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Multiphase Flow Large-Eddy Simulation Study of the Fuel Split Effects on Combustion Instabilities in an Ultra-Low-NO_x Annular Combustor

This paper describes the application of a coupled acoustic model/large-eddy simulation approach to assess the effect of fuel split on combustion instabilities in an industrial ultra-low-NO_x annular combustor. Multiphase flow LES and an analytical model (analytical tool to analyze and control azimuthal modes in annular chambers (ATACAMAC)) to predict thermoacoustic modes are combined to reveal and compare two mechanisms leading to thermoacoustic instabilities: (1) a gaseous type in the multipoint zone (MPZ) where acoustics generates vortex shedding, which then wrinkle the flame front, and (2) a multiphase flow type in the pilot zone (PZ) where acoustics can modify the liquid fuel transport and the evaporation process leading to gaseous fuel oscillations. The aim of this paper is to investigate these mechanisms by changing the fuel split (from 5% to 20%, mainly affecting the PZ and mechanism 2) to assess which mechanism controls the flame dynamics. First, the eigenmodes of the annular chamber are investigated using an analytical model validated by 3D Helmholtz simulations. Then, multiphase flow LES are forced at the eigenfrequencies of the chamber for three different fuel split values. Key features of the flow and flame dynamics are investigated. Results show that acoustic forcing generates gaseous fuel oscillations in the PZ, which strongly depend on the fuel split parameter. However, the correlation between acoustics and the global (pilot + multipoint) heat release fluctuations highlights no dependency on the fuel split staging. It suggests that vortex shedding in the MPZ, almost not depending on the fuel split, is the main feature controlling the flame dynamics for this engine. [DOI: 10.1115/1.4031871]

Introduction

Moving toward very high overall pressure ratio engines to reduce pollutant emissions requires to push the lean burn technologies toward their limits. Inherent drawbacks of these new technologies have therefore to be accounted for at the design stage. This observation is especially true when innovative lean combustion chambers with multipoint injection systems are used since they are prone to combustion instabilities, a phenomenon investigated here in the LEMCOTEC[2] engine. These thermoacoustic instabilities correspond to the coupling between acoustics and the unsteady heat release. This interaction usually involves intermediate convective mechanisms such as vortex shedding [1] or fuel oscillations [2]. Under some conditions, this coupling can become unstable giving rise to strong pressure oscillations in the chamber, which can affect significantly the engine performance or even damage the combustion chamber [3].

Predicting such unstable acoustic modes appearing in annular gas turbines has been the topic of multiple research activities over

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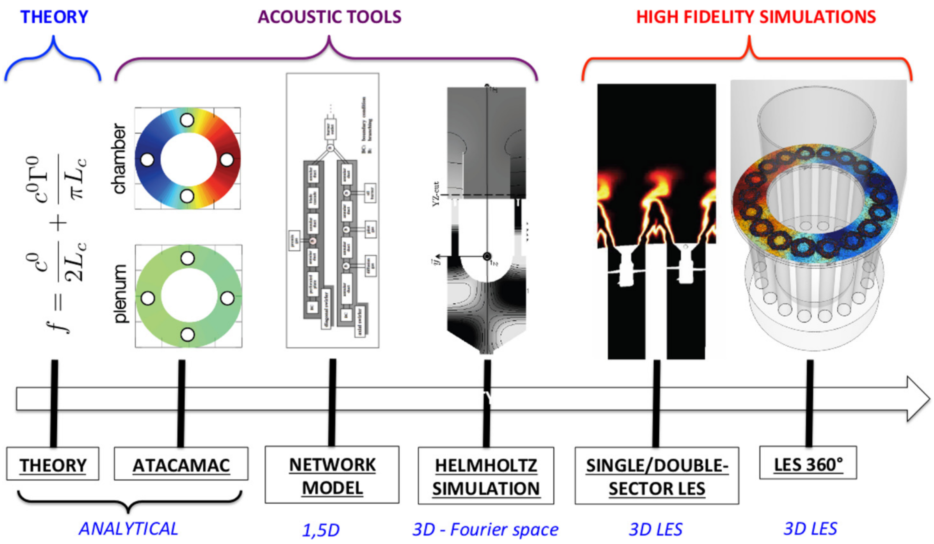

Fig. 1 Tools developed at CERFACS for combustion instabilities: low-order models (ATACAMAC), Helmholtz simulations (AVSP), and large eddy simulations (AVBP)

the last decade [3,4]. To tackle the complexity of this problem, numerical methods have progressed in three directions as shown in Fig. 1: (1) Analytical and low-order models have been developed [5,6] to reduce computational costs and provide clues on the underlying phenomena involved in combustion instabilities, (2) 3D acoustic tools [7,8] have been used to predict unstable modes in complex industrial combustors, and (3) large-eddy simulation (LES) of isolated sectors or full 360 deg annular chambers have been performed [9,10].

Today, all these tools have to be used together to identify unstable modes and assess the sensitivity of the growth rate to uncertain parameters (geometric details, operating points, etc.) or models (turbulence, boundary conditions, etc.) [10]. These methodologies are applied in this paper on the liquid-fueled annular chamber LEMCOTEC. In particular, two intermediate mechanisms controlling thermoacoustic oscillations are investigated: (1) a classical gaseous type where acoustics ($\hat{p}$) generates a vortex shedding (i.e., unsteady vorticity $\hat{\omega}$), which propagates downstream and interacts with the flame [1] (Fig. 2, top), and (2) a multiphase type where acoustics can modify the liquid fuel transport, its evaporation generates gaseous fuel oscillations [2] ($\hat{\varphi}$, Fig. 2, bottom). The global heat release fluctuations $\hat{q}$ can therefore be modeled by [11]

$$\frac{\hat{q}}{\bar{q}} = \underbrace{\hat{\rho}/\bar{\rho}}_{\text{Negligible}} + \underbrace{\text{FTF}_p(\omega)\frac{\hat{p}}{\bar{p}}}_{\text{Vortex shedding}} + \underbrace{\text{FTF}_\varphi(\omega)\frac{\hat{\varphi}}{\bar{\varphi}}}_{\text{Fuel oscillations}} \tag{1}$$

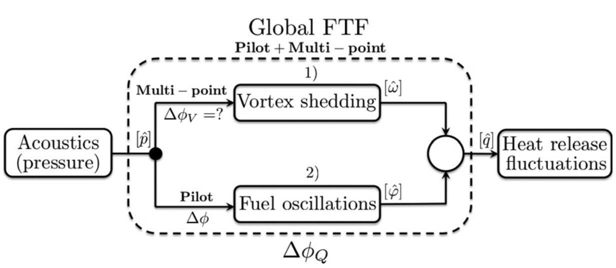

Fig. 2 Block diagram showing mechanisms 1 (vortex shedding $\hat{\omega}$) and 2 (fuel oscillations $\hat{\varphi}$), leading to heat release oscillations $\hat{q}$

where FTF_p is the flame transfer function (FTF) corresponding to the flame response to the vortex shedding induced by acoustics ($\hat{p}$ or $\hat{u}$) and wrinkling the flame surface, FTF_φ is the flame response to the equivalence ratio fluctuations $\hat{\varphi}$, and $\bar{a}$ and $\hat{a}$ correspond to the mean and Fourier transform of any variable a. The relative density fluctuation $\hat{\rho}/\bar{\rho}$ is neglected here since $\hat{\rho}/\bar{\rho} = \hat{p}/\gamma\bar{p} \ll 1$ (small acoustic disturbances assumption).

In industrial configurations equipped with multipoint injection systems, these two mechanisms (Fig. 2) can appear simultaneously at several locations because of the fuel injection generating multiple flames: some flames can exhibit the first mechanism while the others can be affected by the second mechanism, or even a combination of them. For example, in a configuration with two flames, where vortex shedding controls "Flame 1" and fuel oscillations control "Flame 2," Eq. (1) becomes

$$\frac{\hat{q}}{\bar{q}} = \underbrace{\alpha\text{FTF}_p(\omega)\frac{\hat{p}_1}{\bar{p}}}_{\text{Flame 1}} + \underbrace{(1-\alpha)\text{FTF}_\varphi(\omega)\frac{\hat{\varphi}_2}{\bar{\varphi}}}_{\text{Flame 2}} \tag{2}$$

where α, known as the fuel staging or fuel split, corresponds to the ratio between the fuel mass flow rate injected at the injector 1 and the total mass flow rate $(1+2)$. Thus, changing the fuel distribution α might become an additional degree-of-freedom to stabilize the configuration [12]. However, experimental or numerical study of the effect of this fuel split on instabilities in modern annular gas turbines is still missing.

The identification of these two mechanisms as well as the effect of fuel split on azimuthal thermoacoustic instabilities are investigated numerically here in the LEMCOTEC annular engine containing an innovative multipoint injection system. First, eigenmodes of the configuration are studied using an analytical model and validated by 3D Helmholtz simulations. Then, a multiphase flow LES is forced at the eigenfrequencies found for three different fuel split values to investigate flame responses to acoustics. To the best of the authors' knowledge, acoustically forcing a multiphase flow LES was never done before, although this is a necessary step to better understand the thermoacoustics in complex industrial configurations. Results reveal that pilot and multipoint flames behave differently to the pressure oscillations: gaseous oscillations in the PZ and vortex shedding in the MPZ. Finally, the phase lags of the different mechanisms are extracted and compared, showing that vortex shedding in the MPZ controls combustion instabilities at this operating point.

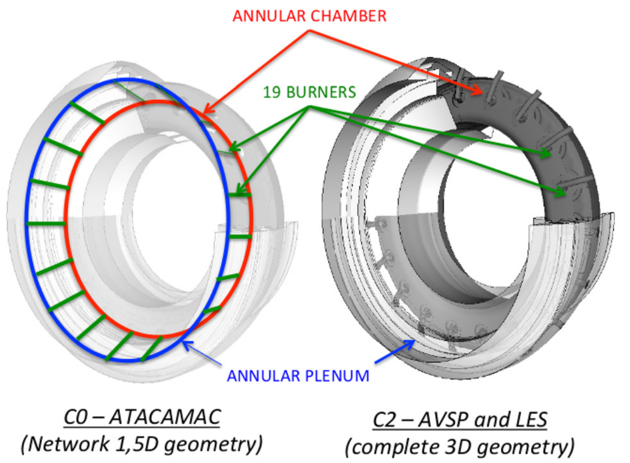

Fig. 3 The ultra-low-NO$_x$ annular configuration LEMCOTEC with $N = 19$ identical sectors. Network model for ATACAMAC (C0—left) and a complete configuration with detailed swirlers for LES (C2—right).

The Ultra-Low-NO$_x$ Annular Configuration LEMCOTEC

The target configuration is the ultra-low-NO$_x$ combustor currently developed by SNECMA as part of the LEMCOTEC project (Fig. 3, right). Each of the $N = 19$ identical sectors (Fig. 4) comprises a flame tube, an inner as well as an outer bypass lines, and a multipoint injection system to achieve low emission targets while keeping operability for the whole power range. This type of injection system is designed to generate two distinct flames:

(i) The PZ is controlled with a central fuel injector and an axial swirler. The resulting central pilot flame burns near stoichiometric conditions. The high temperature of the recirculating flow is a strong stabilization mechanism at low-power conditions.

(ii) The MPZ is controlled with a radial swirler and a multipoint injector (multiple holes in the inner part of the swirler). Injection of fuel in this swirling environment promotes efficient atomization and rapid mixing between liquid fuel and air. The fuel–air ratio in this zone is chosen to obtain lean conditions. The multipoint flame provides most of the power at high-power conditions such as takeoff and cruise. Lean burn and associated low flame temperature is indeed essential to accomplish low emission levels.

Gaseous air from the compressor is injected at the diffuser exit and enters the annular plenum as well as the swirler with a high temperature and pressure (typically around several MPa), corresponding to the takeoff operating point retained in this study as a high-power regime. Liquid fuel is injected in both the PZ and MPZ and mixes with air after evaporation. The fuel split parameter α, defined as the ratio between the mass flow rate in the PZ to the total fuel mass flow rate, is varied from 5% to 20% (i.e., mainly affecting the pilot injection), the reference case being $\alpha = 10\%$. The global equivalence ratio is $\varphi = 0.42$, leading to an ultra-lean combustion regime to ensure low pollutant emissions.

Eigenmodes of the Annular Combustor

Prior to a complete stability analysis, the forcing pulsation ω, used to excite mechanisms 1 and 2 (Fig. 2) in LES, has to be determined. Two different strategies have been developed recently to analyze azimuthal modes in 360 deg configurations: (1) 3D Helmholtz solvers, like AVSP [8], have been adapted to annular chambers [7,8] and (2) analytical approaches, such as ATACAMAC [6] used here, have been proposed to avoid the costs of 3D formulations. This last class of approach is used, and validated against AVSP, to determine eigenmodes as well as anticipating acoustic/flame coupling on the LEMCOTEC engine containing $N = 19$ burners at low cost (predesign stage).

Acoustic Modes With Passive Flames. First, ATACAMAC is used with passive flames (i.e., no FTF) to provide a first clue on forcing frequencies. ATACAMAC, developed at CERFACS [6], is based on a quasi one-dimensional network modeling the annular plenum and the annular chamber connected by N burners (Fig. 3, left). The chamber outlet corresponds to a chocked nozzle, approximated by an acoustic boundary condition $u' = 0$.

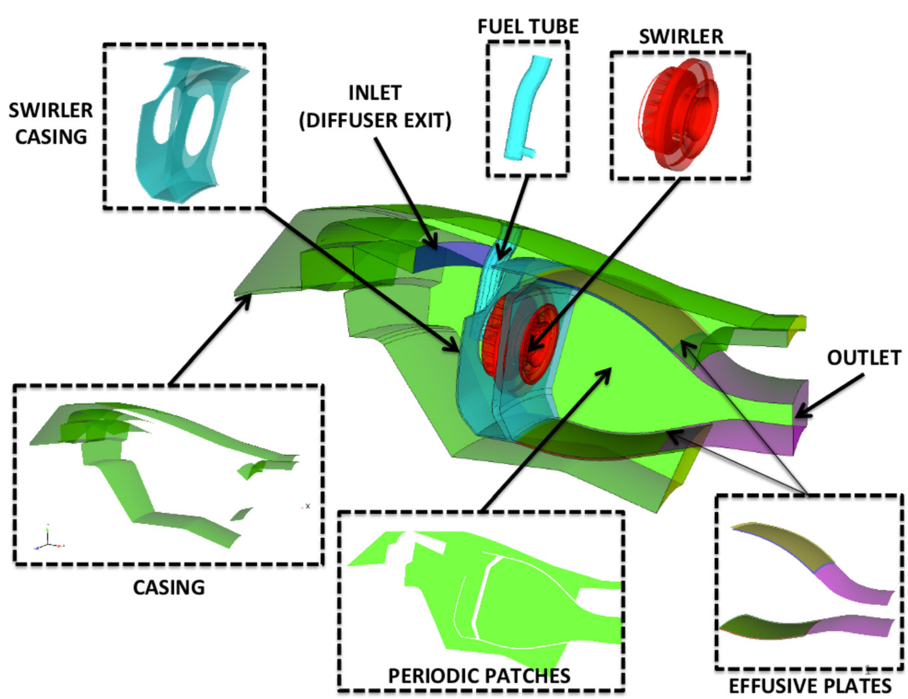

Fig. 4 Single sector of the industrial ultra-low-NO$_x$ configuration LEMCOTEC

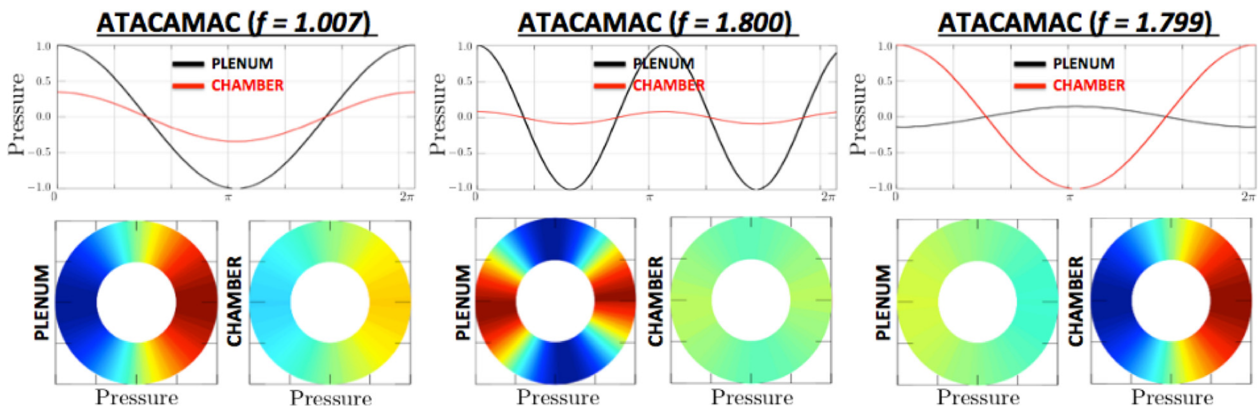

Fig. 5 ATACAMAC results of the first three azimuthal modes of the LEMCOTEC configuration with $N = 19$ burners and passive flames: normalized frequency (top), pressure plots over the azimuthal direction (middle), and pressure fields in annular cavities (bottom)

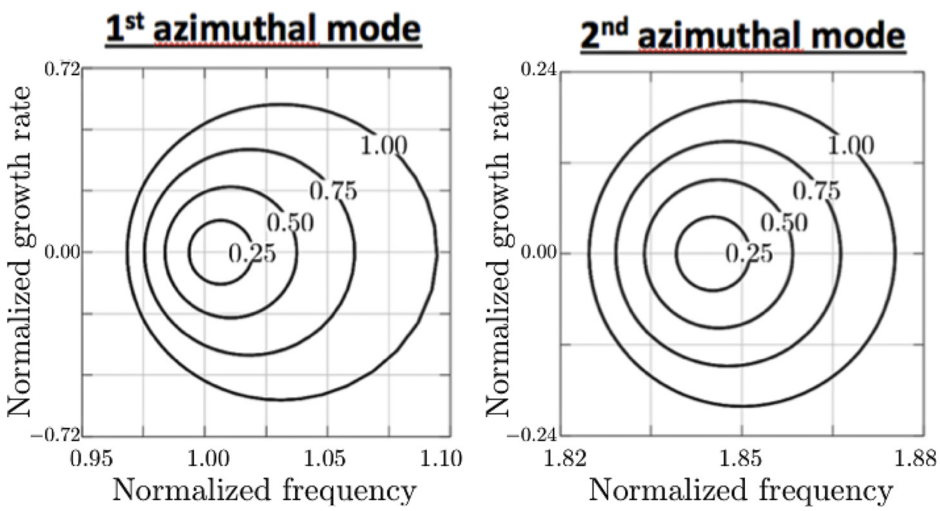

Fig. 6 Stability maps obtained by ATACAMAC for the first and second azimuthal modes of the annular engine versus varying FTF$_u$ amplitudes ($n_u = 0.25$–1.0) and phase lags ($\Delta\phi_u = 0$ –2π)

However, no data is available for the plenum inlet. For the sake of simplicity, a condition $u' = 0$ was also used for the plenum inlet.

ATACAMAC results[3] for the first three azimuthal modes are displayed in Fig. 5 and are compared with the 3D Helmholtz solver results [8]. Both frequencies and mode structures predictions given by ATACAMAC (f) and AVSP (f^*) are in good agreement and can be identified:

(i) Mode at $f = 1.007$ ($f^* = 1.0$) is the first azimuthal mode associated to the plenum geometry. Both tools show that acoustic activity is also present in the annular chamber (50% of the pressure level in the plenum).
(ii) A longitudinal mode at $f^* = 1.429$ is obtained by AVSP but not ATACAMAC since only azimuthal modes are thought for.
(iii) Mode at $f = 1.800$ ($f^* = 1.847$) is the second azimuthal mode associated to the plenum. No acoustic is observed in the chamber.
(iv) Mode at $f = 1.799$ ($f^* = 1.83$) is the first azimuthal mode of the chamber. Note that such results show that simple analytical tools are able to separate and identify close acoustic modes ($f^* = 1.79$ and $f^* = 1.80$) at the predesign stage.

Analytical Acoustic Modes With Active Flames. The ATACAMAC tool has been validated against 3D Helmholtz simulations and a good agreement is found for passive flames. However, Bauerheim et al. [6] have shown that incorporating delayed processes, as the ones presented in Fig. 2, can modify both the coupling between annular plenum and chamber (and so eigenfrequencies at which forcing has to be performed) and hereby the stability analysis. Figure 6 displays the frequencies and growth rates depending on the input flame transfer function, which links the acoustics pressure $\hat{p}$ to the unsteady heat release $\hat{q}$: $\mathrm{FTF}_p = \hat{q}p_0/\hat{p}q_0 = n_p e^{j\Delta\phi_Q}$. Note that using a correlation with the acoustic pressure $\hat{p}$ or the axial velocity $\hat{u}$ leads to equivalent results in the harmonic regime, since they are related by the impedance $Z(\omega) = \hat{p}/(\rho^0 c^0 \hat{u})$.

ATACAMAC results (Fig. 6) show that the azimuthal modes of the LEMCOTEC engine are "weakly coupled," i.e., eigenfrequencies are not strongly modified by the flame/acoustic interactions: $f^* = 1.0$, 1.43, and 1.84 can hence be used as forcing frequencies in LES. Moreover, for weakly coupled modes, stability is given by [6]

$$\mathrm{Im}(\omega) \propto n_u(\alpha) N \sqrt{\frac{\gamma_b T_u^0}{\gamma_u T_b^0}} \sin(\Delta\phi_u(\alpha)) \tag{3}$$

where $\mathrm{Im}(\omega)$ is the growth rate of the azimuthal mode, N is the number of burners designed to comply with light-around

[3]Frequencies and growth rates have been normalized by the output of the Helmholtz solver AVSP corresponding to the first azimuthal mode.

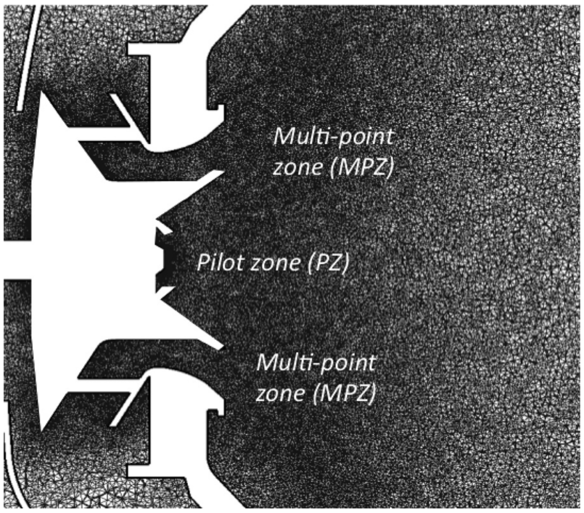

Fig. 7 Mesh around the swirler, PZ and MPZ. Details of the swirler and injection system have been blanked.

constraints, while T^0 and γ are the temperature and the ratio of the constant volume and constant pressure heat capacities in the unburnt (u) and burnt (b) gases depending on the operating condition of the engine. n_u and $\Delta\phi_u$ are the amplitude and phase lag of the classical FTF describing the interaction between the unsteady combustion and the acoustic velocity ($\text{FTF}_u = q'u_0/u'q_0 = n_u e^{j\Delta\phi_u}$), linked to the FTF_p previously described.[4] Therefore, the stability depends only here, at first order and without taking into account losses, on the phase-lag $\Delta\phi_u(\alpha)$, other parameters being always positive. This ensures that the following study of multiphase flow mechanisms encountered in the LEMCOTEC engine equipped with a multipoint injection system can be treated focusing only on phase lags and evaluating its dependency with the fuel split α (this assumption does not hold for strongly coupled modes [6]).

Large-Eddy Simulation

LES is widely recognized as an accurate method [13] to study ignition [14], temperature profiles at the combustor exit, and combustion instabilities [9] in complex configurations. Coupled to analytical tools, LES results can provide essential clues on the underlying phenomena driving thermoacoustic instabilities.

Mesh and Numerical Setup. Multiphase flow LES presented hereafter are obtained using the AVBP solver on a single sector of the annular combustor with periodic boundary conditions in the azimuthal direction. Filtered fully compressible multispecies Navier–Stokes equations are solved on an unstructured grid containing 28×10^6 cells, corresponding to a characteristic length of 0.35 mm in the flame region (Fig. 7). A centered spatial scheme with explicit time-advancement of third order in both space and time is used [15]. Turbulent subgrid stresses are modeled with the WALE approach [16]. The air inlet and combustor outlet are described by Navier–Stokes characteristic boundary conditions (NSCBCs) [17] to ensure proper treatment of acoustic wave propagation as well as reflection. Walls are considered no-slip and adiabatic.

The liquid phase (kerosene) is modeled using an Eulerian approach with the assumption of a locally monodisperse liquid phase. This methodology, implemented in AVBP, has been intensively validated [18]. First, this Eulerian approach has been compared with a Lagrangian approach and experimental [19] data on

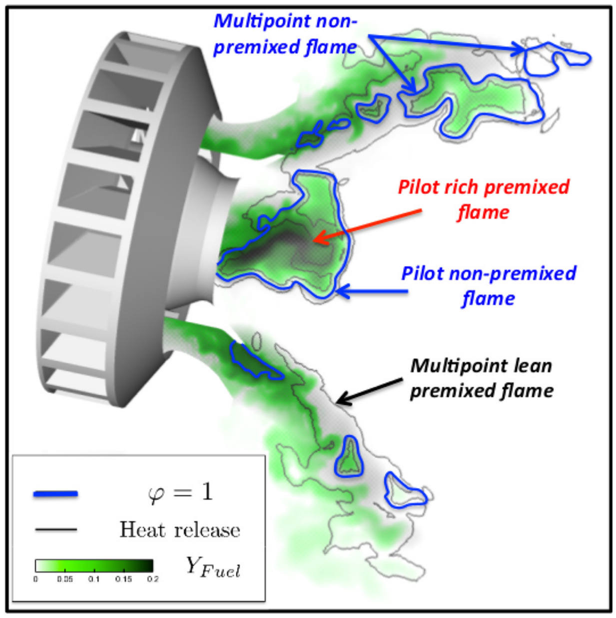

Fig. 8 Instantaneous flame nature (premixed or nonpremixed), for the case $\alpha = 10\%$, identified using the fuel mass fraction field and isocontours of heat release (thin lines) and the stoichiometric lines (φ=1, large lines)

a liquid jet in crossflow configuration. More complex validation cases have been also performed, for example, on the TLC configuration containing a multipoint injection system, similar to the one studied here. Comparisons between Eulerian [18,20] and Lagrangian [18,21] approaches with experimental data showed a good agreement. Recently, Eulerian approach has been applied to simulate the complete ignition sequence of a liquid-fueled gas turbine [22]. Similar validations (Eulerian versus Lagrangian approaches, isolated sector versus 360 deg configuration, etc.) are currently conducted at CERFACS with AVBP on the LEMCOTEC engine, regarding ignition sequences and temperature profiles issues.

In this study, several fuel split ($\alpha = \dot{m}_{PZ}/(\dot{m}_{PZ} + \dot{m}_{MPZ})$) are tested to assess its impact on flame dynamics and phase-lag $\Delta\phi$ (Fig. 2): $\alpha = 5\%$, 10%, and 20%. The fuel injection method by upstream reconstruction methodology [23] is used to model the fuel spray generated by the atomizer. However, no LES model is incorporated to take into account the interaction between acoustics and atomization. Consequently, this study only considers the effects of acoustics on evaporation and transport for the liquid phase. Chemistry is described by a six species, two-step reduced mechanism with pre-exponential adjustments to correctly reproduce flame speed and temperature for kerosene–air combustion over the whole range of flammability. The locally adaptative dynamic thickened flame model [24] is used to resolve the flame on the LES grid by taking into account the turbulence/chemistry interactions [25] depending on the local equivalence ratio φ. This is mandatory for multipoint systems leading to complex flame structures (Fig. 8) with a large range of equivalence ratio (typically here from 0 to 2.0).

Flame Shape and Dynamics

ATACAMAC has been applied to the LEMCOTEC engine (Fig. 5) to provide eigenfrequencies of the system. From a stable computation, an acoustic wave at the eigenfrequencies found by ATACAMAC is injected at the outlet into the computational domain using the NSCBC methodology [17]. This wave propagates upstream and interacts with the flame before leaving the computational domain at the inlet (nonreflecting boundary conditions are therefore required). Since the ATACAMAC results have shown that modes of the configuration are weakly coupled [6], the

[4] $\text{FTF}_u = q'u_0/u'q_0 = q'p_0/p'q_0 \times p'u_0/u'p_0 = q'p_0/p'q_0 \times p'/\rho^0c^0u' \times \rho^0c^0u^0/p^0 = \text{FTF}_p \times Z(\omega) \times \gamma M$.

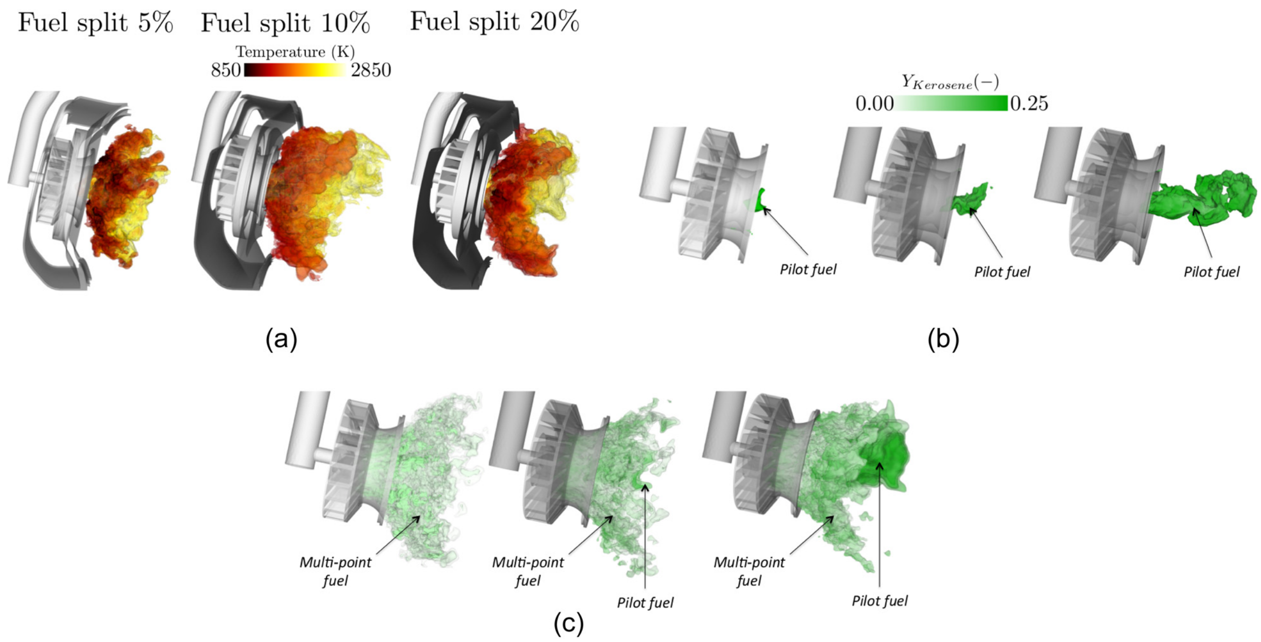

Fig. 9 Isocontours of heat release colored by temperature (top), isocontour of fuel mass fraction (rich, middle), and (lean+ reach, bottom) to visualize the flame shape as well as the pilot (middle) and multipoint (bottom) flames versus the fuel split parameter: 5% (left), 10% (middle), and 20% (right)

stability of the configuration can be studied by investigating phase lags between the unsteady combustion and acoustics. The global unsteady heat release $q'(t)$, or fuel oscillations $Y'_{\mathrm{kero}}(t)$, will be recorded and correlated to the axial velocity fluctuations $u'(t)$ or pressure $p'(t)$ giving access to these phase lags. The forcing is axial and performed on a single sector since the azimuthal mode in the annular plenum or annular chamber acts like a clock imposing an axial fluctuating mass flow rate in the burners [3,26].

Unsteady Combustion in a Multipoint Industrial Combustor. The three frequencies obtained by ATACAMAC ($f^* = 1.0$, 1.43, and 1.83) for the three fuel splits ($\alpha = 5\%$, 10%, and 20%) have been computed with an acoustic pressure level $p'/p_{\mathrm{mean}} = 0.5\%$ to be consistent with the linear framework assumption. Fuel split is modified by changing the pilot axial injection velocity $u_0 = u_0(\alpha)$. First, unsteady combustion mechanisms of a multiphase flow LES containing a pilot and multipoint flames have to be identified. Note that no precessing vortex core (PVC) is observed in both the unforced and the forced cases, but a flapping motion of the pilot gaseous fuel jet appears.

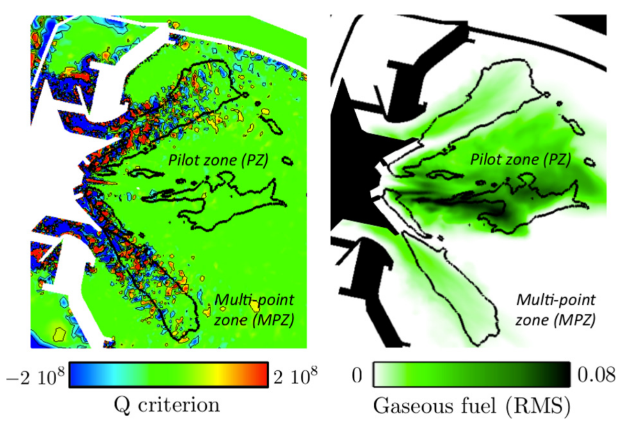

Fig. 10 Q-criterion (left) and gaseous fuel oscillations (RMS values, right) in the longitudinal cut plane. Both the multipoint and pilot mean flames (isocontour of the mean heat release) are superimposed in solid black lines.

Increasing the fuel split corresponds to increasing the liquid fuel mass flow rate in the PZ, resulting in a longer fuel jet which enhances interaction between the fuel zone and acoustics. Figure 9 displays the instantaneous flame shapes for different fuel splits. The multipoint fuel injection is weakly affected by the fuel split, whereas the pilot fuel injection is drastically modified: the isocontour of rich fuel mass fractions $Y_{\mathrm{kero}} = 0.1$ is five times longer when $\alpha = 20\%$ compared with $\alpha = 5\%$. It suggests that the acoustic interaction will be dependent on the fuel split in the PZ, but not in the MPZ. This paper proposes a methodology to confirm this idea and unveil key mechanisms due to the flame/acoustic interaction.

Moreover, Fig. 10 shows the two mean flame locations (multipoint and pilot) to be compared with the instantaneous Q-criterion indicating vortices (left) and gaseous fuel fluctuations (RMS values, right). It illustrates that the MPZ and PZ are affected by different phenomena (Fig. 2), detailed in the sections Pilot Flames: Gaseous Fuel Oscillations and Multipoint and Global Flame: Vortex Shedding:

(i) The multipoint flame is wrinkled by vortices ($\hat{\omega}$) induced by acoustic waves ($\hat{p}$) interacting with the swirler.
(ii) The pilot flame is affected by gaseous fuel oscillations, which modify the local equivalence ratio ($\hat{\varphi}$) and then the heat release ($\hat{q}$).

Pilot Flame: Gaseous Fuel Oscillations. In the PZ, the liquid fuel evaporates to generate gaseous fuel, which can then mix with air and burn in the flame front. Acoustic forcing acts on both the fuel transport ($u_0(\alpha) + u'$) and the evaporation taking place upstream of the flame front. Acoustic and fuel oscillations in the PZ are displayed in Fig. 11, showing that a fuel oscillation occurs for the whole frequency range considered here. These fuel oscillations are characterized by the normalized quantity $\widetilde{Y'_{\mathrm{kero}}} = Y'_{\mathrm{kero}}/p'_{\mathrm{max}}$, where Y'_{kero} is the fluctuation of the mass fraction of gaseous kerosene and p'_{max} is the amplitude of the pressure oscillations. Figures 11 and 12 also reveal that phase lags between acoustics and fuel oscillations depend on both the forcing frequency f, but also the fuel staging α:

At low forcing frequency ($f = 1.0$, Fig. 11, left), the pressure and kerosene fluctuations are in phase. However, at higher forcing

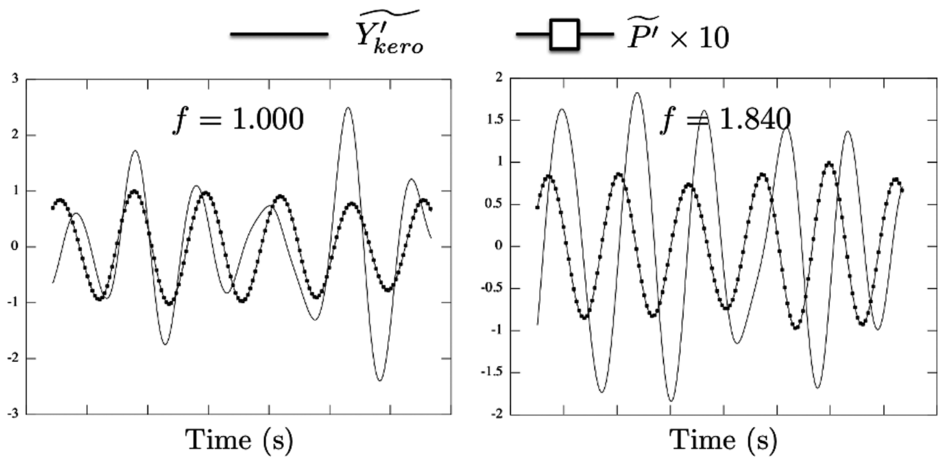

Fig. 11 Normalized relative pressure $\widetilde{P'} = p'/p'_{max}$ and fuel mass fraction $\widetilde{Y'_{kero}} = Y'_{kero}/p'_{max}$ oscillations in the PZ for the case at $\alpha = 10\%$ and forcing frequencies $f = 1.0$ (left) and $f = 1.84$ (right). A filter at the forcing frequency is applied to remove hydrodynamic and turbulent oscillations.

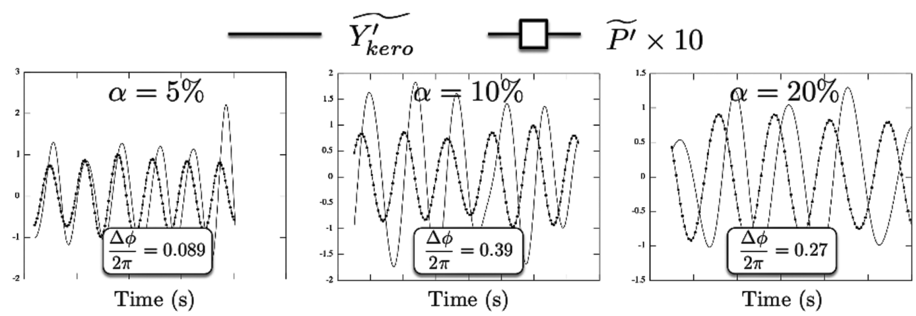

Fig. 12 Normalized relative pressure $\widetilde{P'}$ and fuel mass fractions $\widetilde{Y'_{kero}}$ oscillations for the case at $f = 1.84$ and fuel splits $\alpha = 5\%$ (left), $\alpha = 10\%$ (middle), and $\alpha = 20\%$ (right). Normalized phase-lags $\Delta\phi/2\pi$ between fuel and pressure oscillations are extracted.

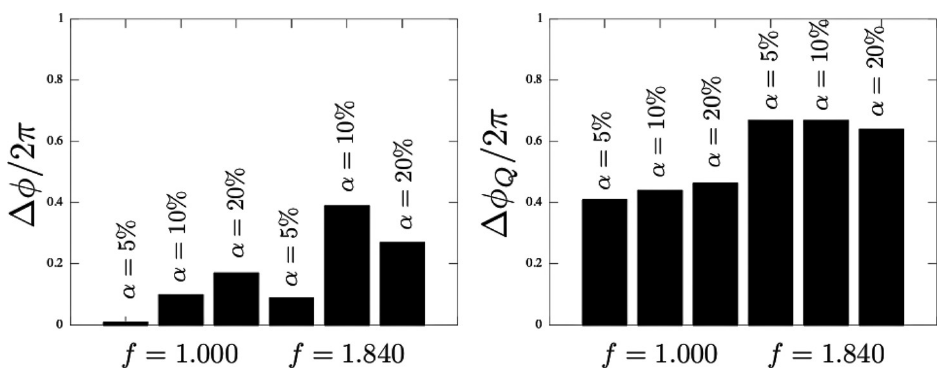

Fig. 13 Phase lags associated with the pilot gaseous fuel oscillations ($\Delta\phi$, left), and the global flame dynamics (pilot + multipoint, $\Delta\phi_Q$, right) for cases forced at $f = 1.0$ and 1.84 and fuel split $\alpha = 5\%$, 10%, and 20%

frequencies ($f = 1.84$, Fig. 11, right), the pressure and fuel mass fraction oscillations are in quadrature. The resulting relative fuel oscillation is one order of magnitude larger than the forcing pressure amplitude for both cases.

At constant forcing amplitude, Fig. 12 shows that modifying the fuel split parameter drastically changes the fuel oscillation process, characterized by its intensity $I_{vap} = \widetilde{Y}'_{kero}/\widetilde{P'}$ and its normalized phase-lag $\Delta\phi/2\pi$

$$\widetilde{Y}'_{kero} = I_{vap}\widetilde{P'}(t - \Delta\phi/\omega) \quad (4)$$

Using low fuel split (e.g., $\alpha = 5\%$) leads, therefore, to an in-phase fuel oscillations ($\Delta\phi/2\pi \ll 1/4$), while for higher fuel splits ($\alpha = 10\%$ and 20%), oscillations of fuel and pressure are in quadrature phase ($\Delta\phi/2\pi \approx 1/4$). The intensity I_{vap} is almost constant ($I_{vap} \approx 12$–15) for all cases.

Multipoint and Global Flame: Vortex Shedding. The pilot flame has been investigated and found to change drastically with the fuel split. However, even if Fig. 9 highlights only minor changes in the multipoint flame, it carries most of the power of the engine, and therefore, a small variation with the fuel split can generate a significant modification of stability. As shown in Fig. 10, the MPZ is controlled by vortex shedding due to acoustics. However, extracting vorticity waves and computing phase lags between this phenomenon and acoustics remain a complex task. To workaround this issue, the global phase lag between the whole unsteady heat release $\Delta\phi_Q$ (pilot + multipoint) is extracted and compared with $\Delta\phi$ (Fig. 2, PZ only). The idea is that the global FTF is a combination of the pilot and multipoint mechanism, as mentioned in Eq. (2)

$$\Delta\phi_Q = f(\Delta\phi_V, \Delta\phi(\alpha)) \tag{5}$$

where $\Delta\phi_V$ is associated to the vortex shedding mechanism, while $\Delta\phi(\alpha)$ is associated to the gaseous fuel oscillations. Since the pilot flame strongly depends on the fuel split α (Fig. 13, left), but not the multipoint flame (Fig. 9), the comparison between $\Delta\phi_Q$ and $\Delta\phi$ will give access to which mechanism is affecting the system: (1) If $\Delta\phi_Q$ also depends strongly on the fuel split α, like $\Delta\phi$ does, then the gaseous fuel oscillation at the PZ is controlling the instabilities; (2) otherwise $\Delta\phi_Q$ does not depend on the fuel split α, which implies that vortex shedding at the MPZ is dominating.

The filtered heat release and pressure fluctuations are correlated for several fuel split values ($\alpha = 5\%$, 10%, and 20%), giving access to the phase-lag $\Delta\phi_Q$, found constant here (Fig. 13, right). For all fuel split values, $\Delta\phi_Q/2\pi \approx 0.41 - 0.46$ for $f = 1.0$ and $\Delta\phi_Q/2\pi \approx 0.64 - 0.67$ for $f = 1.84$. Consequently, the phase lag of the whole system is almost insensitive to the fuel staging α (Fig. 13, right). It suggests that vortex shedding in the MPZ is the key mechanism leading to combustion instabilities, whereas the pilot flame has only a marginal effect in the present case. Nevertheless, this second mechanism, proved to change drastically with the fuel split α ($\Delta\phi$ in Fig. 13, left), could impact other key features of the engine such as pollutant emissions and temperature profiles at the turbine inlet. Moreover, fuel oscillations in the PZ may have a significant role in other operating conditions, like the idle regime where most of the power is supplied by the pilot flame ($\alpha \approx 100\%$).

Conclusion

In this paper, a multiphase flow LES and an analytical model (ATACAMAC) for thermoacoustic modes are combined to provide characteristic phase lags of two mechanisms leading to thermoacoustic instabilities: (1) the generation of vortex interacting downstream with the flame and (2) gaseous fuel oscillations. This methodology is applied on the annular combustor LEMCOTEC containing an innovative multipoint injection system, which complexifies the situation: two different flames are generated, which can be controlled by one or a combination of the two previous mechanisms. The objective is therefore to identify and investigate which mechanism controls the global flame dynamics. First, ATACAMAC is used to obtain the acoustic information required to force the configuration. Then, multiphase flow LES are forced at these frequencies at different fuel splits to study its effect on acoustic/flame interactions. Such a forced multiphase flow LES was never performed before, and constitutes one key result of this paper. Finally, the characteristic phase lags associated with the two mechanisms are extracted in the PZ and MPZ. It reveals that the PZ is controlled by gaseous fuel oscillations, which depends strongly on the fuel staging. However, the MPZ is driven by vortex shedding wrinkling the flame front, which is independent of the fuel split value. The study of the global (pilot + multipoint) flame dynamics indicates that the system is globally insensitive to the fuel split, which suggests that vortex shedding in the MPZ is dominating, while gaseous fuel oscillations depending on the fuel staging has only a minor effect. It also proves that acoustically forced multiphase flow LES is a suitable approach to analyze underlying multiphase flow phenomena leading to combustion instabilities in complex industrial annular combustors.

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