Numerical simulation of cryogenic flames under high frequency acoustic modulation

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1 Introduction

Liquid rocket engines (LREs) may develop high frequency combustion instabilities resulting from a complex coupling between transcritical coaxial jet dynamics, cryogenic combustion and transverse acoustic modes of the chamber [1]. Despite decades of sustained research, the fundamental mechanisms driving this phenomenon are not well understood. This problem is difficult to investigate in full scale configurations for many reasons and in particular because the power density is high and pressure and temperature conditions are extreme. Instrumentation is difficult to install, visualization is not feasible except perhaps through the nozzle but this is limited by the throat diameter and the cost of each test is high. To augment the specific impulse, modern cryogenic LREs operate at pressures exceeding the critical value. In the Vulcain engine of the Ariane 5 launcher the chamber pressure under nominal conditions is over 10 MPa, while the liquid oxygen critical pressure is $p_c(O_2) = 5.04$ MPa. This propellant is injected at a temperature which is well below its critical value $T_c(O_2) = 154$ K. Under such extreme conditions referred to as "transcritical", the working fluid strongly departs from a perfect gas behavior [2]. Its surface tension and latent heat of vaporization vanish and the break-down, atomization and droplet generation processes prevailing at subcritical pressures, no longer occur. This is replaced by mass transfer from the dense oxygen stream to the lighter surrounding stream. Thus, mixing and combustion take place in a flow featuring large density gradients.

To observe high-frequency combustion oscillations, detailed non-reactive and reactive experiments have been carried out on a multiple injector combustor (MIC) mounted on the Mascotte cryogenic test bench at ONERA. This transcritical combustor features five coaxial methane/oxygen injectors and operates under conditions which are representative of those prevailing in full scale engines. The MIC is equipped with a Very High Amplitude Modulator (VHAM), which generates realistic acoustic oscillations with an amplitude of 20% of the chamber pressure [3]. The flame structure under transcritical conditions is now well documented [4, 5]. These data provide useful information for numerical modeling; they have been used to guide simulation of transcritical flows. The interaction of transverse acoustic waves with cryogenic flames has also been addressed. Under high amplitude oscillations, the flame length is strongly shortened, the spreading angle is increased and the flame motion follows the transverse acoustic velocity [6,7]. These observations provide useful clues on the coupling mechanism but are unfortunately limited because the system operates under extreme conditions. Visualization is limited to backlighting and emission imaging. This can be combined with analysis of the signals recorded by pressure sensors flush mounted on the chamber walls.

The objective of the present work is to complement these promising experimental data with simulations in order to investigate the fundamental phenomena driving high frequency instabilities. Two complementary numerical studies are carried out using the Large-Eddy Simulation (LES) framework. The flow solver used in this study is briefly described in Sec. 2. A 3D configuration of a transcritical coaxial injector under acoustic perturbations is simulated in a first step (Sec. 3). This case aims at studying the dynamics of a transcritical flame under different transverse oscillation amplitudes and phases to get a precise insight into the physics of flame/acoustics interactions. These calculations are used to explore the domain of parameters and study the coupling between acoustics and combustion for a wide range of thermodynamic conditions and for acoustic modulation levels which are difficult to reach in the laboratory scale test bench. The second simulation, which is detailed in Sec. 4, is a 2D configuration reproducing Mascotte geometry and operating conditions. While it is clear that 2D simulations bring little physical insight in the complex three-dimensional processes involved in the experiment, this can be considered as a useful test to prepare future 3D calculations. These heavy simulations aim at retrieving experimental results to validate the numerical approach and complement the experimental data.

2 Brief description of the LES solver

The unstructured AVBP solver [8] is used to integrate the three-dimensional compressible Navier-Stokes equations for a multicomponent mixture of fluids. Numerical integration uses a low-dissipation centered scheme, third-order in time and space [9]. This solver is highly efficient for massively parallel computations. Boundary conditions are treated with the characteristic wave decomposition method NSCBC, adapted to real-gas thermodynamics [10]. A real gas version of the AVBP flow solver has been developed more recently [11,12]. This code accounts for real-gas non-idealities by representing the fluid state with the Soave-Redlich-Kwong equation of state [13]:

$$p = \frac{\rho r T}{1-\rho b_m} - \frac{\rho^2 a_m(T)}{1+\rho b_m} \tag{1}$$

with T the temperature and $r = R/W$, where R designates the universal gas constant and W is the molar mass. The coefficients $a_m(T)$ and b_m are calculated according to [14]. Equation 1 is used for a consistent derivation of the pressure dependence of thermodynamic properties (internal energy, enthalpy, specific heats, compressibility, ...). Each of these properties is expressed as the sum of the ideal-gas property and a departure function, as described in [15]. Chemical reaction process is handled using an infinitely fast chemistry model presented in [16].

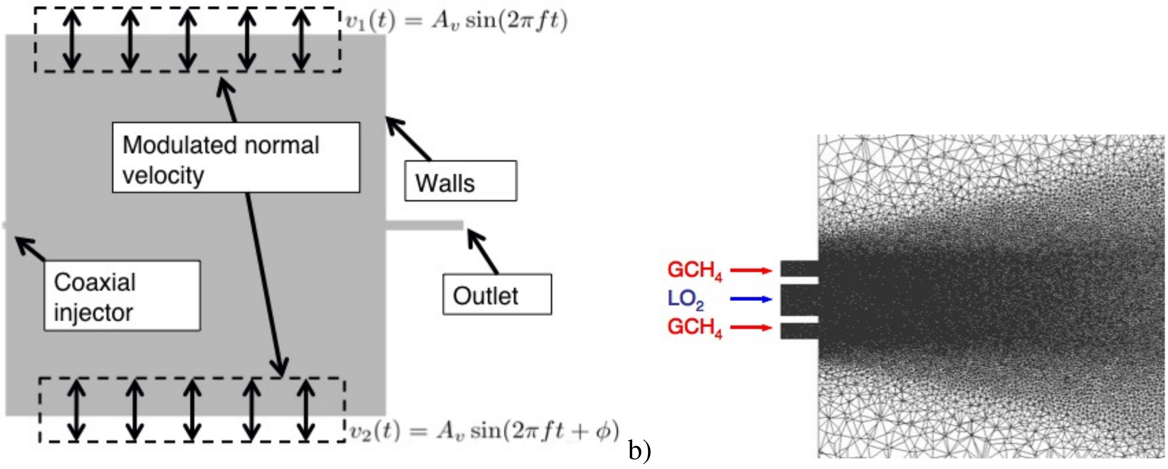
3 LES of a transcritical coaxial flame under transverse acoustic modulation

This configuration is typical of a coaxial laboratory-scale burner, like that examined in [5] and simulated more recently with the AVBP-RG solver in [16]. A similar numerical approach is retained here, but liquid oxygen injection velocity is slightly increased in order to limit the computational cost and perform parametric studies.

A longitudinal slice of the domain is depicted in Fig. 1a. The domain comprises a coaxial methane/oxygen injector (Fig. 1b), a square section chamber, much larger than the injector diameter to avoid confinement effects, and a small diameter exhaust pipe. A closer view of the injector geometry is shown in Fig. 1b. Liquid oxygen is injected by the central post at 100 K and 10 m/s whereas methane is injected at 300 K and 100 m/s, corresponding to a global equivalence ratio equal to 11.6. The chamber is initially filled with hot gases at 1 040 K and is maintained at a pressure of 10 MPa. The mesh comprises 1,900,000 nodes corresponding to 11,000,000 tetrahedra. The mesh is refined near the injector with a constant element size in the injector and on a distance of 10 inner injector diameters. It is then gradually coarsened downstream.

The transverse acoustic modulation is introduced in the computation domain following a method presented in [17]: a normal velocity harmonic modulation is used as a limit condition on two boundaries (Fig. 1a). The velocity modulation takes the form:

$$v_1(t) = A_v \sin(2\pi f t) \qquad v_2(t) = A_v \sin(2\pi f t + \phi) \tag{2}$$



a) b)

Figure 1: Longitudinal cuts of the configuration for transverse acoustic modulation study. (a) Whole domain geometry and boundary conditions (b) Closer view of the coaxial injector.

where v_1 and v_2 are the normal velocities at the upper and lower sides of the chamber respectively, A_v is the oscillation amplitude, f its frequency, t is the time, and ϕ the phase. The frequency modulation f is set equal to 2000 Hz and ϕ is chosen to retrieve successively pressure node ($\phi = \pi$) or pressure anti-node ($\phi = 0$) in the flame vicinity.

An example of result featuring the flame without and with acoustic modulation is plotted in Fig. 2. The modulated simulation shows a shorter flame oscillating with the transverse velocity fluctuations.

4 LES of the MIC configuration

The computational domain is now a 2D longitudinal cut of the MIC configuration. Reactants enter the rectangular chamber through five coaxial injectors and exit through two nozzles located downstream of the chamber. The experimental acoustic excitation is produced by a rotating toothed wheel which closes and opens each nozzle alternatively. In doing so, it modulates 100% of the exhaust flow, generating oscillation amplitudes which reach 20% of the combustion chamber pressure. In order to numerically reproduce this system, outlet target pressure at the two exhaust nozzle boundaries are modulated (Fig. 3). Their temporal evolution is harmonic:

$$p_1(t) = p_0 + A_p \sin(2\pi f t) \qquad p_2(t) = p_0 + A_p \sin(2\pi f t + \pi) \tag{3}$$

where $p_1(t)$ and $p_2(t)$ are the imposed pressures at the upper and lower exhaust nozzles respectively, $p_0 = 7.0$ MPa is the average chamber pressure, A_p is the oscillation amplitude, f its frequency and t is the time. The frequency f is chosen to match one of the chamber eigenfrequencies in order to study resonant interactions.
Liquid oxygen and gaseous methane are injected at 80 K and 288 K respectively. To avoid recirculation

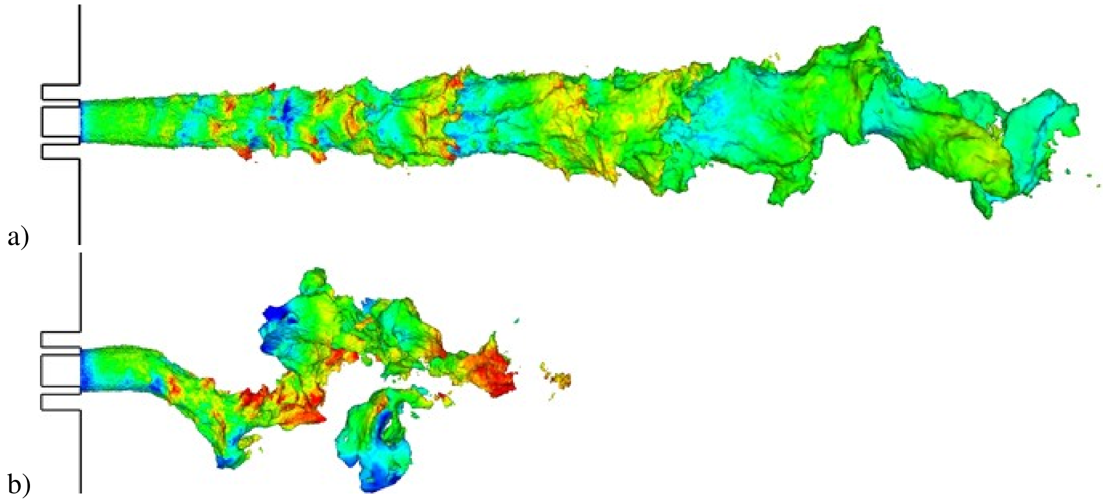


Figure 2: Instantaneous iso-surface of temperature (1500 K) colored by axial velocity (red: 100 m/s ; blue: -10 m/s). (a) Without acoustic modulation (b) With acoustic modulation ($f = 2000Hz$, $\phi = \pi$).

near the injection plane, a methane coflow is injected through the backplane wall, between the injectors at 288 K. Injection velocities are chosen to guarantee the same equivalence ratio as in Méry's Mascotte test series [7]. The mesh, which comprises 400,000 nodes and 900,000 tetrahedra, is depicted in Fig. 3.

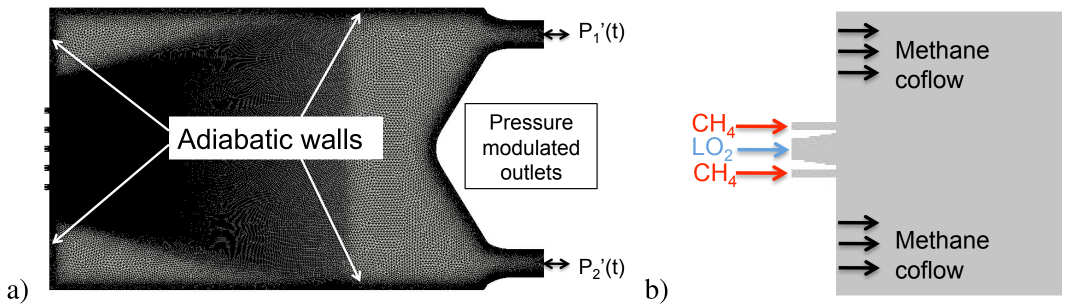


Figure 3: (a) Whole domain geometry and boundary conditions (b) Injection conditions

Illustrative results are given in Fig. 4 and 5. This situation correspond to an excitation frequency of 3 200 Hz, which pertains to the first transverse mode coupled with the second longitudinal mode (1T2L eigenmode) of the chamber.

Three main observations can be drawn from these calculations:

- The method used for introducing acoustic modulations into the computation domain yields suitable levels of pressure oscillations, retrieves the proper mode shape and correctly describes the modal perturbation in the system. As shown in figure 4, the 1T2L mode is correctly established in the chamber. It can be pointed out that this figure is not filtered at the modulation frequency and that the pressure spatial distribution appears naturally,
- Even in 2D, this multiple injector configuration gives rise to a complex, highly turbulent, flow. It clearly highlights the importance of mutual interactions in rocket engine configurations, where, for example, flames form a highly compact arrangement,

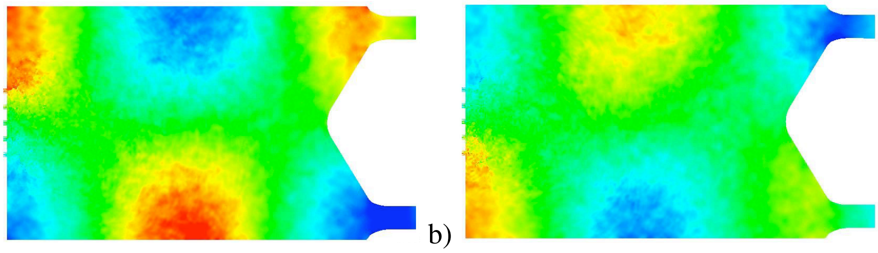


Figure 4: Pressure instantaneous field with a pressure modulation at 3 200 Hz at the nozzle exhaust (Red: 7.7 MPa, Blue: 6.7 MPa). (a) and (b) are snapshots taken in phase opposition.

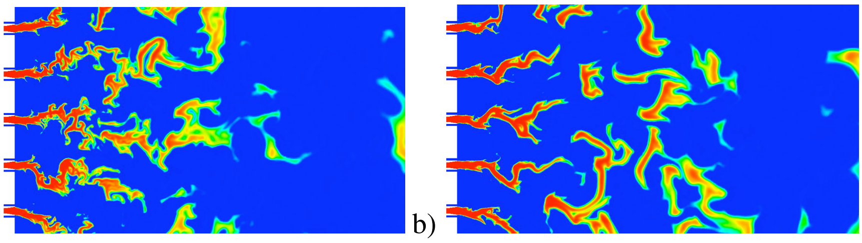


Figure 5: Instantaneous oxygen mass fraction field with a modulation (left) and without any modulation (right)

- First results indicate that the combustion zone becomes more compact when the flames are submitted to transverse acoustic modulation, a result which is consistent with experimental observations.

5 Conclusion

The dynamics of transcritical flames under high-frequency transverse acoustic modulations are simulated using large eddy simulations. Two different methods are exploited to introduce acoustic oscillations into the computational domain. The first method is used to examine the coupling between a single flame and a transverse acoustic motion. The second is used to simulate the flame dynamics in a multiple injector combustor. Encouraging results are obtained. As observed in Mascotte experiments, simulations feature shorter flames under acoustic modulations when compared to non-modulated computations. A 3D simulation of the modulated multiple injector combustor is now being carried out.

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