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PHD THESIS PROPOSAL

Title: AI-based turbulence modelling for compressible flows in space launcher nozzles

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Starting date: October 2024	**Application deadline:** 15 March 2024

Keywords

Turbulence modelling, compressible flows, space launcher, RANS, DNS, artificial intelligence

Education and Skills

School of Engineering and/or Master 2

Strong background in fluid mechanics (theory, in particular turbulence, and numerical methods). Affinity for physical analysis, turbulence modelling and programming. Some knowledge in artificial intelligence.

Summary and objectives

Flows inside space launcher nozzles typically present several complex phenomena that may play a crucial role on the device performance and indirectly on the risks of the launch success. In particular, in real-life applications inside the nozzle there is a high-Mach number flow for which the turbulent boundary layer may separate, depending on the operational conditions, leading to the formation of a complex shock wave system and the emergence of a highly compressible mixing layer downstream of separation (Figure 1). The latter flow phenomenon may also be observed in multi-nozzle engine configurations, as in the scope of study of PIC RLV2 (*Reusable Launch Vehicles)*. Being able to properly reproduce the flow in such conditions is paramount for the space launchers design and remains a major concern for this industry.

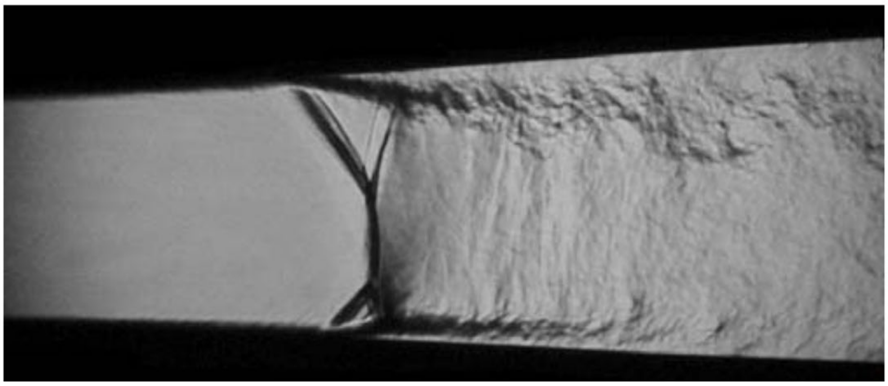

Figure 1 : Spark schlieren image of supersonic nozzle flow separation. Adapted from [1].

Different turbulence modelling approaches exist for turbulent flow simulations. Scale resolving approaches such as Direct Numerical Simulation (DNS), where all turbulent scales are resolved, or even Large-Eddy Simulation (LES), where small scales are modelled and large scales resolved, demand a huge computational effort for this kind of flows. Their use in space launchers design remains therefore prohibitive and faster yet accurate approaches are sought.

Rapid predictions of the turbulent mean flow may be obtained by solving the Reynolds-Averaged Navier-Stokes (RANS) equations. This approach, which aims at modelling all the turbulent scales, requires employing a turbulence model. However, despite the numerous turbulence models existing nowadays, the accuracy of the mean flow prediction in space launcher nozzles needs to be improved to reach satisfactory results. One of the main reasons for unsatisfactory predictions is the absence of compressibility effects in the model development. Indeed, most turbulence models are derived under incompressible assumptions, which no longer hold in the flows observed in space launcher nozzles. The inaccuracy in the predictions obtained with the RANS approach may be therefore problematic for the design stage. In order to illustrate this purpose, in the above-described flow, an accurate description of the mixing layer emerging downstream of separation plays a crucial role on the proper prediction of the boundary layer separation point.

Several efforts have been made in the turbulence modelling community in order to overcome these shortcomings. For instance, some compressibility corrections have been proposed for different eddy-viscosity turbulence models [2-3]. Nevertheless, the existing corrections do not provide enough improvement of the turbulence model performance and may in some cases be activated in regions where it is not suitable. Hence, further investigation on turbulence models corrections in compressible flows, including their proper activation depending on the flow conditions, should be carried out. Besides, the flow in the mixing layer may reattach further downstream resulting in a redevelopment of a turbulent boundary layer. The existing turbulence from the mixing layer above the emergent boundary layer will interact with the latter leading to a turbulent boundary layer in out-of-equilibrium conditions. RANS models nowadays still lack accuracy for the proper prediction of such flows, even for advanced RANS models such as Reynolds-Stress Models [4]. This represents another important aspect for potential improvement of RANS turbulence models accuracy.

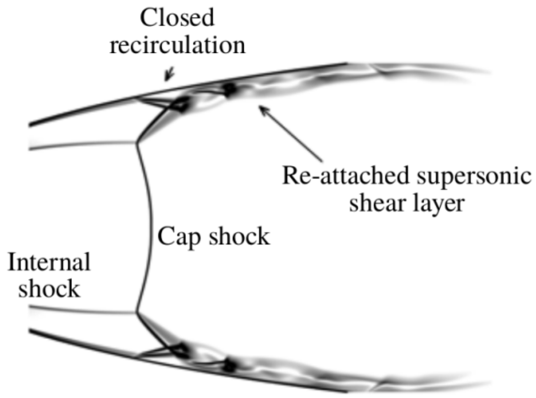

Figure 2 : Sketch of a restricted shock separation (RSS) nozzle flow. Adapted from [5].

The present research project aims at improving RANS models performance in presence of high compressible effects as well as out-of-equilibrium conditions. The study will be addressed in several steps. First, the prevision capabilities of different RANS models will be analysed in a nozzle flow configuration, set up after a corresponding study for the definition of relevant flow conditions. In addition, an investigation of the state of the art of turbulence models corrections will be addressed. Relevant corrections will potentially be evaluated in the mentioned nozzle flow. This first step will allow better defining the state of the art of current turbulence models for the prevision of space launcher nozzle flows. The next step will be the definition of reference test cases for a compressible mixing layer and for a transonic backward-facing step. These test cases will be both then simulated with DNS and will provide high-fidelity databases that constitute a significant contribution for the turbulence modelling community [6]. In the scope of the present project, these databases will be processed by means of Data Assimilation techniques for the identification of turbulence model corrections in compressible flows as well as in out-of-equilibrium conditions. By employing Machine Learning techniques, an augmented RANS model should be proposed and then tested in more complex flow configurations including representative effects of the conditions observed in a space launcher nozzle. For instance, a turbulent boundary layer reattaching downstream of separation, as occurring in restricted shock separation (RSS) in nozzle flows [7] (Figure 2), or a shock-wave/boundary layer interaction could be considered in this regard. Finally, the proposed augmented RANS model will be applied to an industrial configuration of a nozzle in space launcher flight conditions, to demonstrate its improvement with respect to previous RANS turbulence models. Besides, this model will also benefit more advanced modelling techniques, such as hybrid RANS/LES approaches like the ZDES technique [8], that could also be tested in the scope of this project.

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External collaborations

This PhD thesis is foreseen to be cofunded by CNES and ONERA.

Point of contact at CNES: Simon Blanchard (simon.blanchard@cnes.fr)

Host laboratory at ONERA	**Thesis Supervisor**
Department: Aerodynamics, Aeroelasticity, Acoustics Department Location (ONERA’s centre): Meudon **Point of contact**: Jaime VAQUERO Phone: 01.46.73.41.76 Email: jaime.vaquero@onera.fr	Name: Sébastien DECK Laboratory: ONERA / DAAA / MSAT Phone: 01.46.73.43.47 Email: sebastien.deck@onera.fr

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