flow and related sediment transport processes in harbour basins is insufficient. In particular the so-called "estuarine turbidity maximum" (ETM) plays an important role in harbour siltation (Fig. 3). An extensive measurement campaign has been carried out in and around the Botlek Harbour basin (Fig. 1). This campaign included boat surveys and the long-term deployment of a measuring rig (Fig. 2). The measurements gave a unique insight into the ETM of the Rotterdam Waterway and the large siltation rates in the Botlek Harbour. By the boat surveys mechanisms that affect harbour siltation were studied. This included: transport of sediment in a tidal river, exchange of sediment between a tidal river and a harbour basin, and trapping of sediment in a harbour. Such data sets are also invaluable for verifying and improving integrated three-dimensional hydrodynamic and mud transport models, such as Delft3D. Normally during a tidal cycle the salinity at the location of Botlek Harbour differs significantly from almost fresh to saline. On the flooding tide the tip of the salt wedge is advected along the Rotterdam Waterway towards the location of the mouth of Botlek Harbour. This causes density driven exchange flow between the Botlek Harbour and the Rotterdam Waterway (Fig. 4). If this coincides with the ETM, transport of sediment into the harbour occurs (Fig. 5). This process is found to be the dominant cause for sediment transport into the harbour (99.8%). This is further analysed by a decomposition of the time varying velocity, salinity and sediment concentration into dispersive transport components.

This analysis indicates that oscillatory shear dispersion (the covariance of the depth and tidally varying velocity and sediment concentration) makes the most important contribution

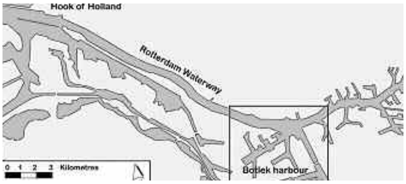


Figure 1 The Port of Rotterdam

Figure 2 The measuring rig

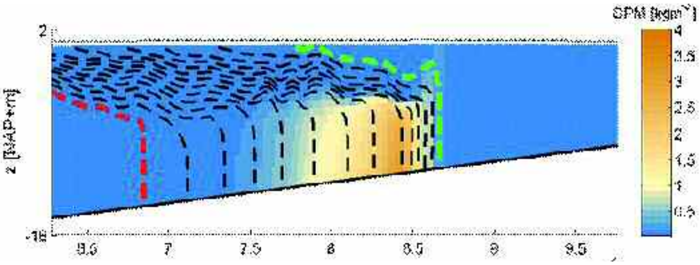


Figure 3 A schematic of an estuarine turbidity maximum (ETM) near the limit of saline water (numerical modelling). The color indicates sediment concentration and the dashed contour lines salinity.

to the total import of s into Botlek Harbour (97%). Hence the increase in near-bed sediment concentration is ascribed to tidal advection of saline water and ETM along the Rotterdam Waterway (Fig. 6a,b). Tidal advection controls the density difference and availability of sediment. Furthermore, it is found that the Botlek Harbour basin is an almost 100% sediment trap. This is ascribed to the combined role of salinity induced density currents and sediment stratification inducing a three layered stratified system. The lower layer consisting of sediment propagates into the basin, becoming thinner and losing its sediment, which is deposited further into the basin. Excursions of the salt water and the associated ETM are observed that are larger than expected from tidal excursions alone. These displacements are a response to changes of the hydrodynamic conditions at the estuary boundaries (diurnal inequality, spring-neap, deviations of the regulated discharge and meteo-tides).
These excursions are likely to affect siltation of upstream harbours, although these events occur occasionally. Therefore, the siltation process of basins along an estuary must be viewed over long time periods. The location of the ETM at the tip of the salt intrusion is a key factor in supplying sediment to Botlek Harbour (Fig. 6a,b). Consequently, the timing of the availability of sediment at the mouth of the harbour, its phase, needs to be considered in siltation studies. It is noted that harbour siltation studies have often been set-up to study siltation induced in the mouths of harbours on a tidal timescale; therefore the hydrodynamic history needs to be considered.

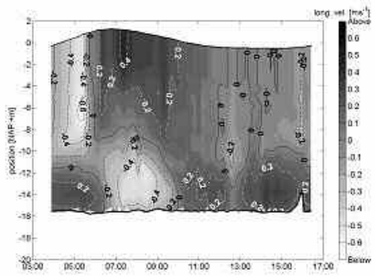


Figure 4 Flow pattern in Botlek harbour mouth (April 2005)

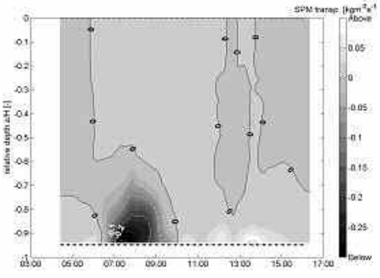


Figure 5 Exchange of sediment in Botlek harbour mouth (April 2005)

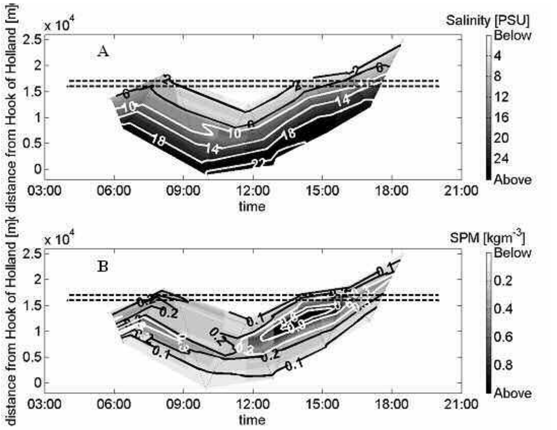


Figure 6 The along channel distribution of near-bed salinity (A) and sediment concentration (B) during the survey on April 2006.
The dashed lines respectively depict the Botlek Harbour and the junction Rotterdam Waterway-Old Meuse-New Meuse

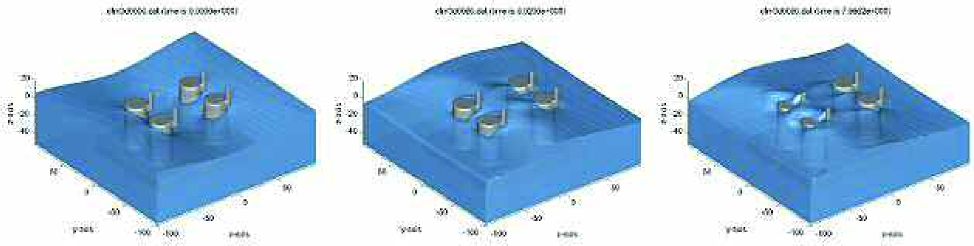
P Wellens
RHM Huijsmans
R Wemmenhove
AEP Veldman

Hydrodynamic interaction of steep waves and structures

The research in the following outline revolves around ComFlow, which is actively developed in the group of Arthur Veldman in Groningen. ComFlow is a 3D Volume Of Fluid Method that is based on the full, non-linear Navier-Stokes equations [1]. Developments in recent years have led to functionality, with which it is possible to introduce free surface waves to the numerical domain, to simulate the flow around a moving structure and to resolve the waves on the downstream side of the structure so that they do not reflect back into the domain. The extremities of the numerical domain, without special measures, act as a solid wall. When waves approach these walls, they will reflect back towards the structure. As it is our intention to simulate realistic events in environments that are as much like the sea as possible, the reflection of waves is undesirable. At the moment, the best way to prevent the reflection of waves in ComFlow is to use a pressure damping zone to reduce the wave height towards the domain edge.

As a result, there will not be a wave left when it reaches the wall. A pressure damping zone needs to be one to fives times as long as the 'significant' wave length present in the numerical domain. Then, ideally, with pressure damping zones on all sides of the domain, the domain will be four to twenty times larger than what is required for the wave impact event on the structure. It hardly seems efficient in terms of computer time and memory to spend so much of it on regions within the simulation that one is not interested in.

Another way to prevent to the reflection of waves, is to solve an extra set of equations near the boundaries of the domain. These equations, or 'boundary conditions', need to be such that waves can enter the domain with the desired accuracy, and, at the same time, leave the domain with as few reflections as possible. The first attempt at accurate boundary conditions was very simple from a numerical point of view: use the results in terms of fluid velocities from a simpler and more efficient simulation as a Dirichlet boundary condition for the velocity. Frequency domain 3D linear diffraction software is simple enough, on one side, to be fast and efficient and, on the other, complex enough to incorporate the desired wave-structure interaction. Theoretically, the potential function that is found with linear diffraction software, can only be used with small amplitude waves, but experiments have shown that the range of application is far greater than would have been allowed from a theoretical point of view. Still, there are limitations to linear diffraction. An important one being, that only the underwater part of the structure is modeled and that deck impact events



Several stages of the flow as a wave passes an offshore Gravity Based Structure.

and green water cannot be simulated. The procedure to simulate these extreme events, then, is as follows: firstly, determine the fluid velocities with linear diffraction at some distance from the structure, where it can be assumed that the most violent impact effects have dissipated and, secondly, use these velocities as Dirichlet boundary condition for the velocity in the numerical domain. These velocities account for waves entering the domain as well as for waves leaving the domain. Results of this approach are displayed in Figure 1.

The procedure with linear diffraction based boundary conditions could quickly be applied to various types of simulation [2]. Although the velocities at the boundary were not entirely correct, a great deal of wave energy was absorbed at the boundaries. For the genuinely extreme wave events, unfortunately, the velocities from linear diffraction are not good enough. Steep waves inside the numerical domain travel at a different phase velocity than predicted with linear diffraction. Consequently, the mismatch in terms of amplitude and phase between the waves inside the domain and the waves predicted with linear diffraction will result in reflections from the boundaries. At present another type of boundary condition is under development [3]. It is based on a set of differential equations that follow from the characteristics of the combined continuity and momentum equations. At the boundaries it is said that waves that travel along these characteristics do not interact. Then waves can enter the domain, while waves that leave the domain, travel through the boundaries with (ideally) no reflection. The differential equations are solved at every time step and the only unknown is the phase velocity of the waves leaving the domain. When a regular wave simulation is performed, the phase velocity is known and can be prescribed as an input parameter.

In irregular waves this is impossible, because all wave components travel at different phase velocities (dispersion). A procedure has been found to dynamically estimate the phase velocity from the solution. If some type of wave profile is assumed over the depth, and in these circumstances it is almost always a hyperbolic cosine, then the wave number, which is a measure for the wave length, can be eliminated from the equations by taking the second derivative of the velocities over the vertical. In this way, a flexible phase velocity independent boundary condition is formulated. At present the characteristic boundary condition is implemented in a testing environment for long crested waves (2D) based on the linearized momentum equations. Matters like the range of application and stability have to be sorted out, before they will be implemented in ComFlow.

Acknowledgements

The authors would like to thank Jo Pinkster, former professor of the Ship Hydromechanics department and Mart Borsboom, Delft Hydraulics, for their respective contributions to this research. This research is supported by the Dutch Technology Foundation STW, applied science division of NWO and the technology programme of the Ministry of Economic Affairs.

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R Kunnen
HJH Clercx
BJ Geurts
GJF van Heijst

Effects of rotation on convective turbulence

The motions in the atmosphere and the oceans are primarily governed by the interplay of two forces: buoyancy and rotation. These forces have opposing effects - buoyancy drives vertical motion while rotation tends to suppress this. Flows in the atmosphere and the oceans are of paramount importance for climate and weather modeling. Similar flow settings may also occur in industrial processes, such as crystal growth or in heat-exchange equipment.

A very convenient model for these flow problems is the rotating Rayleigh-Bénard flow: a horizontally confined layer of fluid is heated from below and cooled from above, and the whole system rotates around a vertical axis. We are studying this problem both numerically and experimentally using non-invasive laser-based techniques.

In the simulations a DNS approach is employed, resolving all dynamically relevant scales of motion. Simulations for cylindrical as well as horizontally unbounded periodic domains are performed. This allows for investigation of ‘atmosphere-like’ flows while still keeping the connection with experiments in the cylindrical geometry. Characteristic flow patterns such as the large-scale flow organization of confined convection [1], and their stability under rotation are studied. Focal points of the DNS are the convective heat flux (expressed by the Nusselt number) and the organization of the flow into vortical plumes [2]. A typical example is given in the figure, identifying strongly localized events of heat-transport in the vertical direction.

The emphasis of the experiments is on velocity measurements using stereoscopic particle image velocimetry (SPIV). A laser light sheet traversing the domain illuminates tracer particles seeded in the fluid (water). Two cameras, placed at off-axis angles, record the particle displacements. By using two cameras instead of one the out-of-plane velocity component is resolved in addition to the in-plane components measured in traditional (one-camera) PIV. Of interest is to monitor experimentally the influence of rotation on the large-scale flow organization in the low-rotation-rate regime, and its effects on velocity/turbulence statistics and vortical flow ordering at higher rotation rates [3].

Temperature isosurface plot obtained from DNS on a doubly periodic horizontal domain. The value used to identify isosurface is slightly above the average temperature. It depicts the thin thermal boundary layer near the heated bottom and the hot vortical plumes crossing the domain. A similar isosurface plot, but mirrored, can be made for a temperature just above the average value.

Future plans include the application of a three-dimensional particle tracking velocimetry technique in the experiment to investigate turbulent dispersion in convective flow, and performing local temperature measurements using laser induced fluorescence.

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AK Kuczaj
BJ Geurts

Numerical simulation of modulated turbulence

Many flow-problems in nature and technology are intimately connected to turbulent transport and small-scale mixing. Examples are the large-scale dispersion of polluting substances in the atmosphere, or the transport of thermal energy in heat-exchangers. The possibilities for improvement and control of these processes closely correspond to our understanding of turbulence.

Numerical simulation is an important tool in studies of turbulent flows, often aimed at a better understanding of the basic mechanisms, or at under-pinning approximate turbulence modeling. It offers unique possibilities of studying the interaction between various physical mechanisms. These interactions form the basis for so-called modulated turbulence, in which refinements of transport processes for specific applications can be investigated.

In recent years, scientists from the Multiscale Modeling and Simulation group in Twente investigated the 'competition' between turbulence and a multitude of physical mechanisms such as rotation, stratification, combustion, electro-magnetic agitation or due to the interaction with large numbers of embedded particles or bubbles. Here we highlight modulation of turbulence occurring in flow past complicated boundaries.

Significant modulation of turbulence arises as a result of the interaction with geometrically complex objects. An example is the flow above the uppermost branches of the trees in a forest, relevant for environmental dispersion, or the flow through a metal foam (Figure 1) used in modern compact heat-exchangers. In such flows the fluid is agitated simultaneously on a large number of length scales. This 'broadband' agitation generates strong deviations from 'standard' turbulence, whose dynamics follows Kolmogorov's energy-cascading.

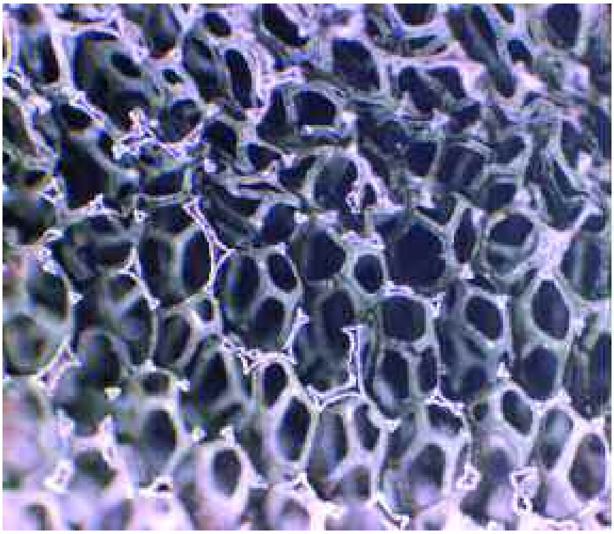

Figure 1 Porous nickel foam has a complex structure that can simultaneously disturb a large range of dynamically important scales.

The controlled alteration of the spectral composition of the flow in such ‘non-Kolmogorov’ turbulence has direct implications for the effectiveness of mixing and heat-transfer.

In numerical simulations, the agitation caused by the flow through and along geometrically complex areas is represented by broadband forcing. As a consequence, a characteristic direct energy transfer from the large to the small scales arises, in contrast to the more gradual cascading of energy observed in standard turbulence. A similar ‘spectral by-pass’ phenomenon has been observed in the flow over the canopy of a forest. The broadband forcing also affects mixing, measured in terms of the surface-area and wrinkling of iso-surfaces of scalar fields. An impression is shown in Figure 2. Both the time-scale on which maximum mixing is reached and the accumulated mixing can be modified by the broadband forcing. This may also have direct implications for combustion processes.

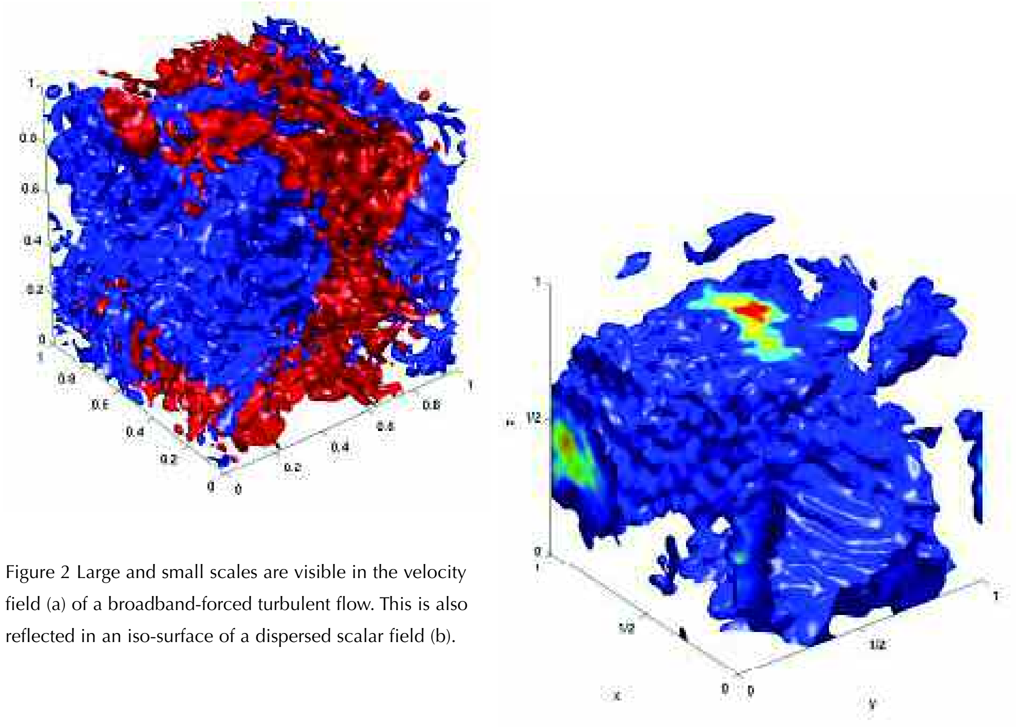

Figure 2 Large and small scales are visible in the velocity field (a) of a broadband-forced turbulent flow. This is also reflected in an iso-surface of a dispersed scalar field (b).

TH van den Berg
D Lohse

Less power consumption with the use of bubbles ?

One of the global issues the upcoming decades will be the energy problem we are all facing. Fossil energy is gradually depleted and more importantly, the use of fossil energy is causing major damage to our environment and climate of the earth. Any way we can reduce the energy usage will be greatly beneficial. One of the possible options to do so is drag reduction. As is long known, drag in a turbulent flow can be reduced by for instance micro-bubbles, or polymer addition; but what isn't known is how the principle actually works, or, do we reach with bubble drag reduction its full potential?

Applicability's

Every object moving through a gas or liquid does this with a least amount of effort if it moves at low velocities, when the flow around the object is laminar. Laminar flow is very energy efficient, but, regrettably, in real life this rarely is the case. More often, the flow around an object is turbulent, which leads to a strong increased energy consumption to travel from A to B. Our research focused on the drag experienced by objects, and to investigate how bubbles are capable to reduce the drag drastically in a turbulent flow; as in lab conditions reductions up to 80% were achieved.

Taylor-Couette setup

The setup we used to investigate the drag experienced by a wall in a turbulent flow is a so called Taylor-Couette setup. It consists of a liquid confined in the gap between two concentric cylinders of which either one of them is rotating. The setup we used was from the group of Prof. Dan Lathrop from the University of Maryland and had an inner cylinder diameter of 32cm, outer cylinder diameter of 44cm, giving a gap with of 6 cm. The total height was 70cm. We measured the torque on the inner cylinder together with the rotation rate of this cylinder. As this setup is a closed system, we can calculate the drag directly from the measured torque.

Microbubbles/Particles

In the bottom of the outer cylinder we injected microbubbles which led to a strong drag reduction of up to 30% as compared to the no-bubble case. To investigate whether the deformable or the buoyant properties of the bubbles are responsible for this effect we redid the experiments by adding glass hollow spheres (same volume fraction) to the liquid. These particles were buoyant, but not deformable. The particles didn't show any drag reduction leading to the obvious conclusion that the deformability is the main driving mechanism behind drag reduction.

Rough walls

Our Taylor-Couette setup was a perfect lab setup: nice smooth walls, highly controlled rotation rate, and temperature control. Real life isn't so nice, so we were interested why the lab results were not reproducible in real life, as the test ship Sheiun Maru from our Japanese colleagues was only able to achieve a power reduction of 5-10%. The big difference with ships in real life is that the hull of a ship is rarely as smooth as our setup was. To investigate the effect of the wall roughness we attached Perspex strips to the cylinders, which would make the laminar boundary layer turbulent. To our surprise, this led to a huge increase of power consumption; of up to 20 times!

Apparently; a lot of energy can already be saved by just keeping the ships hull clean and smooth. Applying bubbles, in the hope to reduce this huge drag a bit is useless: we noticed drag reduction for the rough walled case.

Conclusion

Regarding bubble drag reduction as some sort of holy grail for energy reduction is apparently not justified. To use bubbly drag reduction one needs to have a smooth wall, which is rarely the case. More importantly: a lot more energy reduction can be achieved if one makes sure the walls are smooth, and therefore have a laminar boundary layer. In real life this means no barnacles or other 'obstacles' attached to the ship. Therefore research should as well focus on coatings which could prevent fouling of ships.

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In practice a ship's hull fauls considerably, which causes a significant additional energy consumption

Photo : Australian Quarantine and Inspection Service

HWM Hoeijmakers

The structure of unsteady three-dimensional sheet cavitation

Cavitation describes the formation of vapor in a liquid in regions where the velocity is high and consequently the pressure is low, i.e. lower than the vapor pressure. Cavitation is an important phenomenon in hydraulic and hydrodynamic devices such as ship propellers, pumps and turbines, hydrofoils, valves, dams, spillways and bearings. Cavitation has detrimental effects such as erosion of the surface material, vibrations and noise radiation. Excessive cavitation deteriorates the efficiency of hydrodynamic devices.

In STW project TSF6170 “The Structure of 3D unsteady Sheet Cavitation” the Group Engineering Fluid Dynamics at the University of Twente cooperates with the Group Ship Hydromechanics and Propulsion at Delft University of Technology. In the project the most important form of cavitation in industrial applications is considered: Sheet Cavitation. In these applications mostly unsteady inflow occurs which is known to greatly affect sheet cavitation which becomes time-dependent.

The overall objective of the project is to determine a model for the description of the dynamics of 3D sheet cavitation on hydrofoils. The dynamics of sheet cavitation is important because it determines both the radiated pressure field and the erosive nature of the clouds of vapor shed from a sheet cavity. Furthermore, the sheet cavitation phenomenon is three dimensional in character. Ultimately, a better understanding of the interaction between unsteady inflow and cavitation will create the possibility of active cavitation control.

In the project at the University of Twente an unstructered-grid CFD method is developed for predicting the characteristics of unsteady cavitation in 3D. This method includes models for the transport of the vapor fraction in the cavitating flow regions. At Delft University of Technology an experimental investigation is carried out in their cavitation tunnel, with the ambition to measure simultaneously forces, surface pressures and flow field velocity distributions (PIV). This will result in data on the unsteady shape and volume of the cavity and on the structure of the flow in the closure region of the cavity.

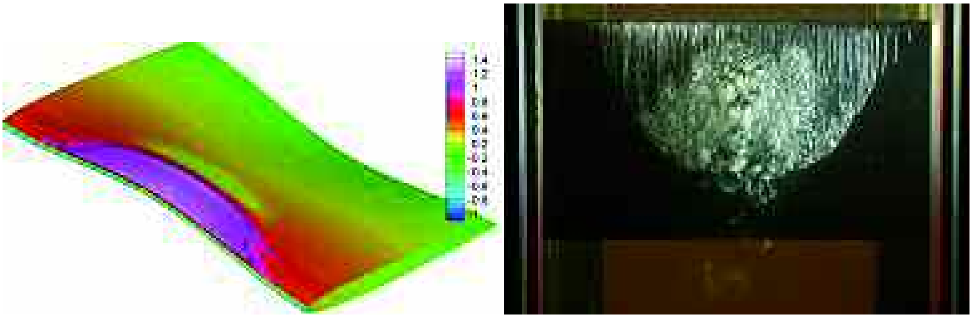


Figure 1 Sheet cavitation on a hydrofoil. Left: Twist-11 hydrofoil designed to feature a mid-span triangular region with cavitating flow. Right: Sheet cavitation as observed in the Delft Cavitation Tunnel

This data is used for the validation of the computational results and the underlying physical models of unsteady sheet cavitation.

Employing the computational method for cavitating flow employing a barotropic flow model, developed at University Twente, hydrofoils have been designed for testing in the Delft Cavitation Tunnel. The design is such that cavitation occurs in the mid-span region of the hydrofoil only, this to avoid the interaction of the cavity with the tunnel wall boundary layers as well as to create a cavitating flow that is representative for the flow occurring on a ship propeller.

User Committee: Marin, Wärtsila, Flowserve, IHC, HRP, van Voorden, RNN, Shell, Twister BV.

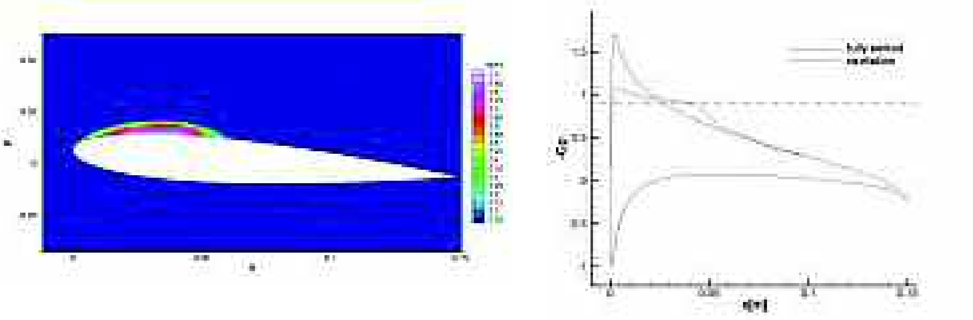


Figure 2 Results of numerical flow simulations of cavitating flow. Left: vapor void fraction. Right: surface pressure distribution along mid-span section for case with and case without cavitation

K Kiger

Multiphase flow measurement : microscale measurement of local wall heat transfer in nucleate boiling

This work focuses on the development and testing of a novel device for studying microscale heat transport dynamics of the heterogeneous nucleate boiling process. This study provides unique experimental data using simultaneous measurement of the temperature and heat flux variations at the surface/bubble interface. The results enable us to address some of the outstanding issues regarding the mechanism of heat transfer in nucleate boiling.

Over the past 50 years, scientists have developed several competing mechanistic models to predict the boiling heat transfer coefficient. Although the models are intended to predict the macroscale heat transfer, their fundamental assumptions lie on complex microscale sub-processes that remain to be experimentally verified.
Two outstanding issues regarding these sub-processes are: 1) the contribution of different mechanisms of heat transfer in bubble growth and 2) vapor/liquid/surface interactions influencing the bubble's role the in heat transfer process. Previous results with a monolithic silicon membrane indicated that a very thin, low-conductivity layer with imbedded temperature sensors was needed in order to obtain high-resolution temperature and heat flux measurement at the bubble/surface interface. The device consists of an array of temperature sensors imbedded within a 12 m thick multilayer Benzocyclobutene (BCB) structure on a 60 µm thick 3.6˘3.6 mm2 square silicon membrane (see Figure 1). BCB was selected among several other low-conductivity polymers such as SU-8, polyimide, and PDMS, because of its microfabrication properties and its stability at high temperatures.

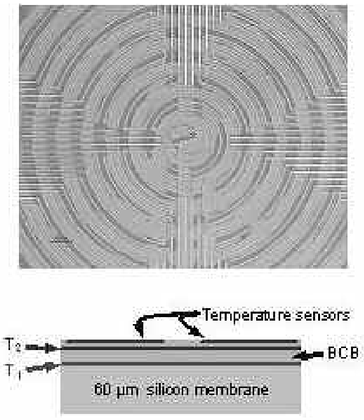


Figure 1 Image of BCB sensor array and schematic cross section of embedded within sensors within the BCB layer

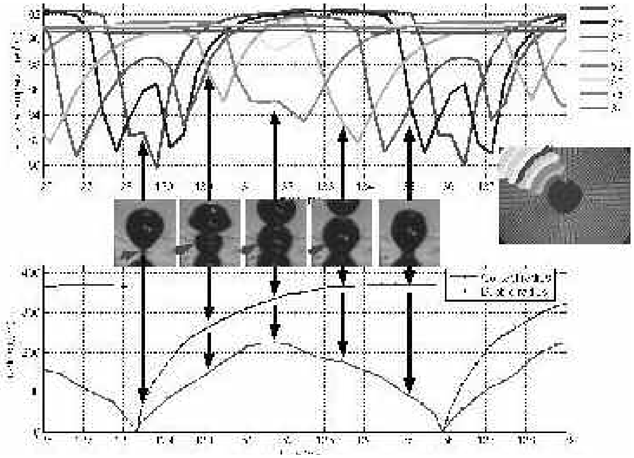


Figure 2 Temperature, bubble diameter and contact area history of a single ebullition event.

The thickness of the BCB layers and the sensor geometry were determined in a design trade off between several factors, including: temperature and heat flux measurement accuracy, sensors response time, and interference with the nucleation process. The silicon membrane is heated by a thin film heater microfabricated on its backside.

Single bubbles are generated from cylindrical cavities fabricated at the center of the array. The sensors can be sampled up to a frequency of 10 kHz, while the growth stages of the bubble can be imaged up to 8000 fps using a CCD camera. Figure 2 shows sample results obtained for a single bubbling event. As can be seen, temperatures of sensors 1 to 5 successively drop immediately after the bubble growth due to the microlayer evaporation underneath the bubble. Following the bubble growth, a second wave of heat removal occurs as the contact line recedes during bubble departure. This is marked on the temperature map by successive wall temperature drops at sensors 5 to 1. Contrary to what has been commonly assumed in classical boiling models, transient conduction to the liquid occurs before the bubble departure, not after bubble departure.

Temperature of the sensors immediately outside the bubble remains invariant, suggesting that the bubble's direct influence on the thermal field is limited to its contact area. Results for these particular conditions show that the microlayer contributes only 12.7% to the bubble growth, contrary to Cooper's model that assumes a dominant contribution for microlayer. It is speculated that this difference is partly due to no waiting time between bubbles, leading to the absence of an interially dominated growth period that would enhance the microlayer's contribution. Finally, it was also determined that all mechanisms of heat transfer have a considerable contribution to the total heat removal from the wall, with specific contributions of 12.8% for microlayer, 23.8% for transient conduction during rewetting, and 63.4% for convection outside the contact area.

S Kenjeres

Tackling turbulence subjected to thermal buoyancy and Lorentz force

Turbulent flows subjected to thermal buoyancy and/or Lorentz force play an important role in many physical phenomena in nature and technology. These phenomena include the origin of planetary magnetic fields, solar storms, atmospheric and environmental flows, processes in metallurgy, reactor-safety, electronic cooling, semiconductor crystal growth, electrochemistry, biotechnology, etc. The immense variety of scales at which these phenomena occur (ranging from size of galaxies and stars to semiconductors crystals and magnetic drug carriers) and intensity of the interactions between fluid flow, turbulence and electromagnetic fields (one- or two-way coupling) make this subject particularly challenging. We addressed mathematical models and numerical simulations based on the continuum unifying principles originating from Navier-Stokes and Maxwell's equations. Special attention is devoted to the originally developed subscale/subgrid turbulence models as well as to the recently proposed 'seamless' hybrid RANS/LES approach. It is shown that proper turbulence subscale/subgrid modelling of the body-force effects must include additional source/sink, redistributive and wall-reflection terms. Only by taking into account all these mechanisms, proper levels of turbulence anisotropy can be predicted. The performances of these newly developed models are tested and validated on the generic/benchmark cases including sole or combined effects of thermal buoyancy/electromagnetic fields (Lorentz force). These generic situations included: the side- and bottom-heated enclosures (with or without magnetic field of different orientations); the unsteady turbulent penetrative convection of an unstable mixed layer; the MHD channel flow subjected to transverse or longitudinal infinite magnetic fields; the MHD duct flow subjected to the transverse finite - length magnetic field - all over a range of working parameters, i.e. Rayleigh, Reynolds, Hartmann and Richardson numbers.

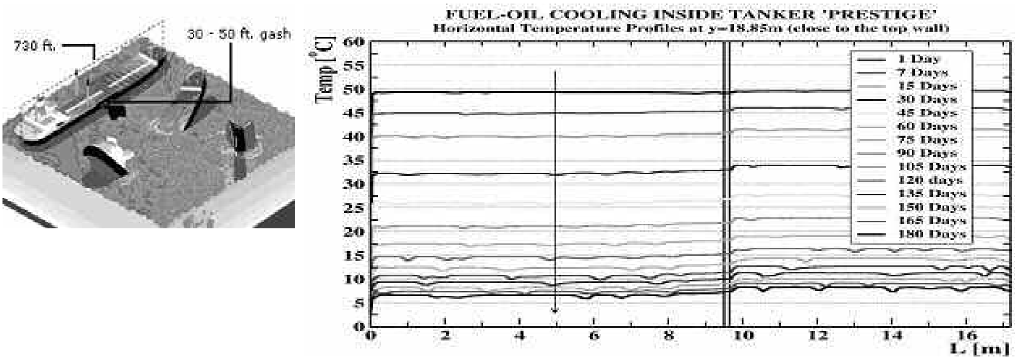


Figure 1 Time dependence of the horizontal temperature profiles close to the top wall of the tanker "Prestige" wreckage at depth of 3500m below see level: Ra~10^{13}, time evolution of 6 Months;

For all considered situations, good agreement with available direct numerical simulation (DNS) and experimental data is obtained. Finally, these models are applied for simulations of the real-scale problems characterized by complex geometry and dynamically defined initial and boundary conditions. Following cases are presented: (I) Effects of stratification and terrain orography on diurnal dynamics of pollutant spreading over urban valleys: (XIV Winter Olympic Games 1984 site, area of Sarajevo), Re~10^{8}, Ra~10^{17}; (II) Numerical simulations of fuel-oil cooling inside the tanker "PRESTIGE", Ra~10^{13}, time evolution over 6 months; (III) Two-way fluid flow/electromagnetic interaction (magnetic dynamo): simulations of laboratory studies based on the Riga-dynamo facilities, Re=5x10^{6}, Re_m=20.

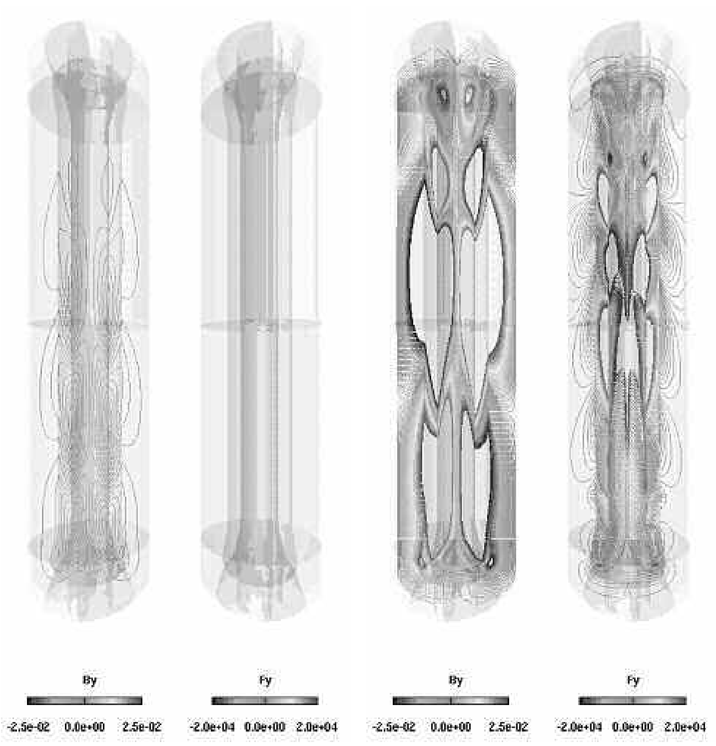


Figure 2 Time evolution of the growth of the axial components of magnetic field and Lorentz force in the saturation regime for realistic Riga-dynamo experiment conditions (two-way fluid flow and turbulence/electromagnetic fields interactions in transient mode), Re_m=20, Re=5x10^{6}

HJH Clercx

Table-top geophysical turbulence

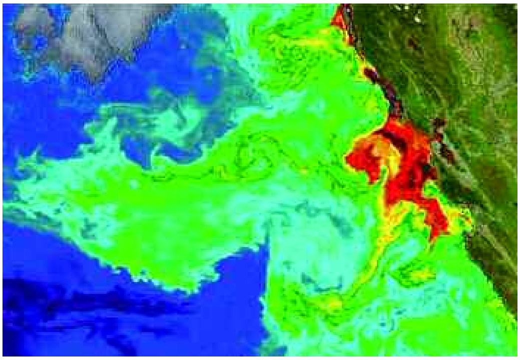
Dispersion of micro-organisms, like plankton and fish larvae, nutrients, (re)suspended (often chemically contaminated) particulate matter, and pollutants in oceans, estuaries and stratified lakes is governed by turbulent geophysical flows. In geophysical flows, the presence of the Coriolis force due to the rotation of the Earth and buoyancy force, as a result of temperature or salt stratification of the fluid, modifies the turbulence properties and the dispersion process of (biologically) active tracers.

Prediction of phytoplankton (algae capable of photosynthesis) blooms, i.e. events of rapid production and accumulation of phytoplankton biomass, and their dispersion is of uttermost importance for economical activities (the fisheries industries, tourism), public health issues and ecology.

The role of turbulent dispersion of micro-organisms on marine-population dynamics is classically investigated with a top-down approach where eddy diffusivity models have usually been used as the simplest parameterisation of dispersion. Such models fail to predict phytoplankton blooms and dispersion as illustrated in the satellite picture. In order to improve large-scale computer models for prognostic purposes, a bottom-up approach to model turbulent dispersion is necessary that includes the strong anisotropic character of geophysical turbulence and the particle-flow interaction.

In the Fluid Dynamics Laboratory at TU/e dispersion in geophysical turbulence is studied in laboratory experiments and with numerical simulations just to provide some of the building blocks necessary for these large-scale computer models.

The laboratory experiments are aimed at understanding the dynamics and Lagrangian properties of rotating turbulence by SPIV and 3D-PTV measurements. For these experiments a new rotating table facility has been build and a high frequency four-camera particle tracking system has been designed in order to resolve sub-Kolmogorov length and time scales for acquiring accurate Lagrangian statistics. Additionally, the effect of rotation on Rayleigh-Bénard convection is investigated by SPIV measurements, with emphasis on flow-structuring, heat transport and two-dimensionalisation of the flow.



Plankton bloom formation off the Californian coast due to upwelling of nutrient-rich cold waters. Rivers and urban areas provide additional nutrients.

Together with the laboratory experiments direct numerical simulations are carried out to understand the dispersion of (inertial) particles in forced stratified turbulence, clustering and aggregation processes in small-scale isotropic and in stratified turbulence, and the flow structuring in rotating Rayleigh-Bénard convection.

ATAM de Waele

Cooling with oscillating gases

The Low-Temperature group of the Eindhoven University of Technology is active in the fields of pulse-tube refrigeration and thermoacoustics. These fields have obtained momentum in the nineteen eighties when revolutionary new ideas surfaced to improve and simplify cooler technologies. Both use oscillating gas flows. In pulse-tube refrigerators the frequencies are in the 1 to 50 Hz range; in thermoacoustic systems in the audio range (50 to 500 Hz). This work is done in close collaboration with industry and with support from STW.

Pulse-tube refrigerators produce cooling without moving parts in the low-temperature regions. This is in contrast to Stirling and GM coolers who have a low-temperature piston or displacer. The most important advantages of having no moving part at low temperatures are high reliability and the absence of mechanical and magnetic interference. The working fluid normally is 4He at pressures of about 7 to 30 bar. The temperature range is 80 to 2.2 K. Using 3He we reached temperatures as low as 1.73 K with the system shown in Fig.1. The temperature range can be extended to temperatures as low as 0.7 K by using superfluid vortex coolers. The efforts in our group are concentrated on the basic understanding of the cooling principle and the exploration of various alternative cooling arrangements.

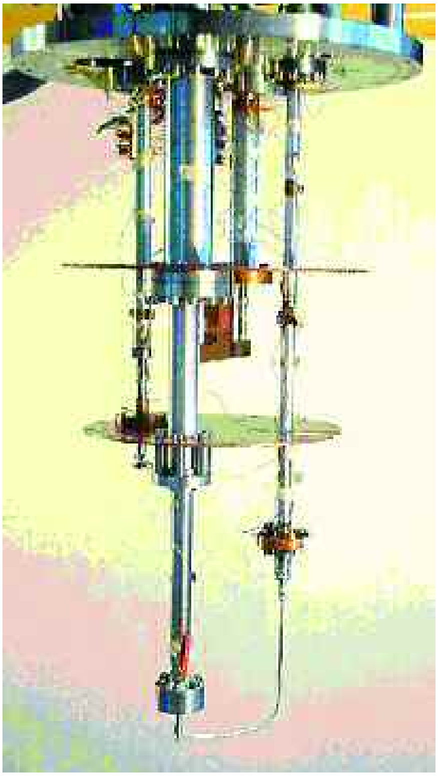


Figure 1 Low-temperature part of a three stage pulse-tube refrigerator. The component in the foreground is the so-called regenerator which contains a large thermal mass in order to store during one part of the cycle and release heat during the other part of the cycle. In the background are three tubes, one for each stage. The two copper plates are used to support heat shields. In our system the lowest temperature of 1.73 K is reached at the lowest point of the regenerator.

We want to increase the coefficient of performance, increase of the operating frequencies, and miniaturize the coolers.

Thermoacoustics, transport of heat with sound, is fundamentally interesting. It may be attractive since certain types of these systems (coolers and engines) have no moving parts at all, not even a compressor at room temperature. There are two types: standing wave and traveling wave machines. Both are under study. Noble-gas mixtures are used to relax the relationship between the dissipation through thermal conduction and viscous effects. Recently we studied thermoacoustic energy conversion starting from a strong steady gas flow, passing a resonating branch in the flow channel, generating sound waves of more than 180 dB (one of the loudest sounds on earth) which in turn produced a temperature gradient, and, finally, produced electrical power via the thermo-electrical effect. Thus energy conversion is realized with the utmost reliability. Presently we study high-amplitude sound waves in interaction with solid walls experimentally (using PIV on the millimeter scale and frequencies of 100 Hz, see Fig. 2) and numerically.

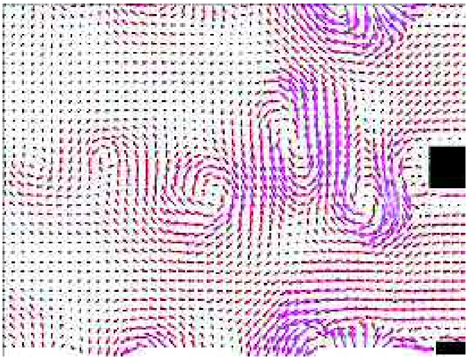


Figure 2 Measured flow pattern around the end sections of plates in an oscillating flow stream.

K Verbiezen
B Bougie
NJ Dam
JJ ter Meulen

Laser diagnostics for quantitative measurements of NO and soot in a transparent heavy duty diesel engine

The emission of NOx and particulates by diesel engines creates immense environmental problems. Reduction of these emissions forms a major challenge for scientists and engineers, and requires a fundamental understanding of the combustion process inside the engine. Hereto the development and application of non-intrusive imaging diagnostics is essential. Not only direct insight is delivered in the combustion process but also data are obtained which are crucial to validate numerical models. The engine forms, however, an extremely hostile environment to perform measurements. In particular the produced soot causes large problems by attenuating both the laser beam and the induced signal by orders of magnitude.

We nevertheless succeeded in developing laser based diagnostic techniques for the quantitative measurement of both nitric oxide and soot particles in an optically accessible heavy truck diesel engine running on low-sulphur city diesel fuel.[1,2] The NO molecules were detected by laser-induced fluorescence (LIF) and the soot particles by laser-induced incandescence (LII), both as a function of time during the combustion stroke. Measurements were performed at different probe locations.

Processing of the observed NO fluorescence signals included a detailed correction, based on additional measurements, for the effect of laser beam and fluorescence attenuation, and for the pressure and temperature dependence of the fluorescence efficiency, based on numerical modelling. These corrections were largest early in the stroke, when quenching rates are high and UV transmission is low. Together, they vary over more than three orders of magnitude during the combustion stroke. Fully quantitative results were realized by an overall calibration using independent concentration measurements in the exhaust gas. The data provide evidence of NO formation during both the premixed and mixing-controlled combustion phases.

In the laser-induced incandescence detection the soot particles are heated up to 4000 K by the pulse of a Nd:YAG laser. The ensuing emitted radiation is measured immediately after the laser pulse as a function of time. From the spectral emission of this LII-signal the temperature of the soot particles after the laser pulse was obtained. The decay rate of the LII-signal was modeled using the model proposed by Kock & Roth[3]. This model incorporates the Knudsen number effects to account for the transition regime during the evaporative and conductive cooling processes. By fitting the measured decay rates, the particle size distribution during the complete cycle could be derived. Assuming a log-normal particle size distribution, an increase of the mean primary particle size was seen during the first stages of the combustion cycle, followed by a decrease later on during the combustion process.

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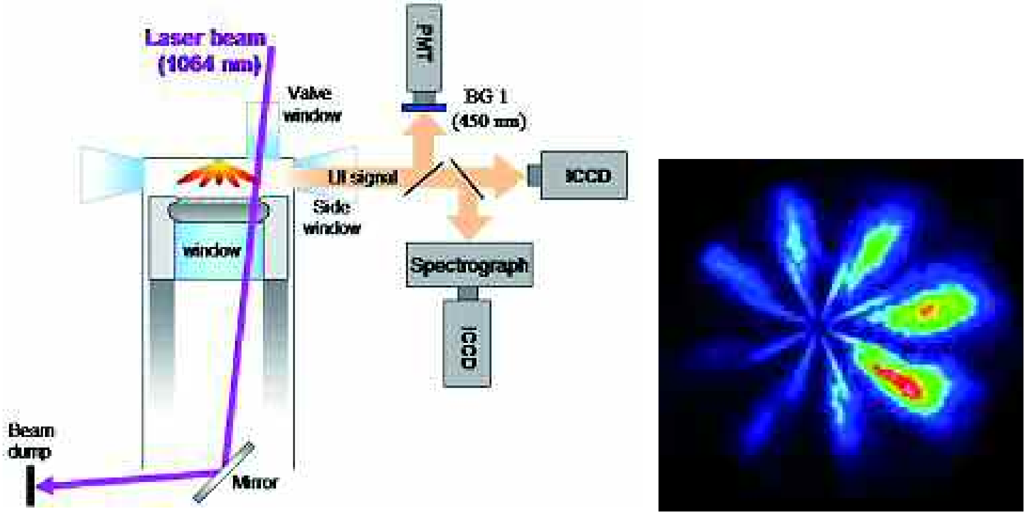
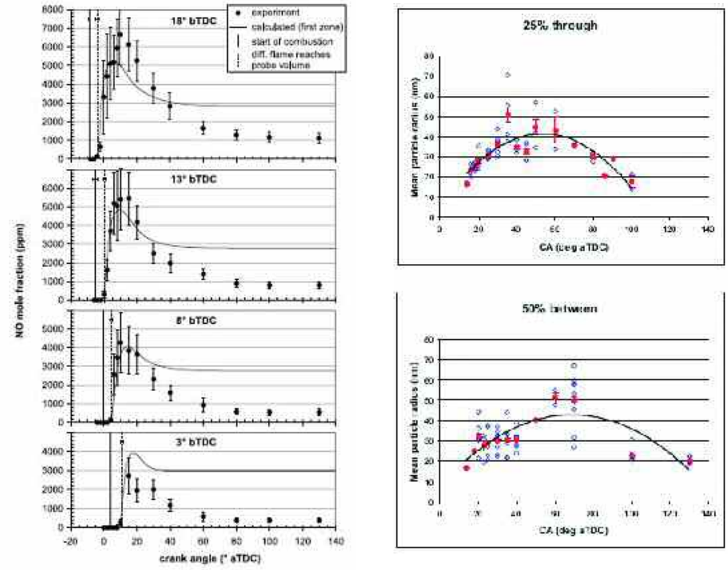


Figure 1 and 2 The optically accessible cylinder of the heavy-duty diesel engine in Nijmegen. The cylinder has been elongated by 40 cm to provide the optical access. One of the four valves has been replaced by a quartz window. Three other rectangular quartz windows are mounted in the cylinder wall. The piston consists of an elongation bolted on the original piston and capped by a flat-bowl crown with a quartz bottom part. Light emitted through the piston window can be observed through slots in the side of the piston elongation and in the side of the cylinder wall via a 45° mirror that can be shifted into the engine during operation. The setup shown is for LII measurements, but the same setup is used for LIF detection. In the lower part a snapshot is shown of the combusting fuel sprays as recorded by a high-speed camera. Clearly visible are the 8 fuel sprays reflecting the light emitted by the glowing soot clouds.



Left hand side: Local NO mole fractions as a function of crank angle and injection timing. The error bars contain cyclic variations as well as the uncertainties in all processing steps. The solid curves are calculated mole fractions. Right hand side: Mean particle size as a function of crank angle for two different probe locations and engine loads. The open symbols indicate the individual measurements, the closed symbols indicate average values. The solid curves are trend lines to guide the eye.

F Scarano
C Poelma
J Westerweel

Three-dimensional velocity by tomographic PIV

Tomographic PIV

Despite the fact that recently Particle Image Velocimetry has recently celebrated its 20th anniversary and that PIV is nowadays a standard measurement technique employed in most fluid-mechanics laboratories, new exciting developments are possible. In particular, the possibility of simultaneously measure the velocity field within a given volume of the flow domain is of paramount importance since it allows to visualize the three-dimensional pattern of coherent structures in turbulent flows. Three-dimensional versions of PIV have been proposed, based either on holography or on the fast can of the light sheet through the measurement volume. A novel approach, Tomographic PIV[1], has been recently developed at TU Delft in a cooperation started in early 2004 with LaVision GmbH. Tomo-PIV is based on a relatively simple working principle: the light scattered by the tracers illuminated over a relatively thick light sheet is recorded from different viewing directions. A mapping function is obtained with a calibration procedure similar to that of the stereoscopic PIV technique. The 3D light intensity field is digitally reconstructed starting from the original images applying a tomographic reconstruction algorithm for sparse emitters. The multiplicative algebraic reconstruction technique (MART) is able to reconstruct particle image intensity field with a relatively high spatial resolution and information density (typically 50,000 particles/Mpixel). The technique so configured can be applied to the study of turbulent flows using the equipment available in laboratories for stereo PIV, provided at least three or four cameras are simultaneously used. Several applications to turbulent flows have been performed in the last two years at TU Delft as well as by other universities and research institutes.

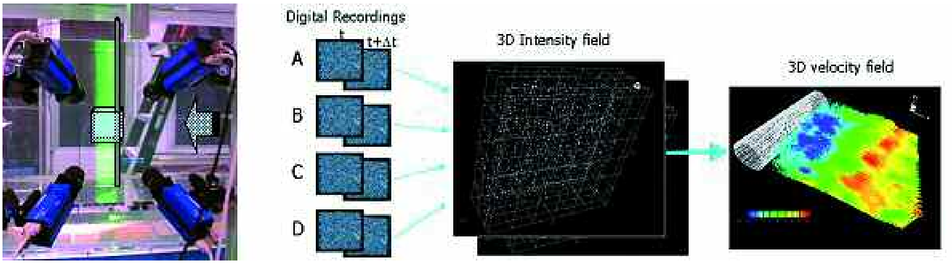


Figure 1 From left to right: illumination and imaging, digital recordings, 3D intensity field and 3D velocity vector field.

Vortex dynamics in cylinder wakes

In a cooperative effort between the Aerodynamics group (Aerospace Engineering) and the Aero-Hydrodynamics Laboratories (3mE) a three-dimensional time-resolved experimental study by means of Tomographic PIV was performed of the wake behind a circular cylinder covering the transitional and turbulent regime[2] spanning a Reynolds number range from 180 to 5540. Experiments were performed in the water channel of Aero & Hydrodynamics Laboratories to achieve temporal resolution with a low-repetition rate tomographic PIV system (4 CCD cameras of 2k˘2k pixels).

The 3D approach additionally allows a direct access to the instantaneous topology for the verification of conceptual models for the vortex wake structure in the transitional and turbulent regime. At Re = 180 the repetition rate of the system allows sampling at a rate of 35 recordings per shedding cycle. The unsteady flow behaviour is characterized by the alternate shedding of vortices from the upper and lower side of the cylinder centreline.

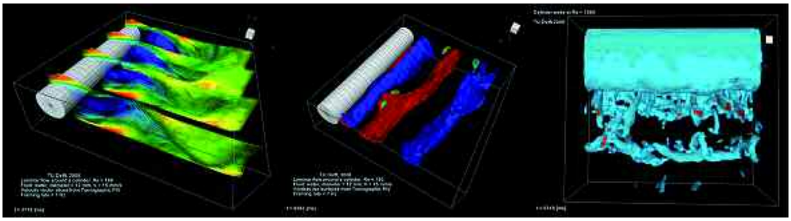


Figure 2 Velocity vector field by slices at Re = 180 (left); Vorticity iso-surfaces at Re = 180 (centre); vorticity magnitude iso-surfaces at Re = 1080 (right)

At Re = 1080, the separated shear layer is elongated and close to transition, with the roll-up process occurring at the maximum downstream position (approximately two diameters from the cylinder axis). The three-dimensional structure of the wake is here still dominated by the counter-rotating pairs (Mode-B). However these structures now have a smaller diameter and appear at a higher spatial frequency with respect to the cases at lower Reynolds number. Moreover, the secondary rollers undergo mutual interaction such as pairing of co-rotating vortices, which distort locally the Kármán roller. After shedding of the main roller, the organization of these structures becomes less apparent, leading to the formation of the Kármán roller embedded in a net of vortex filaments trapped and wrapped around the main structure. This yields a disordered patch of fluctuating vorticity, nevertheless with considerable span-wise coherence. These experiments show that Tomo-PIV offers nowadays a full dimensional visualization of three-dimensional and turbulent flows aiding the comprehension of processes dominated by complex vortex dynamics. Further applications of Tomo-PIV have involved high-Reynolds turbulent boundary layers and their interaction with shock waves in supersonic flows3. The feasibility of Tomo-PIV as a fully time-resolved technique using kilohertz repetition rate PIV hardware has just been verified and its extensive application is yet to come.

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R Garcia-Rojo
S Luding
J Javier Brey

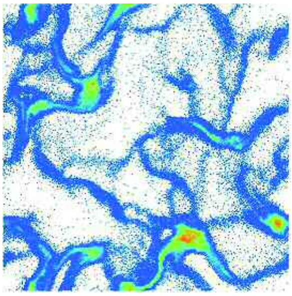
Transport coefficients for dense hard-disk systems

Abstract

A study of the transport coefficients of a system of elastic hard disks, based on the use of Helfand-Einstein expressions is reported. The pressure, the viscosity, and the heat conductivity are examined for different density and system-size. While most transport coefficients agree with Enskog theory below the disorder-order transition, a striking power law divergence of the viscosity with density is obtained at this density. The other transport coefficients show a drop in that density regime, relative to the Enskog theoretical prediction. The deviations are related to shear band instabilities and the contept of dilatancy.

Introduction

Transport coefficients characterize the different mechanisms in non-equilibrium fluid states. At the macroscopic level, they are introduced by phenomenological equations, like the Navier-Stokes equations for a simple fluid, which predict the time evolution of mass, momentum and energy [1]. Each transport coefficient is related to the propagation of one (or more) of these microscopic quantities, bridging therefore the hydrodynamic and the microscopic scale. In the case of low density gases, the macroscopic equations have been justified, their range of validity has been determined, and explicit expressions for the transport coefficients have been obtained using the Boltzmann kinetic equation as starting point [2-4]. At higher but moderate densities, the Enskog equation has also proved to give a quite accurate description of a gas of hard spheres or disks.



In the last years, there has been a revived interest in transport processes in systems composed by hard particles motivated by the study of granular media in general, and granular gases as a special case [5,6,7]. If dissipation is added to the hard disk system, one has a granular gas [3] and one typically observes density inhomogeneities, as displayed in the figure to the left: Low density (white) co-exists with extremely high densities. The color-code indicates the collision rate, being higher in the denser regions (red). The challenge of current research is to predict the transport coefficients for such systems, not only for low densities but also for the highest densities possible.

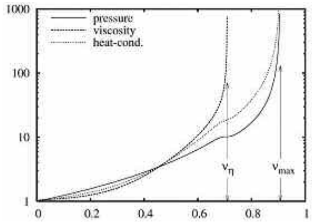
A remarkable and fundamental development in the statistical mechanics theory of transport processes was the derivation of expressions for the transport coefficients based on equilibrium time-correlation functions. These are the so-called Green-Kubo formulas, and they involve different microscopic fluxes [8]. These expressions are of general validity and have been extensively used for the analysis and modelling of transport in denser systems. In particular, they are applied to compute transport coefficients from molecular dynamics simulations. Alternative formal expressions for the transport coefficients are provided by the Einstein-Helfand formulas [8], the simplest of which being Einstein's formula for the self-diffusion coefficient in terms of the second moment of the displacements.

The Einstein-Helfand expressions for the other transport coefficients involve moments of corresponding dynamical variables, which are the time integrals of the microscopic fluxes appearing in the Green-Kubo relations. Considerations about long-time tails in the correlation functions have only recently been considered by Kumaran [9], who proposed a cut-off wavelenght, above which the correlation functions become integrable.

Results

Pressure and the heat conductivity drop at υ_c=0.70 due to the increased mean free path in an ordered configuration and, eventually, diverge at υ_{max}=0.9069. Most interestingly, the shear viscosity diverges at much smaller density, close to the crystallization density, at $\upsilon_\eta = 0.71$. For higher densities, in the solid-like regime for $\upsilon > \upsilon_\eta$, shear seems impossible. This power-law divergence of viscosity at $\upsilon_\eta \sim \upsilon_c$, with values above Enskog theory already becoming visible at intermediate densities, $\upsilon > 0.5$, renders viscosity different from all other transport properties studied. Note however, that the results presented here were obtained from "non-sheared" systems.

The divergence of viscosity can in fact be understood as the reason for shear-band formation [6,7]: A sheared system at high densities typically splits into sheared bands (with lower density) and compressed, denser, ordered bands. From a different point of view, our observations are also consistent with the concept of dilatancy: A dense packing, with $\upsilon > \upsilon_\eta$, can only be sheared by first experiencing dilatancy so that density drops.



Schematic plot of the non-dimensionalized transport coefficients pressure, viscosity, and heat conductivity, in an elastic hard disk system, as function of density (area fractionl). For small densities <<1, all coefficients accord with the predictions from kinetic theory for hard sphere gases. For higher densities around c=0.70, the system of disks shows a transition from a disordered to an ordered state.

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Correspondence for reproduction:
JM Burgers Centre
attn. Mrs. I Hoekstein
Mekelweg 2
2628 CD Delft
The Netherlands
t 015 278 3216
f 015 278 2979
e jmburgerscentrum@tudelft.nl
i www.jmburgerscentrum.org

Burgers Program for Fluid Dynamics (University of Maryland, USA)
i www.enme.umd.edu/burgers/

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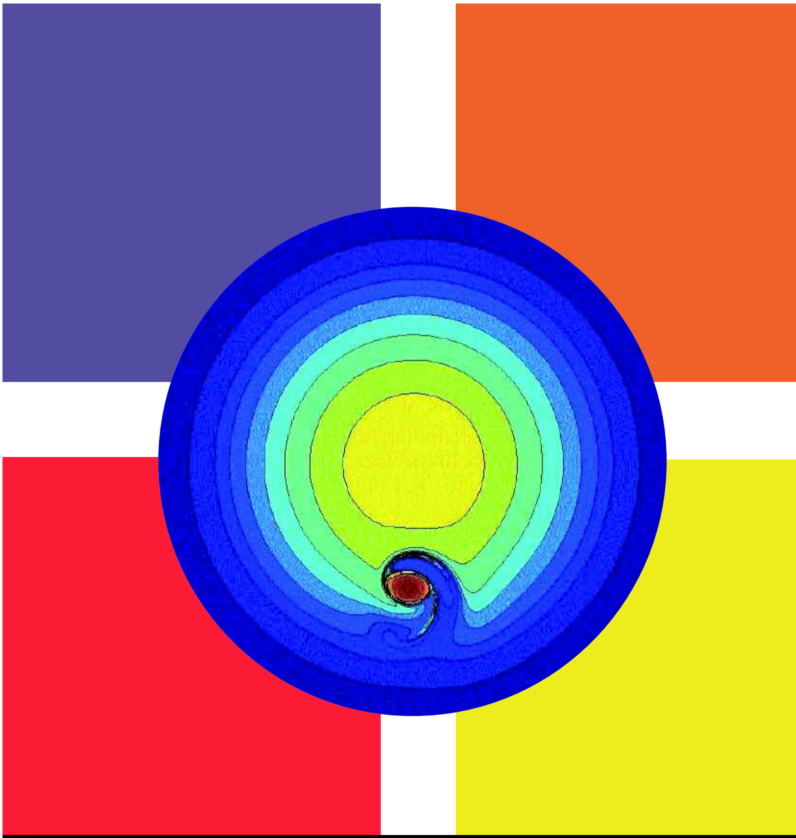

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