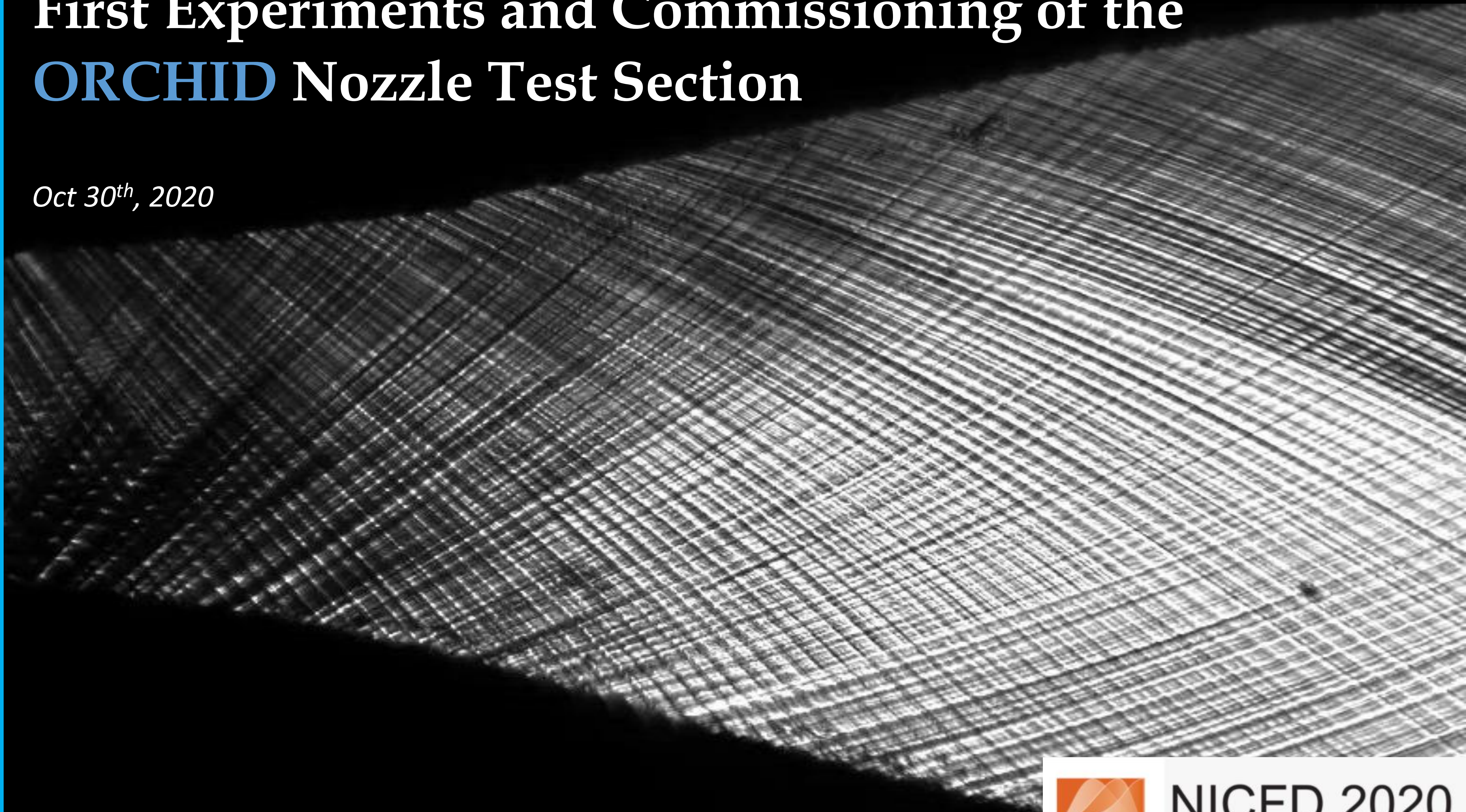
First Experiments and Commissioning of the ORCHID Nozzle Test Section

Oct 30th, 2020



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NICFD 2020
for Propulsion & Power

RESEARCH QUESTION

HOW ACCURATELY can we predict supersonic flows of dense organic vapors and supercritical fluids using complex thermodynamic models implemented in **CFD codes** such as **SU2?**

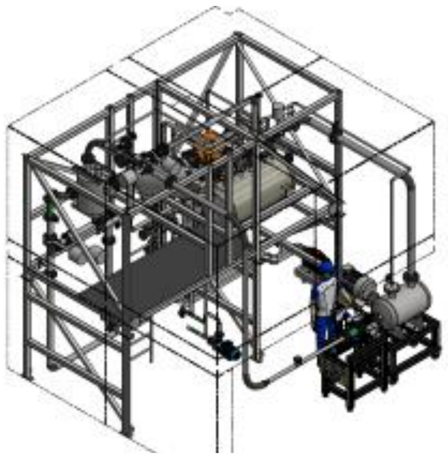
OBJECTIVES:

- **Commission the ORCHID nozzle TS**
- **Obtain the first experimental data for an initial validation assessment of SU2**

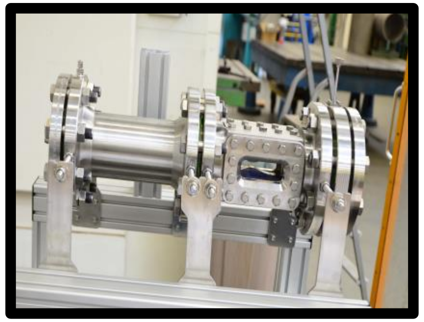
DELIVERABLES:

How The Research Question Could Be Answered

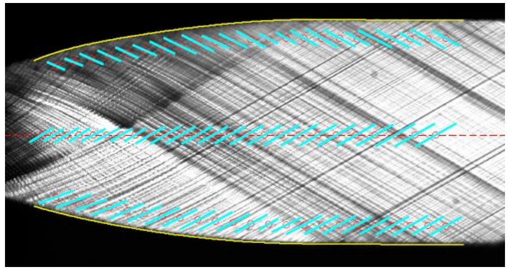
1) Design and realization of a nozzle TS



2) Set up the schlieren measurement chain



3) Development of a post processing tool for Mach number extraction from Schlieren data



General Overview

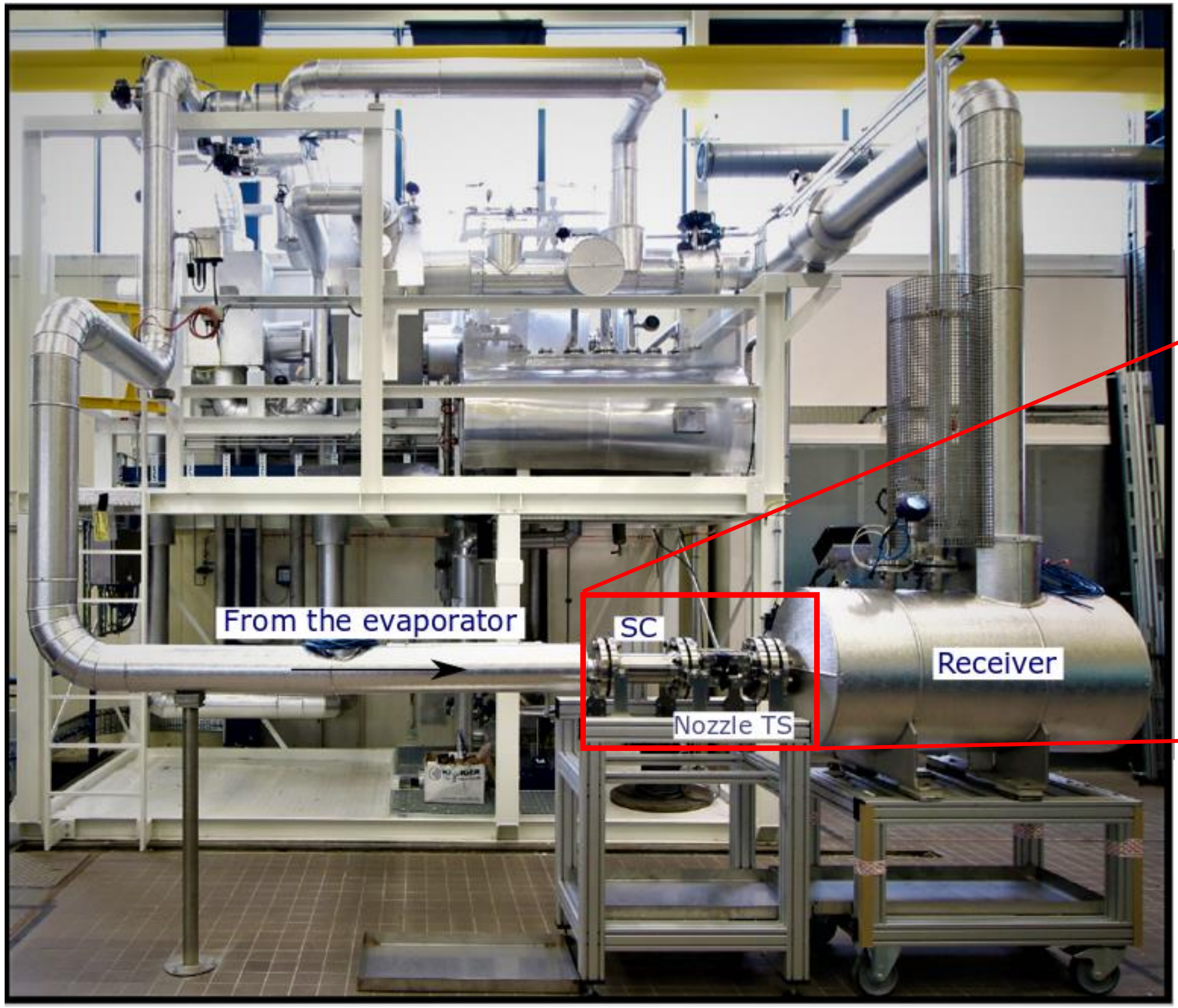
1. **The ORCHID nozzle test section**
   - Layout
   - Schlieren measurement chain and experimental procedure

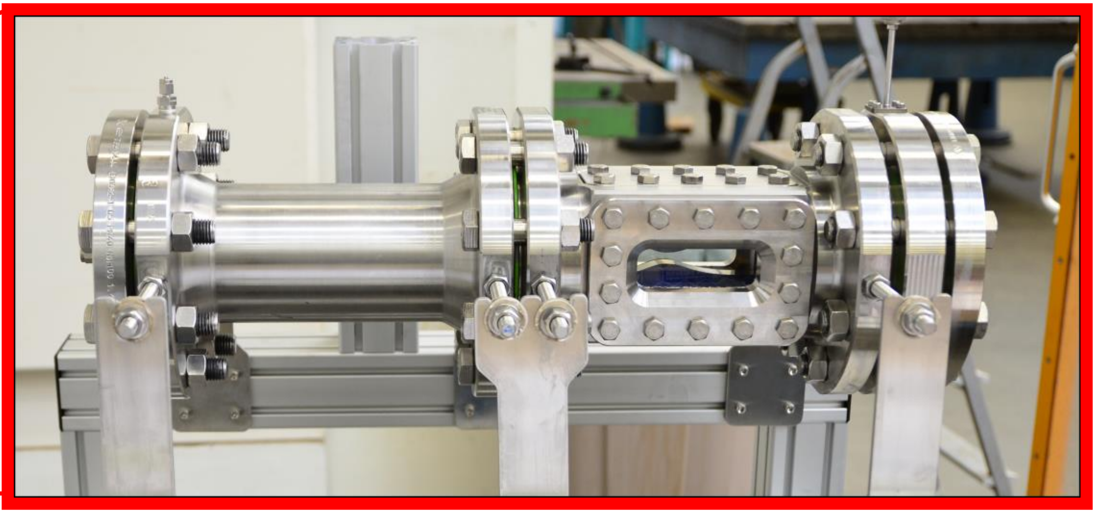
2. **Schlieren Mach line extraction method**
   - Algorithm overview
   - UQ

3. **Experimental and numerical results comparison**

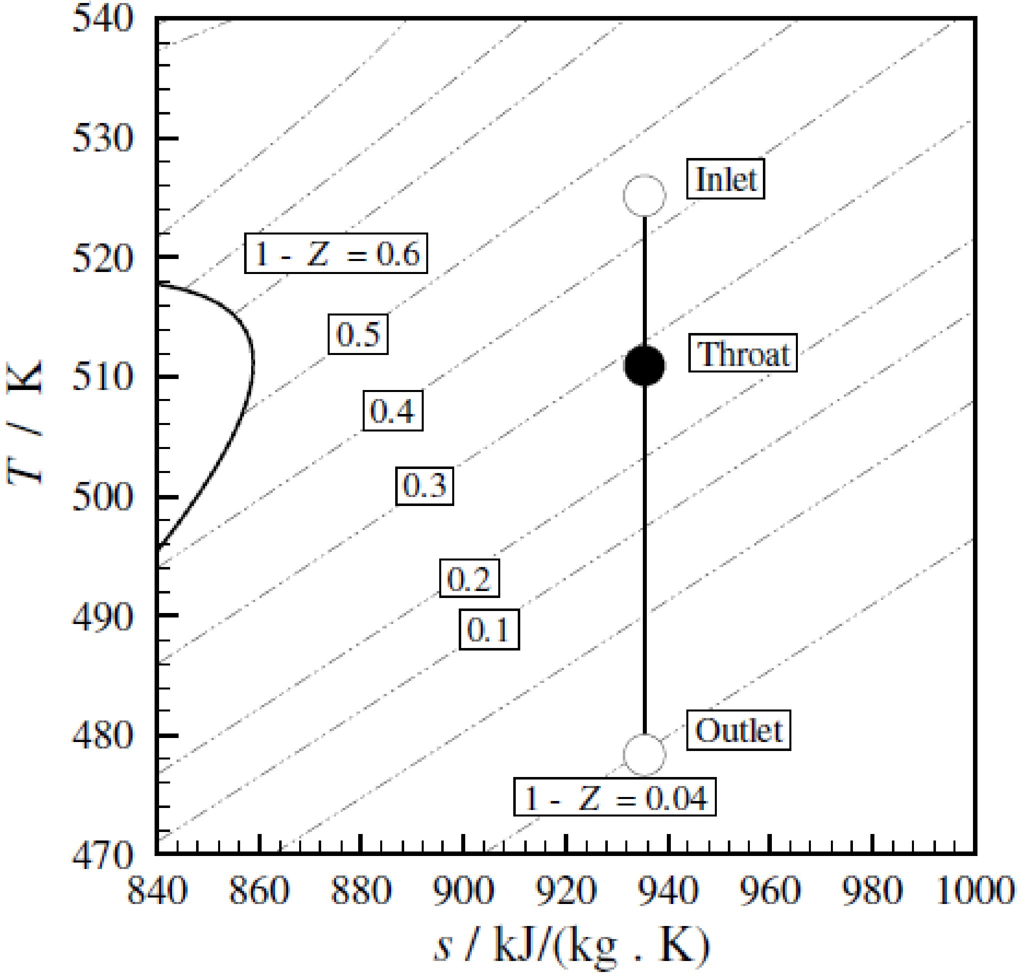
4. **Conclusions**

ORCHID nozzle layout

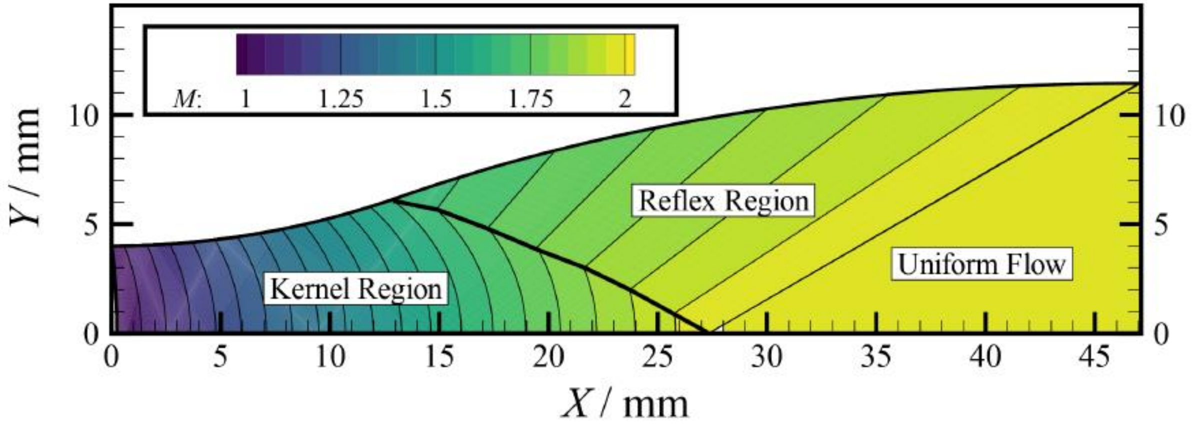




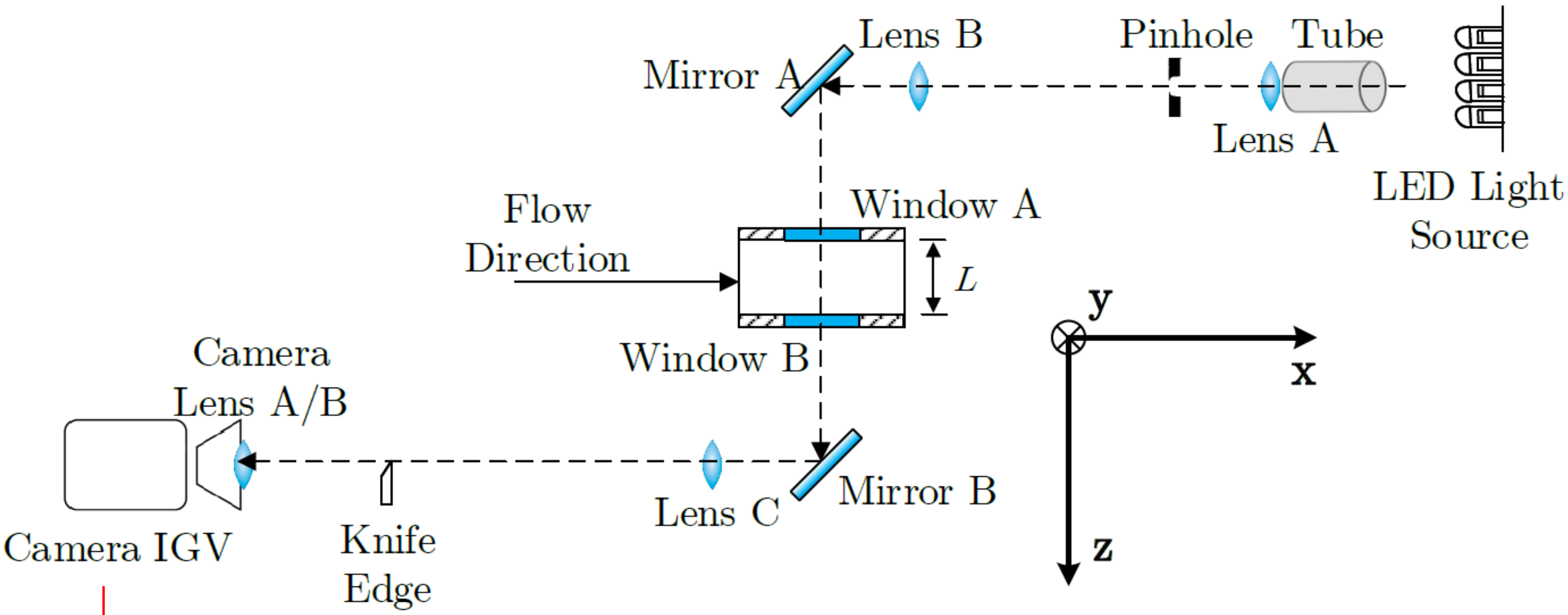
Operating conditions



Fluid	Tot. temp. TT015 / °C	Tot. press. P_{SV}001 / bara	Comp. F. Z_t
MM	252	18.4	0.56
Back p. PT004 / bara	Outlet Mach. M_2	Mass flow FT001 / kg/s	
2.1	2	1.145	



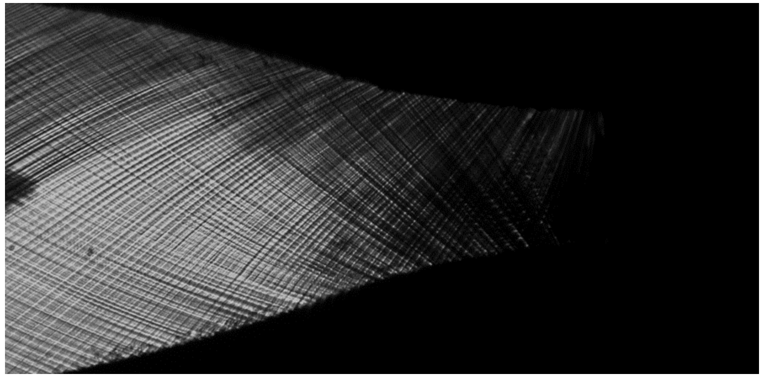
Schlieren Measurement Chain and Procedure



BOBCAT IGV-B1610 16bit CCD camera

(Maximum resolution: 1628 x 1236 pixels) , (Acq. Freq: 24.75 Hz)

Schlieren Measurement Chain and Procedure



Zoomed-in FOV: PR.025 raw single image

TS Warm up

Pre heat to about 180 C for MM

BoP operating conditions reach stable values around chosen P & T

Nozzle TS opens

≈ 20min required to stabilize inlet cond.

Set nozzle back pressure

Schlieren image acquisition

Sufficiently large dataset: For the present case ≈ 2000 images taken at 25 Hz

Close valves

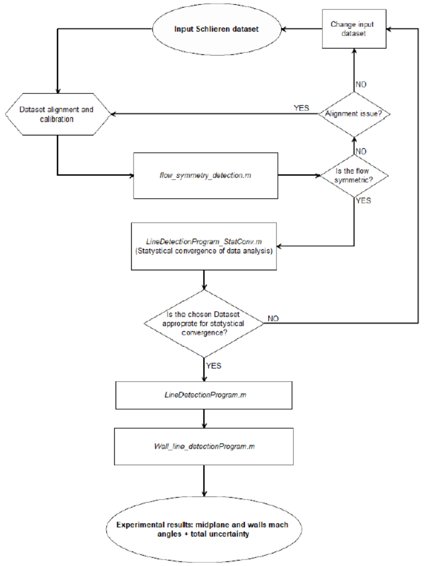
Acquire empty nozzle image for post processing

Schlieren Mach Line Extraction Method

PROCEDURE

+

TOOLS



Schlieren Mach Line Extraction Method

PROCEDURE + **TOOLS**

PROCEDURE		TOOLS
1) Pre-Processing: Dataset shift and rotation correction + Background removal	→	**DaVis + Matlab**
2) Flow Symmetry assessment	→	**Flow symmetry tool (Matlab)**
3) Statistical convergence of data	→	**Statistical convergence tool (Matlab)**
4) Midplane Line Detection	→	**Line Detection tool (Matlab)**

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Schlieren Mach Line Extraction Tools:

Overview of the core algorithm

For each frame

- ❑ Pre-processed schlieren dataset
  - Image enhancement
  - Binarization
  - Canny edge detection
  - Calibration
  - Discretization

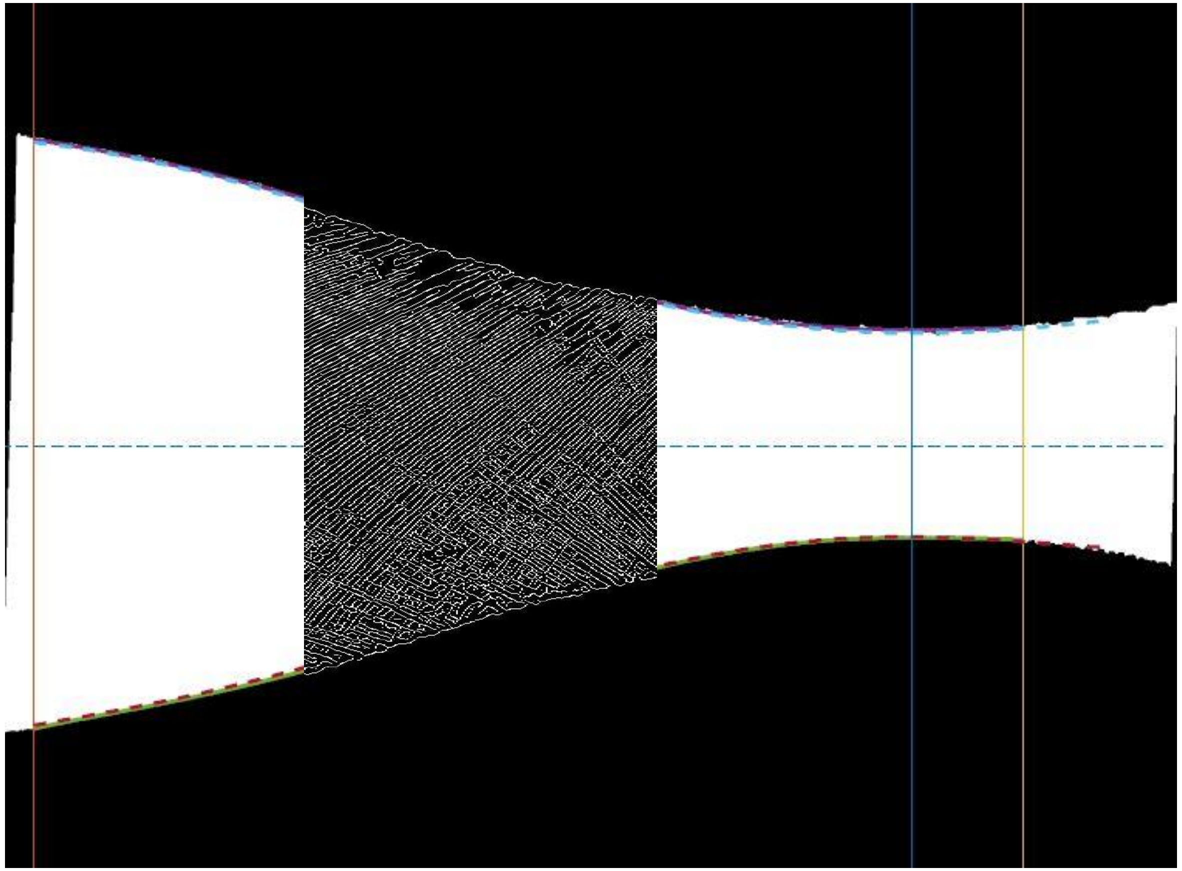
  For each sub-image

  - Hough transform

    Line detection ←→ Adapt line parameters

  - Best line selection
  - Mach angle and number extraction
  - Calculate local type B uncertainty

- ➢ Results analysis and statistics
- ➢ Type A uncertainties evaluation + correlations
- ➢ RESULTS: SRQ values + total uncertainties



Example of the codes calibration phase results + superimposed binarized image with edges.

Error Source Identification and Uncertainty Quantification

Error sources in the experiment:

- ✓ **<u>Test section (TS)</u>**
- ✓ **<u>Schlieren Measurement Chain (SMC)</u>**
- ✓ **<u>Post Processing Tools (PPT)</u>**
- ✓ **<u>Balance of Plant (BoP)</u>**

Negligible

Uncertainty on the SRQ

Uncertainty in the position of the SRQ

Uncertainty in the Boundary Conditions of the nozzle.

INDIRECTLY affecting all the uncertainties of the SRQ

Error Source Identification and Uncertainty Quantification

Uncertainty	Type	Correlation with:	Error source(s)	Derivation
$U_{M,data}$	A	$U_{M,ext}$	BoP, SMC,PPT	$2 \times std.Mach$
$U_{M,ext}$	Derived from $U_{\mu,ext}$	$U_{M,data}$	PPT, SMC	$M\sqrt{M^2-1}U_{\mu,ext}$
$U_{\mu,ext}$	Combined	$U_{\mu,data}$	PPT, SMC	$\sqrt{AR_{95}^2 + U_{Hough,res}^2}$
$U_{\mu,data}$	A	$U_{\mu,ext}$	BoP, SMC, PPT	$2 \times std.\mu$
AR_{95}	Combined	$U_{\mu,data}$	SMC, PPT	$Avg.AR + 2\left(\frac{1}{1+LL^2}\right)u_{LL}$
$U_{Hough,res}$	B	-	PPT	$0.95\,\frac{\theta_{hough}}{2}$

- **Type A**: calculated purely by statistical analysis, connected to the small unpredictability and fluctuations;
- **Type B**: instrumentation error, resolution, calibration etc.
- **Combined:** combination of A and B type uncertainties

Numerical Simulations Details

Boundary conditions:

$$P_{in}^{0} = 18.36 \pm 0.18 \; bar$$

$$\mathrm{T}_{\mathrm{in}}^{0} = 252.4 \pm 0.69^{0} \; C$$

$$P_{out}^{0} = 2.06 \pm 0.25 \; bar \; .$$

SU2
The Open-Source CFD Code

MM Properties:

iPRSV cubic equation of state (FluidProp)

+

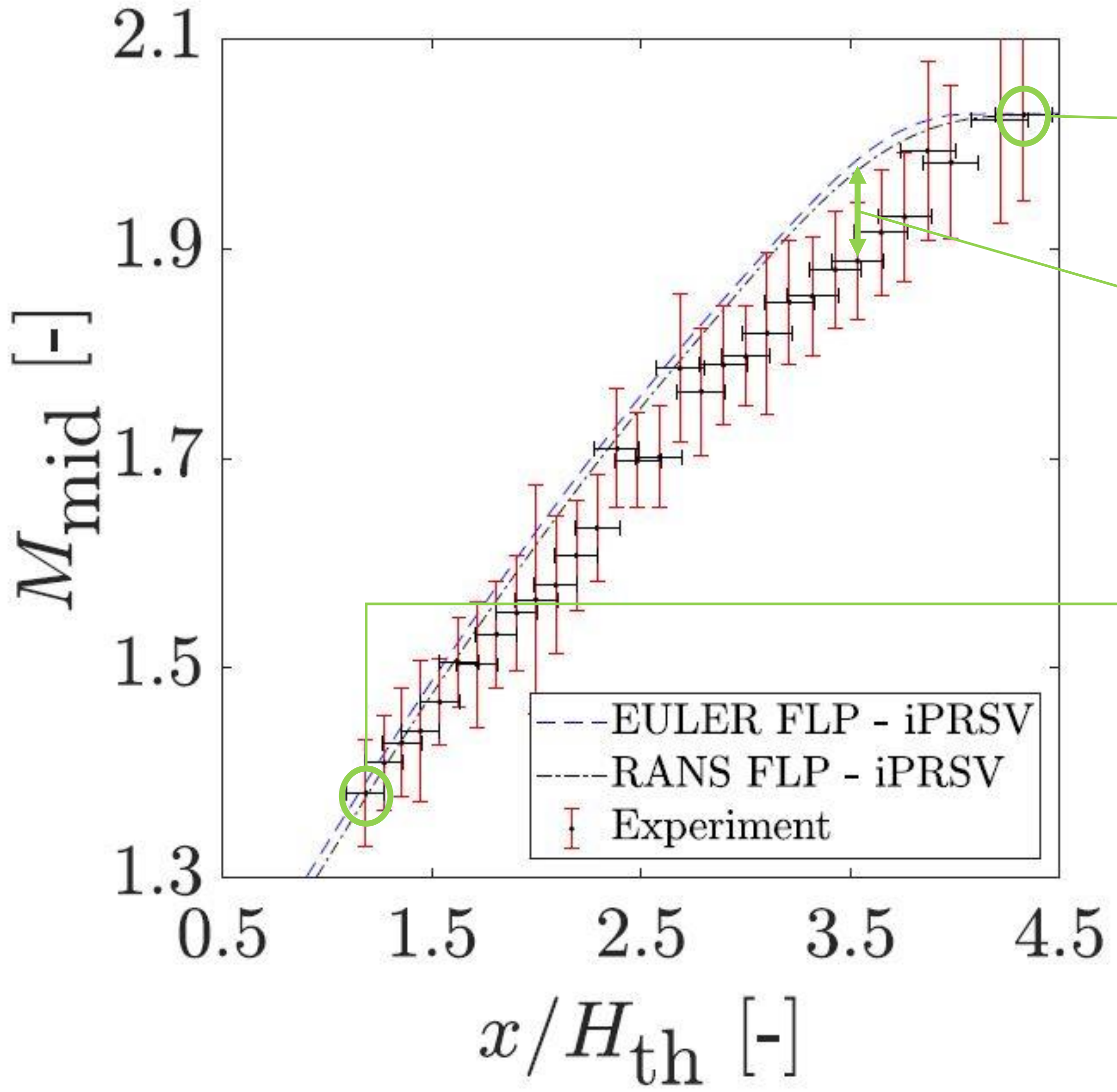
Fourth order polynomial f(T) for the c_P

+

Chung's transport model

- ✓ **EULER implicit (CFL=20), 10000 elements for grid independent results**
- ✓ **RANS closed with SST turbulence model, with additional cells to resolve the walls BL**

Experimental and Numerical results comparison



$M = 2.03 \pm 0.082$

$E_{max} = 4.45\%\ of\ M_{exp}$

$M = 1.38 \pm 0.05$

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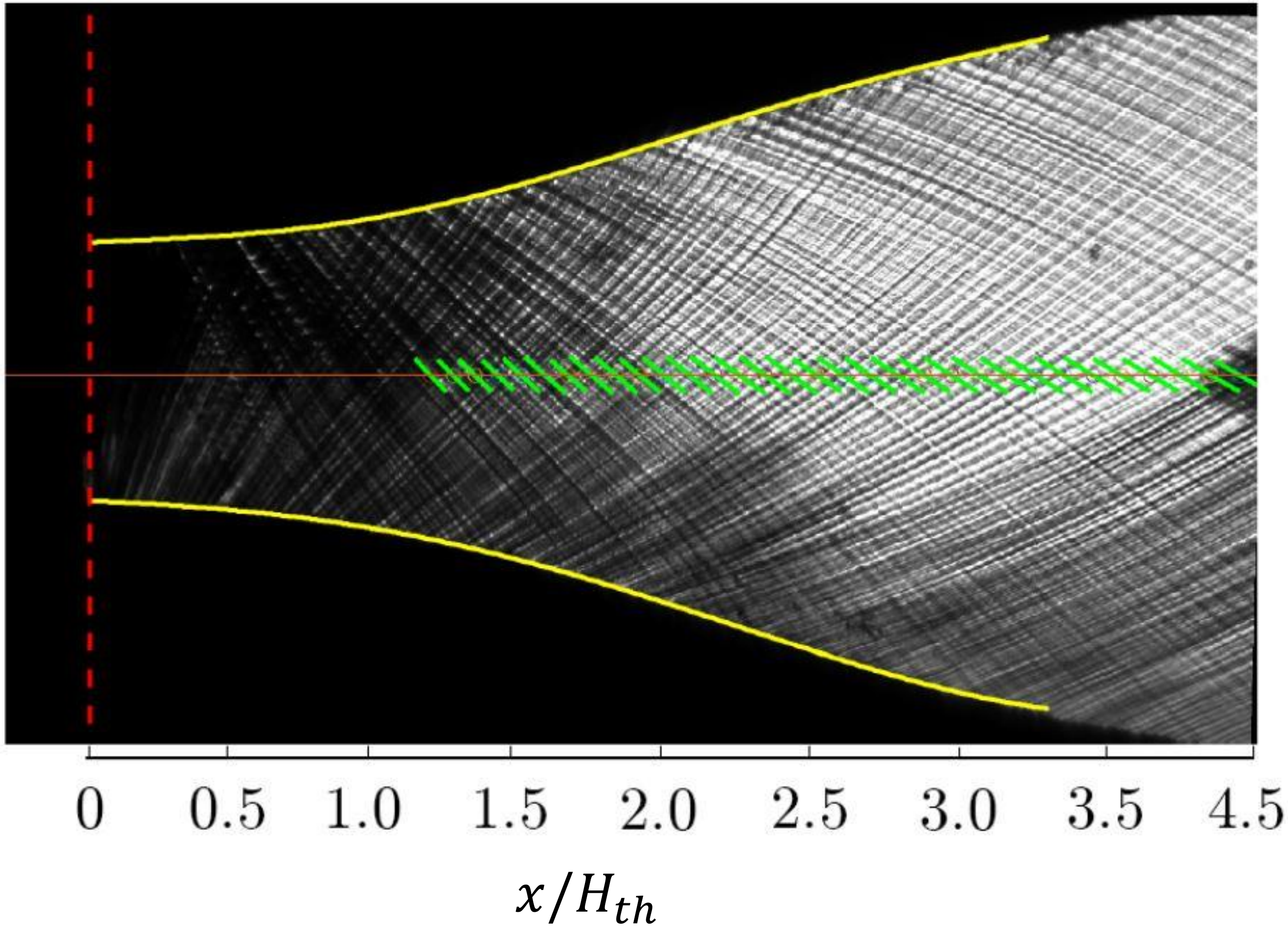
Experimental and Numerical results comparison



Average extracted Mach lines superimposed on the first schlieren image.

CONCLUSIONS

1) The capability of the facility to produce steady state schlieren datasets in the case of supersonic non ideal expansions was proven;

2) An ad-hoc methodology to process schlieren data and to extract the flow Mach number and its total uncertainty has been implemented;

3) The predicted Mach numbers match well with the experimental results at the initial phases of the expansion and at the end of it;

4) The Mach number uncertainty strongly depends on the pixel resolution, brightness level of the image and the FOV;

5) The adopted schlieren measurement chain needs an optimization.

Thank you for the attention.

Questions?