High temperature turbulence
coupling of radiative and convective heat transfer in turbulent flows

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This research (which was part of the PhD project by the first author) was focused on the role of radiation in high temperature participating media and its influence on turbulent heat transfer. One of my research goals was to design a method to allow the simulation of fully coupled radiative and convective transfer resolving all thermal scales. To overcome the challenging computational requirements involved, we developed a custom innovative CUDA implementation of a Quasi-Monte Carlo radiative solver and coupled it to an efficient CPU Direct Numerical Simulation solver. This massively parallel Monte Carlo solver is the fastest to-date and ran on the largest heterogeneous HPC clusters in Europe, including Piz-Daint in Switzerland and the new Marconi-100 in Italy. With the help of this code, we were able to formulate a theory that describes the impact of Turbulence-Radiation-Interactions (TRI) on the overall heat transfer process in high temperature turbulent flows. The theoretical analysis, based on the high-fidelity DNS Monte Carlo data, unveiled the mechanisms governing the temperature field. This was the basis for the development of a low-order approximation that enabled the closure for the radiation-turbulence coupling. This model was proven to predict exceptionally the temperature field for all investigated systems, where standard models fail.

Research objectives

The continuous demand to increase the efficiency of energy conversion systems and the productivity of process plants forces engineers and scientists to use fluids at increasingly higher pressures and temperatures. For instance, to increase the thermal efficiency of power plants, engineers are currently developing a thermodynamic power cycle that operates with carbon dioxide at pressures and temperatures high enough to exceed the thermodynamic critical point. Another example where pressures and temperatures of fluids continuously increase is in the development of more powerful rocket engines.

At these high temperatures, radiation is the most important heat transfer mechanism. In addition, gases like CO_2, H_2O, or CH_4 strongly "participate" in radiative heat transfer, i.e. they emit and absorb thermal radiation at large rates. Therefore, being able to predict the impact of radiative heat transfer on the overall heat transfer process as well as on the flow behaviour is of vital importance to successfully realize these new engineering applications.

In turbulent flows of highly participating fluids, the presence of temperature fluctuations induces fluctuations in the emitted thermal radiation. The radiated thermal energy undergoes re-absorption within the fluid, causing a long range energy transfer, which acts as a damping mechanism for temperature fluctuations. This damping mechanism affects turbulence and mixing levels in case of strong density gradients. A vivid example of this mechanism (taken from our detailed simulations) is presented in Figure 1. These so called turbulence-radiation interactions have only recently been investigated using expensive numerical simulations, made possible by the increased computing power, necessary to handle the problem.

On the other hand, a comprehensive knowledge of the underlying physics is still lacking for significantly participating media (optically intermediate and thick). The reason is that for flows in general geometries with highly participating non-gray fluids, analytical representations are inaccessible, experimental investigations are difficult, and detailed numerical simulations are "simply" computationally unfeasible with conventional codes. The combination of non-gray effects (highly variable absorption spectrum) and large optical depths results in a total disruption of turbulent convection and an unexpected redistribution of the energy within the fluid. This completely changes the well-known patterns of heat transfer and variable property turbulence.

In conclusion, the effect of radiation on turbulent convection in optically dense, non-gray fluids is still unknown. This results in the complete lack of models able to predict turbulence-radiation interactions through the whole scale of motion and optical thickness range. For this reason, several important quantities, such as the mean temperature and the mean radiative fields, cannot be predicted accurately. As such the research objectives of this project were the following:

1. Develop an optimized tool to allow the full coupling of radiative heat transfer and turbulence.

2. Perform high-fidelity Direct Numerical Simulations (DNS) that give access to a complete description of the turbulence-radiation interactions.
3. Provide a clear characterization of the coupling between turbulence and radiation, for different optical thicknesses, variable and spectral radiative properties and including the effects of anisotropic turbulent structures.
4. Reconcile the effect of radiation on temperature by providing scaling relations, which are able to describe the turbulence-radiation coupling independently of the above specified parameters.
5. Develop a simplified model, which allows the calculation of high-temperature turbulent participating flows without the necessity to perform heavy duty simulations.

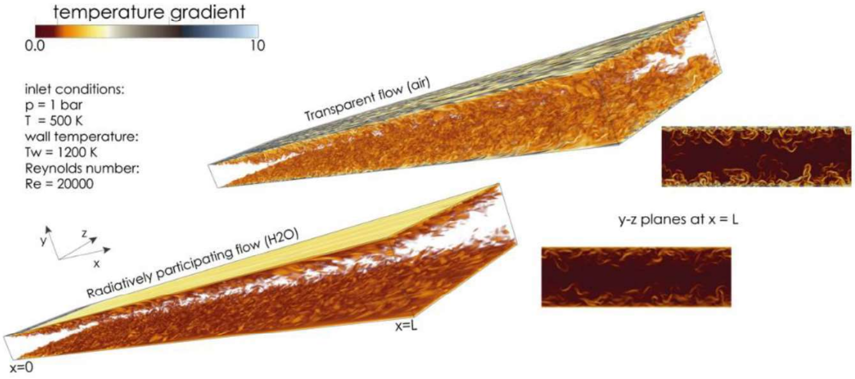

Figure 1: Thermally developing channel flow for two different media. The only difference between the transparent flow (air, top) and the participating flow (H_2O, bottom) is the presence of emission and absorption from the fluid. It is clear that the temperature field is completely disrupted as the gradient decreases significantly. This in turn leads to a great reduction in turbulence intensity for all velocity components. These results were generated with 10000 rays/cell on a mesh with 750 million cells.

Research route and methodology

To study the interaction between turbulence and radiation in high temperature participating flows, the solution of radiative heat transfer for all turbulent length scales had to be made available. Unfortunately, the Radiative Transfer Equation (RTE) is six-dimensional (including directional and wavelength dependency) and a one-to-one coupling of a radiative solver with a DNS solver (which solves the complete range of turbulent scales) had never been attempted due to the exorbitant computational requirements. To circumvent the problem, we developed an innovative method that exploits new generations of High Performance Computing (HPC) centres, by solving the spectral RTE on GPUs with a photon Monte Carlo (MC) method paralleled to a DNS flow solver running on CPUs (schematic shown in Figure 2). The GPU Monte Carlo solver [2] required extensive optimization, both in terms of computer science and exploitation of the physics of the problem to speed up the numerical methods, in order to render the solution feasible. The final version of the code had a staggering 1000 × speedup compared to a usual CPU code and allowed first-of-its-kind high-fidelity simulations of one-to-one coupled turbulence and radiative heat transfer.

With this new solver we were able to perform simulations of high temperature, fully developed channel flow with radiative heat transfer. The setup, consisted of a statistically one dimensional channel flow, periodic in the streamwise and spanwise directions and bounded by a hot and a cold isothermal wall. The participating turbulent flow was simultaneously heated by the hot wall and cooled by the cold wall and capable of absorbing radiation from the hot wall and emitting towards the cold wall. In addition, fluid-to-fluid radiative heat transfer modified the redistribution of the energy within the channel. The thermodynamic and radiative parameters of the turbulent flow (such as the density, optical thickness, and spectral variability) were varied to identify a scaling for the radiative-turbulence coupling.

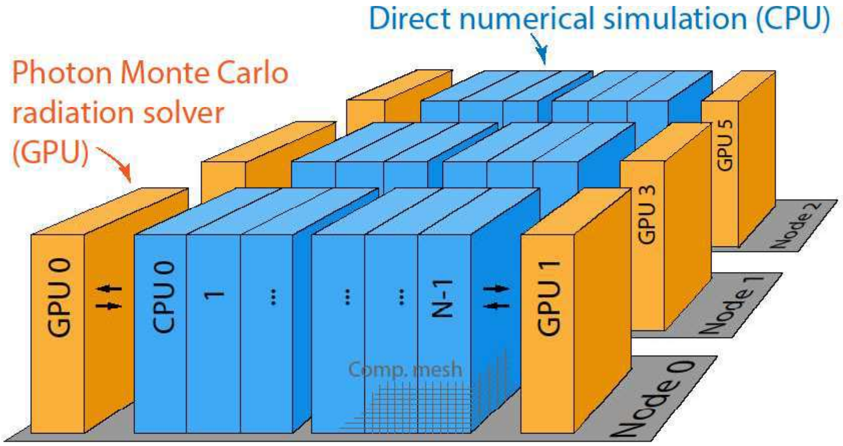

Figure 2: Schematic of the implemented heterogeneous solution method, exemplifying a system with 3 nodes composed of 6 CPU cores and 2 GPUs each.

Main results and achievements

Due to radiation, new terms appear in the energy equation, which are dependent on the "optical thickness" (τ) of the flow, or of the ability of the medium to absorb incoming radiation. We used this last parameter to categorize the effects of radiation on the turbulent heat transfer process by highlighting the contrasting effects of radiative emission and absorption.

The first step was to identify quantities that would encompass the physics of turbulence-radiation interactions. We found one of these quantities to be the "radiative dissipation" ($R_\theta = \langle Q_R' T' \rangle$), which mathematically represents the correlation of the temperature field fluctuations with the radiative field fluctuations. This term includes both aspects of Turbulence-Radiation Interactions (TRI): (1) the development of a fluctuating radiative field by action of turbulence, and (2) the destruction of the thermal fluctuation field caused by the presence of radiative heat transfer.

It is well known that the radiative heat source has a non-monotonic dependency on the absorption coefficient due to the non-local nature of radiation. As such, radiative heat transfer can be divided into three regimes: optically thin $\tau \ll 1$, optically intermediate $\tau \approx 1$, and optically thick $\tau \gg 1$, where the optical thickness can be seen as the ratio of geometrical to radiative length scales. We extended this categorization to TRI by investigating the differences in the radiative dissipation for optically thin, intermediate and thick turbulent flows. It was found that the optical thickness provided much information on the TRI mechanism as the three different regimes were different not only quantitatively but also in terms of behaviour [1]. On the other hand, we unfortunately discovered that the optical thickness alone was not the correct parameter to predict the effects of TRI. In Figure 3 (left) the radiative dissipation integrated over the channel height for many different simulations (legend in the central figure) is shown versus the optical thickness of the channel. A clear scaling pattern based on optical thickness is not evident.

After careful analysis, we identified the cause of the TRI mechanism in the fluctuation of the incident radiation that is the radiative energy absorbed by the flow per unit area. If normalized correctly, this quantity scales monotonically with a modified optical thickness (τ_g), which was introduced to account for the variability of the absorption spectra, and is a function of the absorption coefficient and the turbulent length scale. Normalized absorption fluctuations are shown as function of τ_g in the central plot of Figure 3. Note that the gray line in Figure 3 does not stem from fitting of the data but is mathematically derived. $f(\tau_g) \sim (\tau_g / \langle \omega_c \rangle) \text{atan}(\langle \omega_c \rangle / \tau_g)$ and ω_c represent the characteristic length scales of the temperature field [3] (here averaged among the different simulations). This analysis allowed to construct a mathematical model, based on a scaling parameter, which is able to predict radiative dissipation and, therefore, provides a framework to model the effects of TRI in high temperature turbulent flows. The aforementioned parameter can be considered as a TRI equivalent optical thickness (τ^*). As seen on the right plot in Figure 3, when using τ^*, it is possible to predict the value of the bulk radiative dissipation with a mathematically derived function of τ^*, which reads:

$$f(\tau^*) = \tau^* [1 - (\tau^* / \langle \omega_c \rangle) \text{atan}(\langle \omega_c \rangle / \tau^*)].$$

This parameter was the base for a Reynolds-Averaged Navier-Stokes (RANS) model, which could be applied as a closure to the turbulent heat flux in high temperature turbulent flows. This model has been tested thoroughly with all the DNS performed and showed exceptional results not only in terms of mean temperature field, but also in terms of second and higher order statistics [4]. An example is shown, for three representative simulations, in Figure 4. Here, DNS results for three different participating turbulent channel flows are compared to the RANS simulation using (1) the most used model in literature (0-equation model with $\alpha_t = \mu_t/0.9$, where μ_t is the eddy viscosity and α_t is the eddy diffusivity); (2) a more elaborate model, which calculates α_t from the evolution of budget equations for temperature variance and temperature dissipation; (3) the model developed in this project.

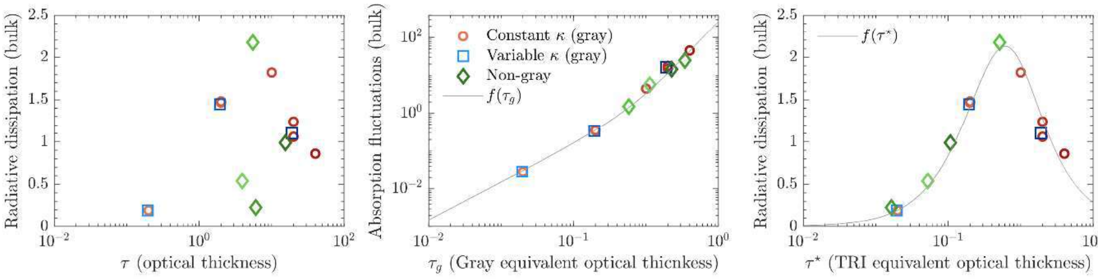

Figure 3: Bulk parameters encompassing TRI for the entire data-set of coupled radiative-turbulent DNS (a mix of gray and non-gray turbulent channel flows, each data point is a single independent simulation where the bulk value is integrated over the whole domain). Left: radiative dissipation plotted against optical thickness, centre: normalized absorption fluctuations plotted against the gray equivalent optical thickness; right: radiative dissipation plotted against the new TRI mean optical thickness.

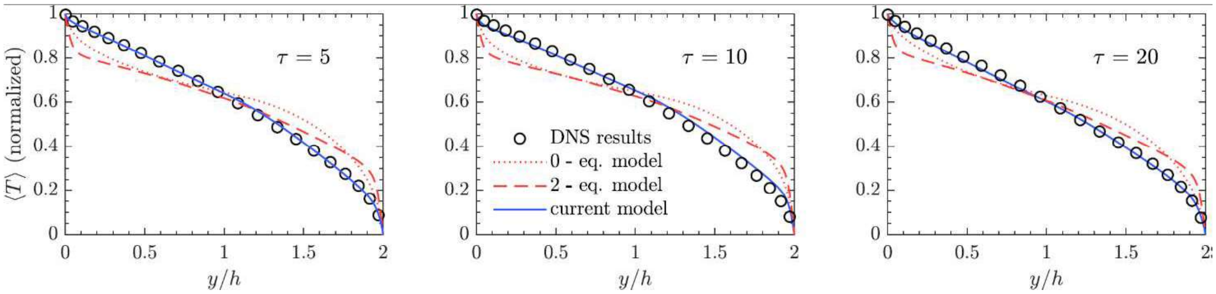

Figure 4: Averaged temperature profile (normalized) in three different fully developed turbulent channel flow simulations with radiative heat transfer. These simulations are periodic in the streamwise and spanwise direction and bounded by a hot and a cold wall in the wall-normal direction. The results are averaged over the periodic directions and shown plotted versus the wall-normal normalized coordinate. From left to right the optical thickness of the channel $\tau = \int_0^2 (I_b)^{-1} \int_0^\infty \kappa_\lambda I_{b\lambda} d\lambda dy / h$ (h is the half channel height, I_b black-body radiation and κ the absorption coefficient) changes from 5 to 10 to 20. DNS results are plotted with circles, while lines come from RANS simulations. The dotted line is a 0-equation model obtained with setting a constant turbulent Prandtl number. The dashed line shows the state-of-art of turbulent heat flux modeling (a 2-equation model calculating temperature variance and temperature dissipation). The blue line is the model developed in this project.

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