Large Eddy Simulation of supersonic non-reactive and reactive flows with an immersed boundary method

Lisa Bouheraoua[1], Guillaume Ribert[2] & Pascale Domingo[3]

CORIA – CNRS, Normandie Université & INSA de Rouen,
76801 Saint-Etienne-du-Rouvray, France
[1] lisa.bouheraoua@coria.fr, [2] ribert@coria.fr, [3] domingo@coria.fr

Background

Supersonic combustion is one of the key technologies to develop hypersonic air breathing propulsion systems such as scramjets engines. However, a number of issues have to be clarified, as this technology is not viable yet. In particular, the flame stabilization at extremely high speeds is a challenge. Cavity flame-holding approaches have been recently viewed as promising solutions [1, 2, 3]. Indeed, these configurations enhance the mixing between reactants and oxidizer and lead to a stable combustion. Despite the need of improving the design of such devices, the extreme operating conditions are not favorable for realistic experiments. The development of high performance computational works is then crucial for the understanding of supersonic combustion. Performing Large Eddy Simulations (LES) in the scramjet cavity flame configuration imposes some preliminary validations to both non-reactive and reactive supersonic flows. Main characteristics, such as shock positions, autoignition and mixing, have then to be correctly reproduced with adequate test cases.

Achievements

Simulations of supersonic flows are performed using a cartesian compressible LES solver. With such structured-grid numerical code, the description of non-rectangular solid bodies becomes an issue and an Immersed Boundary Method (IBM) must be used [4, 5]. In the present study, the ghost cells method has been implemented in the solver SiTComB [6]. Ghost nodes are flagged for the description of the solid geometry, with imposed values computed from their respective image nodes in the fluid domain. A resulting solid boundary condition is then defined. IBM has been applied with success to a Mach 3.5 non-reactive flow past a circular cylinder. In particular, the upstream detached shock is well recovered. This study ensures the proper behavior of IBMs in SiTComB, and the code ability to handle supersonic flow configurations.

Before performing the simulation of a scramjet cavity flame-holder, supersonic turbulent combustion must be studied on a more academic burner such as the one proposed by Cheng and Wehrmeyer [7]. They experimentally studied a supersonic hydrogen flow at Mach 1, surrounded by hot gases flowing at Mach 2. As this computational work involves turbulent combustion, autoignition and fuel-air mixing inside the supersonic flow, the

choice of the combustion model, coupled with LES, is crucial. If a correct detailed based chemistry model improves the accuracy, it induces however very expensive numerical costs. In this context, several simplified chemistry models, such as reduction chemistry or tabulated chemistry, are under study. More particularly, the hydrogen-oxidation is often used to validate these new models, because few elementary reactions and reactive species are involved. As tabulated chemistry approach was firstly developed for low-speed flows computations, this study aims at validating the use of such models to supersonic combustion, in order to discuss its accuracy and efficiency compared to a reduced mechanism. Both combustion models have then been implemented in SiTComB. The reduced mechanism presented here involves three steps and five reactive species. It has been validated for a wide range of premixed and non-premixed laminar flames from previous studies [8, 9]. Tabulated chemistry is introduced in LES by a combination of a presumed Probability Density Function (PDF) and chemical table [10], constructed with monodimensional premixed laminar flamelets and autoignition in a perfectly mixed reactor for various equivalence ratios. An analysis of the interaction between characteristic boundaries and tabulated chemistry is also discussed for the implementation in the code. Then computations of the supersonic co-flowing hydrogen-air flame, with both combustion models are performed. Experimental works of this facility have provided accurate data for dynamics, mixing and combustion modes [7]. By a comparison to these experimental data, the efficiency of each model, in terms of accuracy and computational costs, is determined.

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