Institut Jean Le Rond D'Alembert - Sorbonne Université/CNRS CEA-CESTA

RESEARCH PROJECT:
Data-driven turbulence modeling for highly compressible flows

Contact: Paola Cinnella, Professor (paola.cinnella@sorbonne-universite.fr)

Duration of the Internship: 4 to 6 months

Location: Institut Jean LeRond D'Alembert / Sorbonne Université - Campus Pierre et Marie Curie - 4 place Jussieu 75005 Paris

Possibility to continue with a doctoral program YES. To be started at Fall 2023. The CEA CESTA (Bordeaux) department funds both the present internship and the follow-up PhD. The internship will take place entirely at D'Alembert Institute in Paris. The PhD will be conducted half-time in Paris and in Bordeaux (periods in each location are flexible and will be discussed according to the needs of the project).

Candidates: Graduate student in aerospace or mechanical engineering, applied mathematics or computer science with skills in scientific computing for fluid dynamics. At ease with at least one compiled computing language (Fortran, C, C++) and python or matlab. Parallel computing skills will be appreciated.

1 Context and objectives

High-speed compressible flow in the supersonic and hypersonic regimes represent a challenging topic of interest for many configurations, including objects entering a planetary atmosphere or for atmospheric supersonic and hypersonic flight. In such flows, conversion of massive amounts of kinetic energy into internal energy causes a sudden rise of the flow temperature. At sufficiently high speeds, the effects triggered by the high temperatures may include chemical reactions and vibrational relaxation phenomena on characteristic time scales comparable with the flow time scales. The complex thermochemical state induced by such conditions may affect quantities of interest for the design of high-speed vehicles significantly [1, 2].

At the very high velocity at stake, experiments are difficult or even impossible, and the design process heavily relies on Computational Fluid Dynamics (CFD) models. A major source of uncertainty in the computational prediction of aerodynamic forces and heating for these systems is represented by turbulence modeling. For complex industrial applications, the latter still relies on the solution of the Reynolds-averaged Navier-Stokes equations (RANS), supplemented by constitutive relations for the unclosed terms arising as a results of the non-linearity of the governing equations and of the averaging process. Typically turbulence models have been developed for incompressible flows and then extended without much change to compressible flows. Some authors have recommended corrections of existing models, but these still rely on simplifying hypotheses. In addition to uncertainties associated with the constitutive law for the Reynolds stress tensor and the transport equations of turbulent properties (for instance the turbulent kinetic energy k or the turbulent dissipation ε), several unclosed terms appear in the compressible, Favre-Averaged Navier-Stokes equations, which are usually modeled by means of rough assumptions. One of these is the use of a constant turbulent Prandtl number for expressing the turbulent heat fluxes. Additional unclosed terms appear in the equations for multi-species reacting mixtures. This leads to significant inaccuracies and uncertainties already when dealing with relatively simple configurations, especially when heat transfer phenomena are investigated [3, 4].

Recently, our team conducted several direct numerical simulations of supersonic and hypersonic wall-bounded flows [5, 6, 7]. Preliminary analyses of turbulence modeling assumptions at the light of DNS data were carried out [8], confirming the necessity of developing models providing a more accurate representation of the turbulent stresses, mass and heat fluxes. On the other hand, such databases provide an ideal playground for modern, data-driven turbulence modeling techniques (see, e.g., [9, 10]).

Our team recently investigated an open box machine learning method called SpaRTA (Sparse regression of Reynolds sTress Anisotropy) based on symbolic identification of terms from a library of candidate functions [11, 12]. The methodology has been applied to incompressible separated flow showing potential for providing improved models that generalize well to flows with similar characteristics. Preliminary work has been conducted for extending the methodology to compressible flows [13], but further investigation is needed. Additionally, the approach has been only applied to non-reacting boundary layer configurations. Work remains to be done for developing improved closures for the turbulent heat fluxes and mass fluxes.

The scope of the present project is to move further toward the development of improved models for compressible flows by symbolic identification of corrective terms for the Reynolds stresses and other unclosed terms in the governing equations.

2 Work plan

The present research will be conducted in the frame of a collaboration among several institutions: CEA, Sorbonne Université, Arts et Métiers Institute of Technology. The work plan includes the following tasks

1. **Symbolic identification of model corrections for the Reynolds stress tensor:** starting from the preliminary work of [13], the SpaRTA algorithm will be implemented for a set of supersonic and hypersonic flows. he open-source CFD code SU2 (`https://su2code.github.io/`), will be used as a basis for the developments. Various formulations of data-driven corrections will be considered, and the most accurate, efficient and numerically robust will be selected.

2. **Symbolic identification of model corrections for the turbulent heat flux:** the SpaRTA algorithm will then be extended in order to develop data-driven models for other unclosed term. More specifically we will focus on the turbulent heat flux, a critical quantity for aerospace vehicle design. If time is left, using a similar approach s could be also be used to develop data driven models for the mass fluxes of reacting species (for the higher Mach number cases).

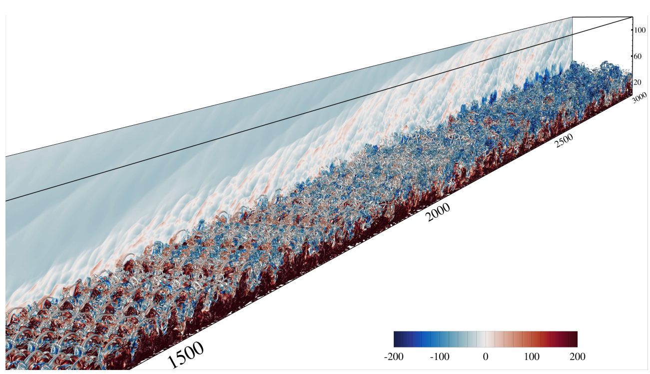

Figure 1: Turbulent boundary layer at Mach 12.48 in thermochemical non equilibrium. Isosurface of the Q-criterion colored by the difference between the roto-translational and vibrational temperature.[7]

References

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