Supercritical Fluid Flow in Rocket Motor Engines

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1 Introduction

Designing a rocket engine combustion chamber requires a particular attention to the cooling system and the propellant injection and combustion. The wall heat transfer is a key-point to increase the life cycle or prevent the failure of combustion chamber walls. Regenerative or forced convection cooling are the most common methods used: a cryogenic fluid, typically hydrogen or methane, in a supercritical state, *i.e.* both the pressure and temperature are above the respective critical values of the fuel, flows in small channels that are imbedded in the chamber walls and the nozzle throat portion, and absorbs heat from the hot-gas side wall. For such configurations, experiments over the past ten years have shown significant thermal-load sensitivity to the channel geometry and fluid properties. For example, the use of high aspect ratio (height/width) cooling channels (HARCC) [1,2] is a promising technique to reduce the near wall temperature of the combustion chamber for a limited pressure drop. After travelling through the cooling system, the coolant fluid is injected into the combustion chamber in which a very high pressure of the order of 10 MPa and above prevails. The identification of the resulting supercritical flame stabilization mechanism is essential to provide insight into the supercritical combustion dynamics, *i.e.* guidance for the injector design of liquid rocket engines. A poor flame stabilization may lead to harmful instabilities or flame blow-off [3]. For instance, at low (0.15 MPa) [4] and intermediate (1.0-2.5 MPa) [7] pressures the experimental results show that the methane flame is lifted off from the rim of the LOx post, and less stabilized compared to LOx/H_2 flame. However, at near- and supercritical pressures, experiments show that the flame is attached/anchored in the vicinity of the LOx post [5]. This high pressure observation is similar to the behavior of the supercritical LOx/H_2 flames studied by Mayer *et al.* [6]. In addition, Singla *et al.* [7] observed that the LOx droplets penetrated into the inner flame resulting in a secondary flame and a larger expansion angle, when both LOx and CH_4 were injected at trans-critical conditions, *i.e.* pressure is above critical but temperature is below critical. However, LOx droplet penetration was not observed when CH_4 was in gaseous phase, and when the LOx was injected at subcritical temperatures. In addition, quite a few experimental and numerical studies on supercritical mixing and combustion have been conducted for both LOX/H_2 and LOX/CH_4 systems [8-13]. However, the flame stabilization and subsequent development is still not well understood for supercritical LOX methane combustion.

In the present article, both issues are studied with one LES (Large eddy simulation) numerical code (see for example [14]), which has the following characteristics: a preconditioning scheme is applied to simulate either sub- or super-sonic flows; the spatial discretization is achieved with a fourth-order, central-difference scheme (acronym 4CD) in generalized coordinates; to ensure computational stability and to prevent numerical oscillations in regions with steep gradients, a fourth-order scalar dissipation with a total-variation-diminishing switch developed by Swanson and Turkel is used. A unified treatment of general fluid thermodynamics, based on the concepts of partial-mass and partial-density properties is established for the modified Soave-Redlich-Kwong equation of state. Transport properties, such as viscosity and thermal conductivity, are evaluated using an extended corresponding-state theory. Mass diffusivity is obtained by means of the Takahashi method, calibrated for high-pressure conditions. More details are given in [15] and [16] for the present large eddy simulations (LES) of a channel flow and LOx/CH_4 combustion of a shear coaxial injector.

2 Channel Flow Simulation

The channel flow configuration mimics the HARCC or EH3C (Electrically Heated Curved Cooling Channel) experimental facilities [17,18]. H_2 flows at 119 m/s with an inlet temperature fixed to T_{inj} = 78 K (> 33.15 K, the H_2 critical temperature), inside a rectangular channel having the following dimensions: Lx = 188 mm, Ly = 0.5 mm and Lz = 4.6 mm. Note that only $Lx/2$ is considered here to reduce the computation cost. The channel walls are adiabatic except that the bottom wall is heated to a temperature of T_s = 650 K. The same channel configuration is used for the methane flow, but with a methane inlet temperature of T_{inj} = 296 K and a bottom wall temperature of 465 K. We simulate a non-periodic channel flow with a reference pressure is 3.7 MPa. This is well above the critical pressure of H_2 (1.3 MPa) but below the critical pressure of CH_4 (4.6 MPa). The mesh system consists of 500 × 150 × 150 points in the *x, y,* and *z* directions, respectively, with a near wall refinement for the sidewalls; the mesh system is divided into 10×3×3 blocks to run on the same number of processors.

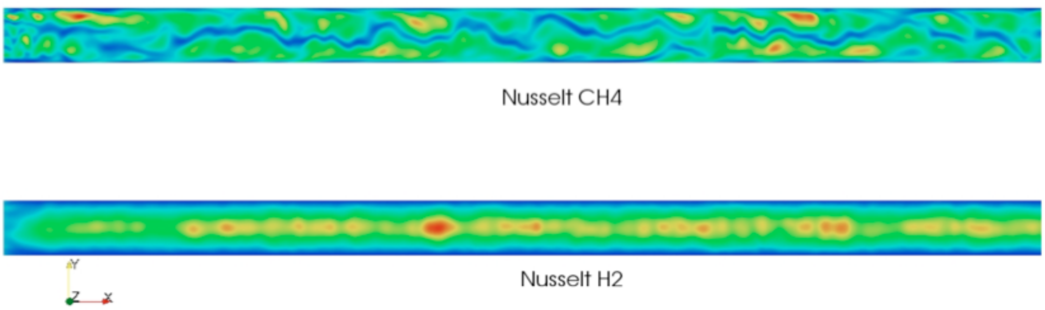

Figure 1. CH_4 and H_2 Nusselt number using the original code (4CD).

The topologies of the Nusselt number for the H_2 and CH_4 flows in Fig. 1, exhibit a very different behavior. The Nusselt number is given by the following relation:

$$Nu = \frac{\partial \langle T^* \rangle}{\partial z^*} \quad \text{with} \quad \langle T^* \rangle = \frac{T_s - \langle T \rangle}{T_s - T_{inj}} \quad \text{and} \quad z^* = \frac{z}{D_h}$$

where D_h is the hydraulic diameter. For the CH_4 test case, the heat exchange is minimum in the center part of the channel flow and maximum near the lateral walls; for H_2, we have the opposite. To decrease the impact of the numerical scheme on these simulations, 4CD is switched to a WENO formulation [16] and results on H_2 test case is plotted in Fig. 2. A much more turbulent behavior is observed with pockets of hot and cold fluid. This difference may be explained by the introduction of artificial viscosity required to stabilize such a flow with a 4CD numerical scheme. The Reynolds number being quite low, the additional viscosity damps down most of the turbulent structures and yields a laminar-like flow. This additional viscosity is not present when the WENO scheme is used. The numerical dissipation is then less important and coherent structures can naturally develop. As a consequence, the resolved heat transfer increases as observed on the Nusselt number fields in Figs. 1 and 2. Decreasing the additional viscosity associated to the 4CD scheme makes the code blowing up; as a consequence, the number of mesh points should then be increased. Finally, in Figs. 1 and 2, only the resolved part of the Nusselt number is considered. A sub-grid scale term should be added to compare the numerical results with the experimental one.

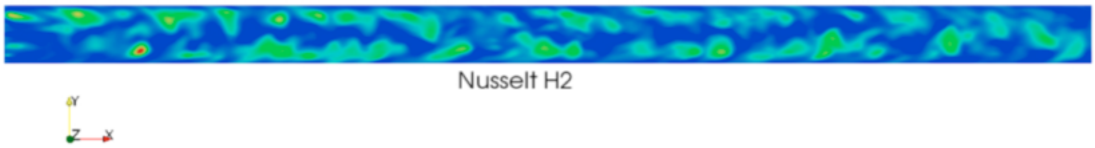

Figure 2. H_2 Nusselt number using the WENO methodology.

3 LOx/Methane Combustion

A systematic numerical study [9] is performed to investigate the supercritical mixing and combustion of LOx and methane in a typical shear coaxial injector, using a steady laminar flamelet model (SLFM) [19] and the extended flamelet/progress variable approach (E-FPVM) [20]. In SLFM, the thermochemistry state relation is established through a steady-state flamelet approach featuring detailed oxygen/methane chemistry with 16 species and 16 chemical reactions [21]. For E-FPVM, the flamelet library is generated using the FlameMaster code developed by Pitsch [22] with the reduced kinetic mechanism by Peters and Rogg. Two- and three-dimensional simulations are conducted to study the flame stabilization, and the flow and combustion dynamics. For the two-dimensional test case, both turbulent combustion models predict a flame attached to the splitter plate. The flame structure is composed of two flame fronts. Unburned liquid oxygen shed off from the liquid oxygen due to the shear stress from the fast and hot combustion products, resulting in larger expansion of the flame. Then the unburned oxygen ligaments continue to mix with methane in the outer region, forming secondary flames, which were also observed in Singla *et al.*'s work [7]. However, the secondary flames here are formed from the entrainment of large-scale oxygen sturcutres into the fuel rich stream, and insufficient small scale mixing of fuel and oxidizer, which is different from those observed in Singla's experiments, where droplets penetration of the flame accounts for the secondary flame. For the three-dimensional configuration, a co-flowing methane (outer) and oxygen (inner) streams are injected through a coaxial nozzle separated by a 0.38 mm thick LOx post. The inner diameter of the LOx post is 3.42 mm, and the outer diameter of the methane annulus is 5.18 mm. The injector geometry is chosen to match the one employed in an experimental study of high-pressure LOx/methane combustion [23]. Figure 3 shows the iso-surface of the vorticity magnitude colored by the mixture fraction. The two double circles represent the location of the injector backplane. In the near field, large toroidal structures represent the strong shear layer between the oxygen and methane streams. These structures rapidly break up into finer structures associated with mixing of the two propellants. These three-dimensional flow structures determine the mixing process and thus the combustion dynamics, but cannot be modeled in the two-dimensional splitter plate case. Thus, the three dimensional study provides extra insights into the flow structures and flame dynamics that was not possible in the two-dimensional study. This study is still in progress and is expected to provide substantial improvement in understanding supercritical combustion associated with shear coaxial injectors.

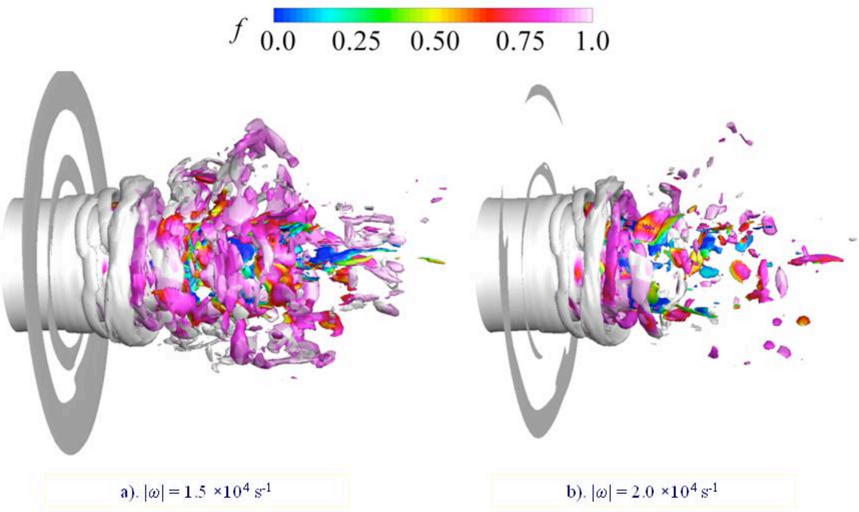

Figure 3. Snapshots of vorticity magnitude iso-surface colored by the mixture fraction. Pressure is set to 10 MPa, T_{LOX}=120 K, T_{CH4}=300K. Injector dimension: D_{LOX}=3.42 mm, LOX post δ=0.38 mm, D_{CH4}=5.18 mm.

4 Conclusion

Dealing with supercritical flows requires a special treatment of thermodynamics and numerics. For the cooling channel study, a shock-capturing WENO numerical scheme has been extended to real gases and applied to the simulation of supercritical fluids. Compared to the fourth-order, central- difference scheme, the WENO formulation exhibits a better behavior for such a complex flow. More precisely, the intrinsic viscosity of the numerical scheme is sufficient to achieve numerical stability and resolve flow structures and heat transfer that are cancelled out with the 4CD scheme associated with too much artificial viscosity. Nevertheless, a much more refined mesh should be used to clearly improve the results. A subgrid scale term should also be added to the Nusselt definition in order to include the contribution from subgrid scales.

Concerning the reactive test case, the flamelet model and flamelet/progress-variable model have been successfully applied to the large- eddy simulations of LOX/methane flames at supercritical pressures. The results show that the flame is always anchored in the recirculation zone immediately after the splitter plate. Turbulence is not strong enough to extinguish the non-premixed flame. The flame stabilization is found to be achieved through the recirculation zone formed in the near region of the splitter plate. The flamelet/progress-variable case further confirms that the artificially quenched flame can be re-established as far as the quenching distance is within the recirculation zone. The study is extended to three-dimensional simulation of a typical shear-coaxial injector. The preliminary results confirm the flame stabilization mechanism, and show that strong three-dimensional flow structures dominate the mixing and combustion processes. Further study is being conducted to provide more quantitative knowledge to the flow and combustion dynamics of supercritical fluids associated with a shear coaxial injector.

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