

THERMO-ACOUSTIC INSTABILITIES IN THE PRECCINSTA COMBUSTOR INVESTIGATED USING A COMPRESSIBLE LES-PDF APPROACH

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Abstract

This work predicts the evolution of self-excited thermo-acoustic instabilities in a gas turbine model combustor using large eddy simulation. The developed flow solver is fully compressible and comprises a transported sub-grid probability density function approach in conjunction with the Eulerian stochastic fields method. An unstable operating condition in the PRECCINSTA test case involving flame oscillation driven by thermo-acoustic instabilities is the chosen target configuration. Good results are obtained in a comparison of time-averaged flow statistics against experimental data. The flame's self-excited oscillatory behaviour is successfully captured without any external forcing involved. Power spectral density analysis of the oscillation reveals a dominant thermo-acoustic mode at a frequency of 300 Hz providing remarkable agreement with experimental observations. Moreover, the predicted limit-cycle amplitude closely matches the experimental value obtained with rigid metal combustion chamber side walls. Finally, a phase-resolved study of the oscillation cycle is carried out leading to a detailed description of the physical mechanism closing the feedback loop.

Keywords: Engine, Gas Turbine and Spray Combustion; Combustion Dynamics; Large Eddy Simulation; Stochastic Fields Method

Introduction

Thermo-acoustic instabilities are a phenomenon often encountered during the development stages of modern low emission aero-engine or stationary gas turbine combustors designed to operate under lean partially premixed conditions. Characterised by strong oscillations of the dynamic pressure and heat release rate, these instabilities can arise when a resonant feedback loop between the combustion chamber acoustics and the reactive flow dynamics is established. The time delay between the acoustic perturbation and the subsequent flame response must therefore be in phase to fulfil the Rayleigh criterion [1]. This leads to an increase of the oscillation amplitude until a limit cycle is reached where the amount of acoustic energy added to the system equals its energy losses. When operating in these limit cycle conditions, major problems such as higher sound and pollutant emissions, increased heat flux to the walls, flame extinction and flashback, or in severe cases even component failures may occur.

Large eddy simulation (LES) is a tool capable of facilitating the prevention of thermo-acoustic instabilities in the early design cycles of a novel combustor. In LES the governing transport equations describing the reactive flow field are spatially filtered and closed through turbulence and combustion models accounting for the sub-grid scale (*sgs*) contributions. In most cases, these *sgs* contributions are expected to be small when a sufficiently fine domain discretisation is achieved. When dealing with self-excited thermo-acoustic phenomena, a fully compressible LES formulation is needed in order to allow for the propagation of acoustic waves represented by temporal fluctuations in the pressure field. Potential coupling

mechanisms between the flame, flow and acoustics inside a combustion chamber can thus be directly accounted for. Such self-excited LES often prove challenging, however, as they require careful consideration of all geometrical parts making up the domain as well as accurate boundary conditions including acoustic impedances at all inlets and outlets. Examples of numerical works utilising a compressible LES approach to study self-excited thermo-acoustic instabilities in gas turbine combustors are e.g., [2–9].

The objective of the present work is to apply a recently developed computational method for predicting complex combustion dynamics based on a flame burning regime independent probability density function (*pdf*) approach. The combined LES-*pdf* methodology in its compressible formulation is presented below followed by an overview of the target test case and its numerical set-up. The method’s capabilities, especially in terms of the predicted thermo-acoustic behaviour, are then assessed against available measurement data. A selection of relevant results are discussed including time-averaged flow statistics, dynamic pressure and heat release rate signals as well as a phase-resolved analysis of the observed oscillation cycle.

LES-*pdf* approach

Filtered equations of fluid motion:

The governing equations of fluid motion are obtained by applying a spatial, density weighted filter to the continuity and Navier-Stokes equations:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho} \tilde{u}_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial \bar{\rho} \tilde{u}_i}{\partial t} + \frac{\partial \bar{\rho} \tilde{u}_i \tilde{u}_j}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \frac{2}{3} \mu \frac{\partial \bar{u}_k}{\partial x_k} \delta_{ij} \right] - \frac{\partial \tau_{ij}^{sgs}}{\partial x_j} \quad (2)$$

where ρ denotes the density, u_i and x_i are, respectively, the velocity and spatial coordinate in i -direction, t is the time, p is the pressure, μ represents the viscosity and δ_{ij} is the Kronecker delta. The *sgs* stress tensor τ_{ij}^{sgs} is closed through a dynamic version of the well-known Smagorinsky turbulence model [10], introducing a *sgs* viscosity μ_{sgs} to mimic the diffusion process on the dissipative small-scales. The isotropic parts of the viscous and *sgs* stresses are absorbed into the pressure.

The scalar transport equations:

A system’s instantaneous chemical state can be expressed in terms of transport equations for, respectively, the specific mole number n_α of each of the N_s species α present in the mixture and the enthalpy h . The species diffusive fluxes are represented by Fick’s law together with the assumption of equal diffusivities and in the enthalpy equation the heat flux is represented by Fourier’s law with a unity Lewis number assumption. The resulting equations are:

$$\frac{\partial \rho n_\alpha}{\partial t} + \frac{\partial \rho u_i n_\alpha}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\frac{\mu}{\sigma} \frac{\partial n_\alpha}{\partial x_i} \right) + \rho \dot{\omega}_\alpha; \quad 1 \leq \alpha \leq N_s \quad (3)$$

$$\frac{\partial \rho h}{\partial t} + \frac{\partial \rho u_i h}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\frac{\mu}{\sigma} \frac{\partial h}{\partial x_i} \right) + \frac{\partial p}{\partial t} + u_i \frac{\partial p}{\partial x_i} + \rho \dot{\omega}_\alpha \quad (4)$$

The filtered forms of equations (3) and (4) are not used in the present work because of the difficulties encountered in evaluating the filtered values of the chemical source terms in equation (3). The species and enthalpy equations can be conveniently written in the following

genetic form:

$$\frac{\partial \rho \phi_\alpha}{\partial t} + \frac{\partial \rho u_i \phi_\alpha}{\partial x_i} = \frac{\partial}{\partial x_i} \left[\left(\frac{\mu}{\sigma} \right) \frac{\partial \phi_\alpha}{\partial x_i} \right] + \rho \dot{\omega}_\alpha; \quad 1 \leq \alpha \leq N_s + 1 \quad (5)$$

For chemical species, the last term on the rhs of equation (5) represents the chemical source term while for enthalpy, it includes the pressure gradient terms and radiative heat loss (neglected here).

Transported probability density function approach:

A joint *sgs pdf*, $\tilde{P}_{sgs}$, for the N_s species and enthalpy is introduced to account for the influence of the sub-grid scale contributions on the species formation rates. It represents the filtered product of the fine-grained one-point *pdf* of each scalar as follows:

$$\tilde{P}_{sgs}(\underline{\psi}; \mathbf{x}, t) = \frac{1}{\bar{\rho}} \int_{\Omega} \rho G(\mathbf{x} - \mathbf{x}', \Delta(\mathbf{x})) \times \prod_{\alpha=1}^{N_s+1} P_\alpha = \prod_{\alpha=1}^{N_s+1} \delta[\psi_\alpha - \phi_\alpha(\mathbf{x}', t)] d\mathbf{x}' \quad (6)$$

where ψ_α is the sample space of the scalar ϕ_α and δ is the Dirac-function. Following [11] and taking into account the approach discussed in [12], an exact equation describing the evolution of $\tilde{P}_{sgs}$ can be derived:

$$\begin{aligned} \bar{\rho} \frac{\partial \tilde{P}_{sgs}(\underline{\psi})}{\partial t} + \bar{\rho} \tilde{u}_i \frac{\partial \tilde{P}_{sgs}(\underline{\psi})}{\partial x_i} + \sum_{\alpha=1}^{N_s+1} \sum_{\beta=1}^{N_s+1} \frac{\mu}{\sigma} \frac{\partial \tilde{\phi}_\alpha}{\partial x_i} \frac{\partial \tilde{\phi}_\beta}{\partial x_i} \frac{\partial^2 \tilde{P}_{sgs}(\underline{\psi})}{\partial \psi_\alpha \partial \psi_\beta} = \\ - \underbrace{\sum_{\alpha=1}^{N_s+1} \frac{\partial}{\partial \psi_\alpha} \left[\bar{\rho} \dot{\omega}_\alpha(\underline{\psi}) \tilde{P}_{sgs}(\underline{\psi}) \right]}_{\text{I: source term (closed)}} + \underbrace{\frac{\partial}{\partial x_i} \left[\left(\frac{\mu}{\sigma} + \frac{\mu_{sgs}}{\sigma_{sgs}} \right) \frac{\partial \tilde{P}_{sgs}(\underline{\psi})}{\partial x_i} \right]}_{\text{II: sgs pdf transport (gradient closure)}} \\ - \underbrace{\frac{C_d}{2\tau_{sgs}} \sum_{\alpha=1}^{N_s+1} \frac{\partial}{\partial \psi_\alpha} \left[\bar{\rho} (\psi_\alpha - \tilde{\phi}_\alpha(\mathbf{x}, t)) \tilde{P}_{sgs}(\underline{\psi}) \right]}_{\text{III: sgs micro-mixing (LMSE closure)}} \end{aligned} \quad (7)$$

where the *sgs* micro-mixing constant is $C_d = 2.0$ and the *sgs* micro-mixing time scale is given by $\tau_{sgs} = \bar{\rho} \Delta^2 / \mu_{sgs}$. In this formulation, the source term $\dot{\omega}_\alpha$ (I) appears in closed form. The second and third term on the right-hand side of the equation represent *sgs* transport of the *pdf* (II) and *sgs* micro-mixing (III). These terms are approximated by a gradient closure analogous to the Smagorinsky model and the linear mean square estimation (LMSE) closure [13], respectively.

Stochastic fields method:

The fully Eulerian stochastic fields method is employed as a solution method to the sub-grid *pdf* evolution equation (7) as proposed in [14]. For this purpose, $\tilde{P}_{sgs}(\underline{\psi})$ is represented by an ensemble of N stochastic fields $\xi_\alpha^n(\mathbf{x}, t)$ assuming that $1 \leq n \leq N$ and $1 \leq \alpha \leq N_s + 1$:

$$\begin{aligned} \bar{\rho} d\xi_\alpha^n + \bar{\rho} \tilde{u}_i \frac{\partial \xi_\alpha^n}{\partial x_i} dt = & \bar{\rho} \dot{\omega}_\alpha^n(\xi^n) dt + \frac{\partial}{\partial x_i} \left[\left(\frac{\mu}{\sigma} + \frac{\mu_{sgs}}{\sigma_{sgs}} \right) \frac{\partial \xi_\alpha^n}{\partial x_i} \right] dt \\ & - \frac{C_d}{2} \frac{\bar{\rho}}{\tau_{sgs}} \left(\xi_\alpha^n - \tilde{\phi}_\alpha \right) dt + \left(2\bar{\rho} \frac{\mu_{sgs}}{\sigma_{sgs}} \right)^{1/2} \frac{\partial \xi_\alpha^n}{\partial x_i} dW_i^n \end{aligned} \quad (8)$$

where dW_i^n denotes increments of a Wiener process, different for each stochastic field but independent of the spatial location $\mathbf{x}$. It is approximated by time-step increments defined as $\eta_i^n(dt)^{1/2}$ where η_i^n is a $\{-1, 1\}$ dichotomic random vector. Averaging over the stochastic fields results in the filtered value of each scalar.

PRECCINSTA combustor

Test case review:

The swirl-stabilised PRECCINSTA gas turbine model combustor was studied in an experimental test campaign [15] at the German Aerospace Center (DLR) and was shown to exhibit flame oscillation driven by thermo-acoustic instabilities under certain operating conditions. A significant number of experimental investigations have since been carried out attempting to identify the underlying mechanisms involved in the flame oscillation. Among the different phenomena studied in these works are the dynamics of coherent vortex structures [16–20], the interaction between velocity and equivalence ratio fluctuations [21] and the transition between bistable flame shapes [22, 23].

Most computational studies on the other hand, have focused on validating LES combustion models based on the reference case involving ‘stable’ operating conditions with a global equivalence ratio of $\phi_{glob} = 0.83$ and thermal power of $P_{th} = 30$ kW. Only very few investigations dealt with the oscillating flame behaviour of the PRECCINSTA combustor and its underlying mechanisms at play. Roux et al. [2] utilised a compressible LES method in combination with acoustic analysis to compute both a non-reacting and reacting flow $\phi_{glob} = 0.75$, $P_{th} = 27$ kW. Comparison of their results to experimental data showed reasonable agreement for both the predicted acoustic and hydrodynamic mode found in the cold flow as well as the thermo-acoustic mode obtained with combustion. Their study also underlined the importance of resolving the radial swirler instead of starting all computations from the combustion chamber inlet plane. Franzelli et al. [5] were the first to simulate the oscillating flame case $\phi_{glob} = 0.7$, $P_{th} = 25.1$ kW measured in [15] and considered in the current work. Their compressible LES reproduced a self-excited frequency of 390 Hz compared to the experimental value of 290 Hz. The overestimation was argued to be the result of a falsely modelled impedance at the fuel injection inlets. It was furthermore concluded that resolving the fuel-air mixing - as opposed to prescribing a fully premixed mixture at the domain inlet - is crucial for the prediction of thermo-acoustic instabilities in this test case.

Finally, Lourier et al. [6] performed a scale adaptive simulation (SAS) and additional experimental measurements of the oscillating flame case with adjusted acoustic boundary conditions. The inflow nozzle was equipped with a choked orifice plate 15 cm upstream of the air plenum to create a well-defined acoustic inlet boundary. This however, led to a marginal decrease of the thermo-acoustic frequency by about 15 Hz. Furthermore, rigid metal combustion chamber side walls were securely mounted to mitigate acoustic damping observed in the initial measurement campaign due to loosely mounted quartz glass windows. As a result, power spectral density (PSD) analysis of the air plenum and combustion chamber pressure signals showed an increase in the oscillation amplitude of around 10 dB.

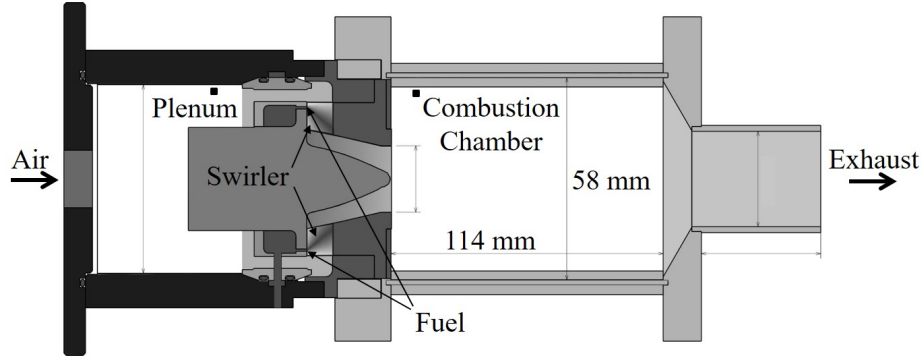


Figure 1: Schematic of the PRECCINSTA combustor showing the pressure probe locations.

The employed SAS model transitioned between a LES and an unsteady Reynolds-averaged Navier-Stokes (URANS) solution depending on the grid resolution. The fuel supply plenum and channels were included in the simulation based on the findings in [5]. Very good agreement was obtained in the SAS for both the thermo-acoustic frequency and its amplitude with a relatively small over-prediction of about 15-25 Hz and 5 dB, respectively.

Computational set-up:

The developed flow solver is based on the in-house, pressure-based, second-order accurate finite volume method BOFFIN (BOundary Fitted Flow INtegrator) [24]. It utilises a fully compressible formulation in order to account for acoustic wave propagation and eight stochastic fields to describe the influence of the sub-grid scale contributions [25]. The solver's default model parameters remain unchanged [26] and all chemical reactions are represented by an augmented reduced mechanism (ARM) [27] involving 15 steps and 19 species. Non-reflective boundary conditions [28, 29] are implemented to minimise numerical wave reflection at the domain inlets and outlet and all wall boundaries use a logarithmic law-of-the-wall formulation. The investigated operating condition $\phi_{glob} = 0.7$, $P_{th} = 25.1$ kW and detailed geometry (Figure 1) of the PRECCINSTA combustor are identical to case (1) of the initial experiments of Meier et al. [15]. The target inflow temperature and pressure for both air and fuel are set to 320 K and 1 bar, respectively. The computational mesh consists of 2.7 million grid points with refinements in the reaction zone and fuel-air mixing regions. Previous studies [30, 31] of the 'stable' flame case have shown that an application of non-adiabatic combustion chamber walls noticeably improves the near-wall scalar field and can induce flame lift-off in line with experimental observations. Hence, wall heat transfer is included in the current work via isothermal temperatures of 1400 K and 700 K prescribed at the combustion chamber side and base plate walls. No forcing of the inlet velocity is applied in this work to ensure that any potential oscillatory behaviour observed in the simulation is fully self-excited.

Results and discussion

Time-averaged flow statistics:

Radial profiles of the mean axial and radial velocity at different downstream positions are shown in Figure 2. Overall, good agreement with the initial experiments of Meier et al. [15] can be reported. Both the location and strength of the inner recirculation zone (IRZ) and outer recirculation zone (ORZ) are accurately reproduced. The incoming jet of fresh gases, represented by two pronounced velocity peaks, experiences a minor inwards shift with downstream position. This shift in combination with underestimated peak values in the radial

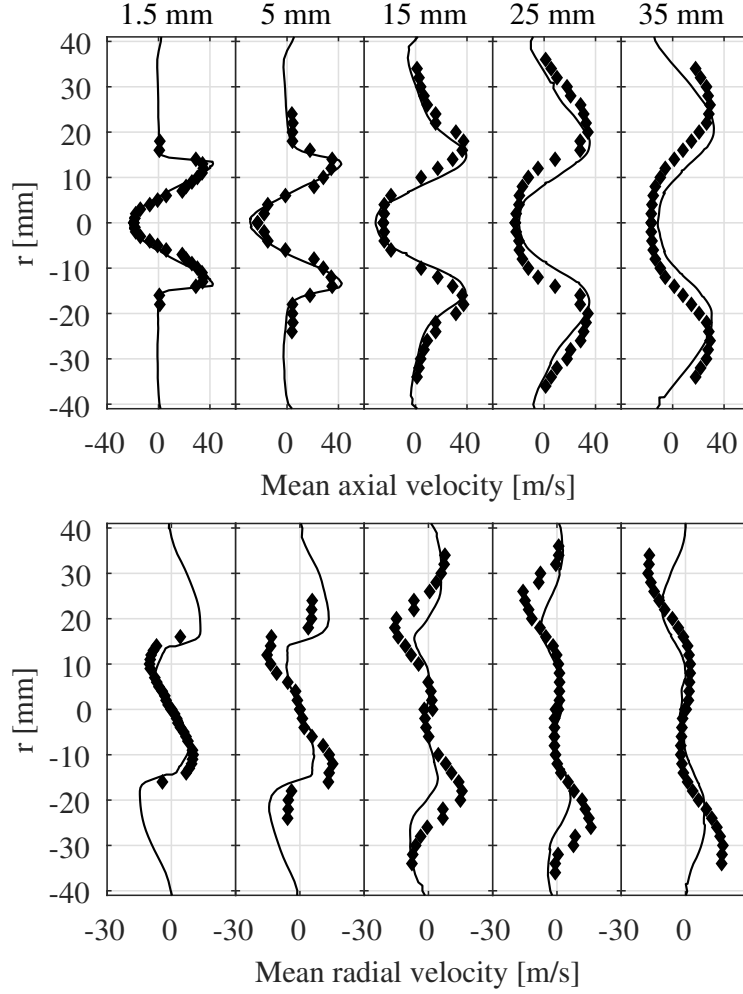


Figure 2: Radial velocity profiles from the LES (—) and experiments (◆).

velocity indicates a smaller mean spreading angle and expansion of the jet into the combustion chamber.

The accompanying under-prediction of the mean length and spreading angle of the flame can be determined from the temperature profiles displayed in Figure 3. Nevertheless, the general temperature distribution in the IRZ and ORZ is retrieved, suggesting the applied wall heat transfer treatment is realistic, and the mean flame position and shape are qualitatively captured. A marginally increased mean flame lift-off height is observed close to the centreline, implying a longer duration of flame detachment [32] from the central cone bluff body compared to the measurements. Temperature fluctuations of up to 500 K, visualised as RMS profiles in Figure 3, are expectedly high in both simulation and experiment due to the oscillating nature of the flame. However, LES results show an almost constant level of fluctuation inside of the inner shear layer (ISL), $-16 \text{ mm} \leq r \leq 16 \text{ mm}$, whereas experimental data reveals a dip of RMS values in between the inner and outer shear layer (OSL), $10 \text{ mm} \leq r \leq 16 \text{ mm}$. The computed location of the incoming jet is therefore less steady over the full oscillation cycle. A stronger flame angle oscillation - or flapping of the flame - can be concluded, which likely contributes to the under-predicted mean spreading angle observed for the jet and flame. The increased flapping motion is potentially induced by swirl number fluc-

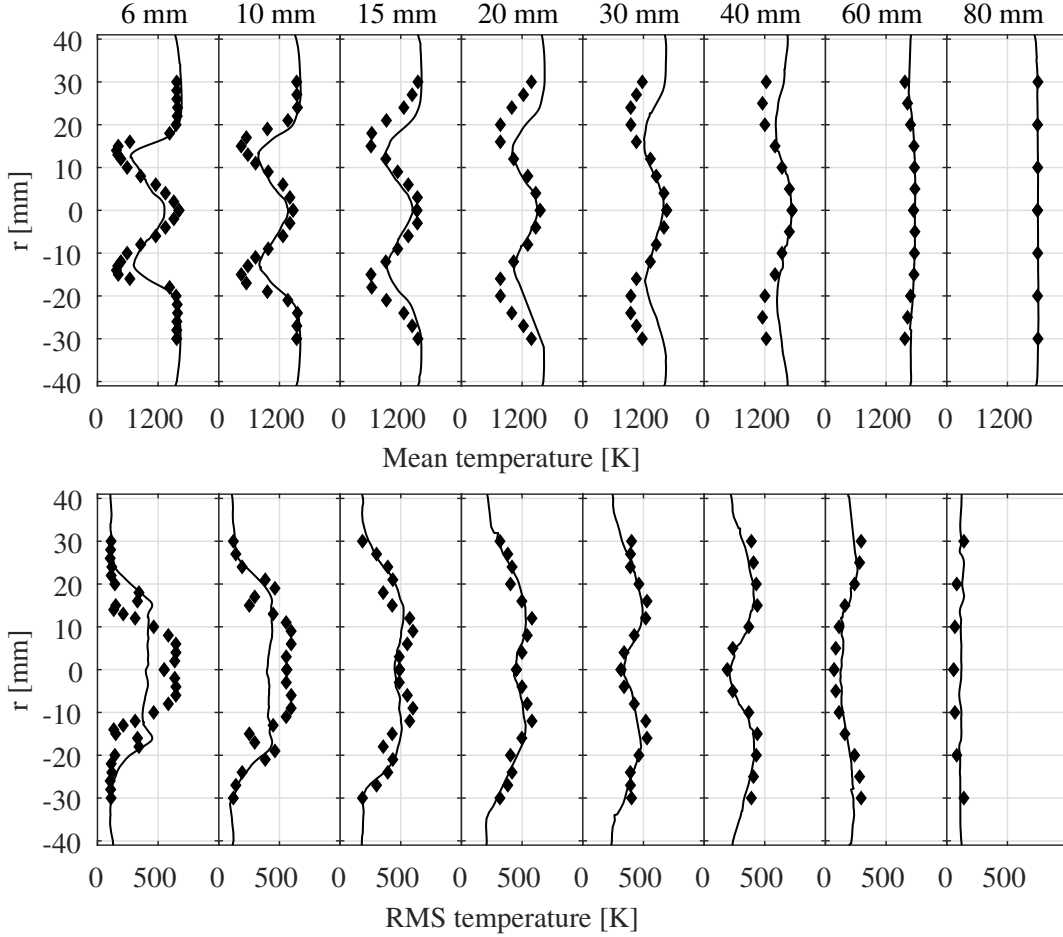


Figure 3: Radial temperature profiles from the LES (—) and experiments (◆).

tuations due to stronger acoustic perturbations [33]. These are caused by a higher amplitude limit-cycle oscillation obtained in the simulation, as discussed in the following section.

Dynamic pressure and heat release rate signals:

Time series of the dynamic pressure in the air plenum and combustion chamber as well as the integrated heat release rate fluctuations are displayed in Figure 4. Both the heat release rate and combustion chamber pressure are in phase satisfying the Rayleigh criterion. Constant mean amplitudes in the pressure signal translate into a growth rate equal to zero, thus indicating a limit-cycle oscillation. The existing modes are revealed via PSD analysis providing a dominant peak for the air plenum, combustion chamber and heat release rate at approximately 300 Hz. This peak represents the thermo-acoustic frequency and is in remarkable agreement with experimental measurements of about 290 Hz [15]. A second peak is clearly visible at around 600 Hz representing the first harmonic, also reported experimentally. However, the computed PSD amplitudes of the thermo-acoustic mode are overestimated by about 13 dB in both air plenum and combustion chamber. This overestimation is a result of acoustic damping [6] occurring at the combustion chamber side walls in the initial experiments. Excellent agreement is obtained when comparing the present PSD amplitudes to the additional measurements carried out by Lourier et al. [6] who used tightly fitted rigid metal walls to mitigate the effects of acoustic damping. Overall, the dynamic behaviour of

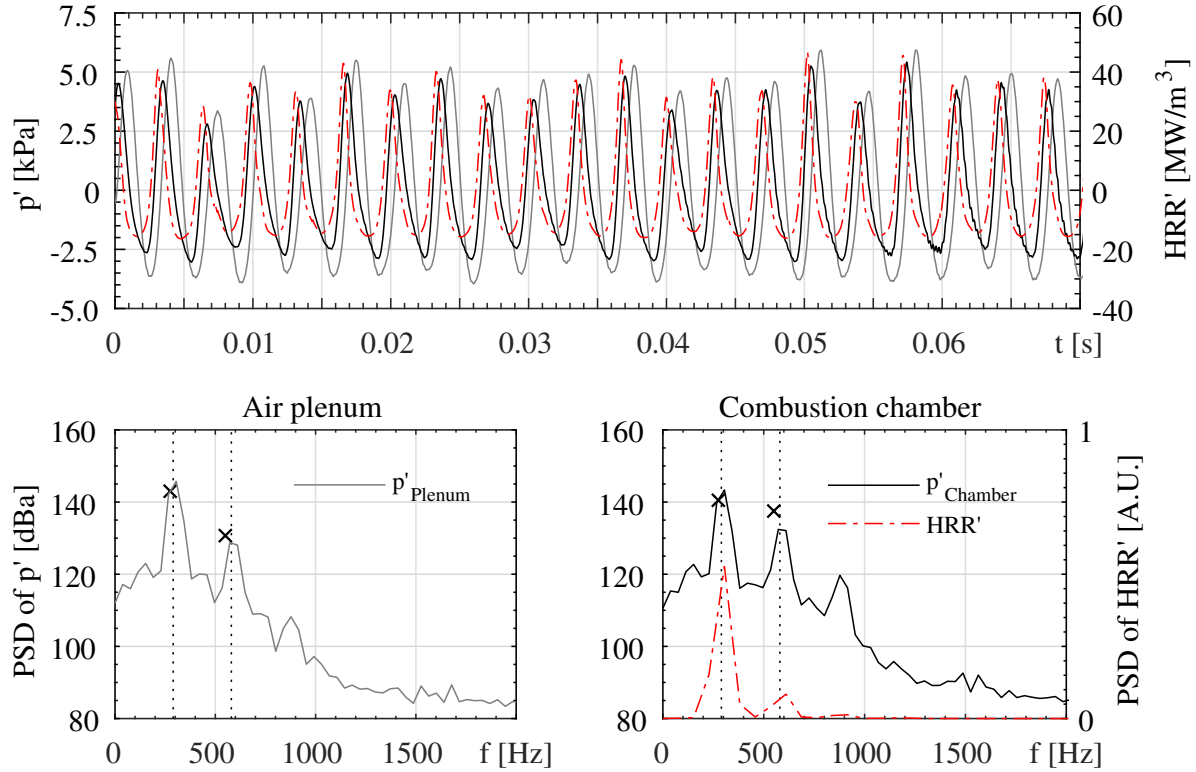


Figure 4: Dynamic pressure and integrated heat release rate (HRR) fluctuations and their respective power spectral density (PSD) signals in the air plenum and combustion chamber. Dominant peaks measured in the experiments are plotted as vertical dotted lines (frequencies only) for quartz glass walls [15] and as $\times$ -markers for rigid metal walls [6].

the combustor is shown to be well captured as self-excited thermo-acoustic instabilities are successfully reproduced at the correct frequency and amplitude.

Phase-resolved analysis of the oscillation cycle:

While the quantitative velocity and scalar fields are influenced by the acoustic pressure amplitude in the combustor, the physical feedback mechanisms driving the thermo-acoustic coupling remain largely unaffected by this and can still be investigated. A phase-resolved analysis of the oscillation cycle is therefore carried out and eight different phase angles (Ph 1-8) are introduced as illustrated in Figure 5. Starting from Ph 1, the evolution of the main flow properties at each phase is described below, based on Figure 6.

At Ph 1, fresh gases enter the combustion chamber with a high mass flow rate and equivalence ratio, as characterised by the high velocities and CH_4 mass fraction concentrations in this region. Large amounts of unburnt reactants are thereby convected into the main flame zone enhancing combustion. The increasing heat release rate approaches its maximum between Ph 2 and 3 elevating the pressure inside the combustion chamber and generating a pressure wave that propagates up- and downstream within the domain. A negative pressure drop between the combustion chamber and air plenum develops decreasing the mixture mass flow rate and hence supply of fresh gases into the reaction zone. As a result, the bulk flow inside the swirler becomes almost stagnant. CH_4 , on the other hand, is still injected at an almost constant rate since the fuel jets are only weakly affected by the pressure oscillation due

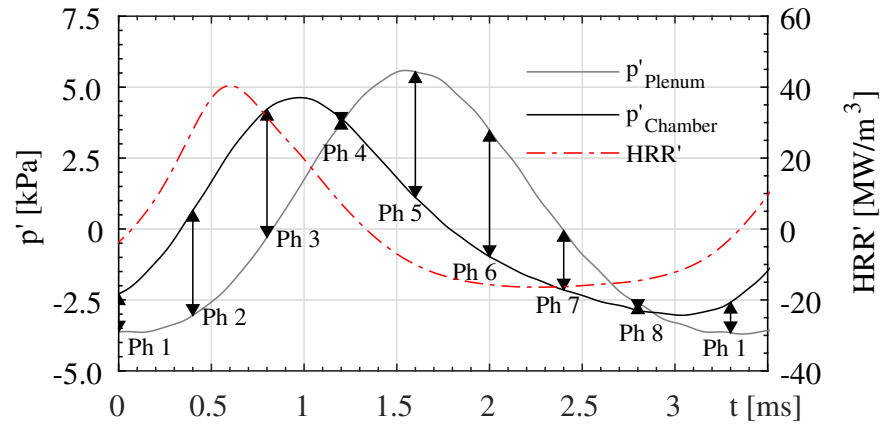


Figure 5: Definition of eight different phase angles in relation to one full oscillation cycle of the integrated heat release rate (HRR) and dynamic pressure in the air plenum and combustion chamber.

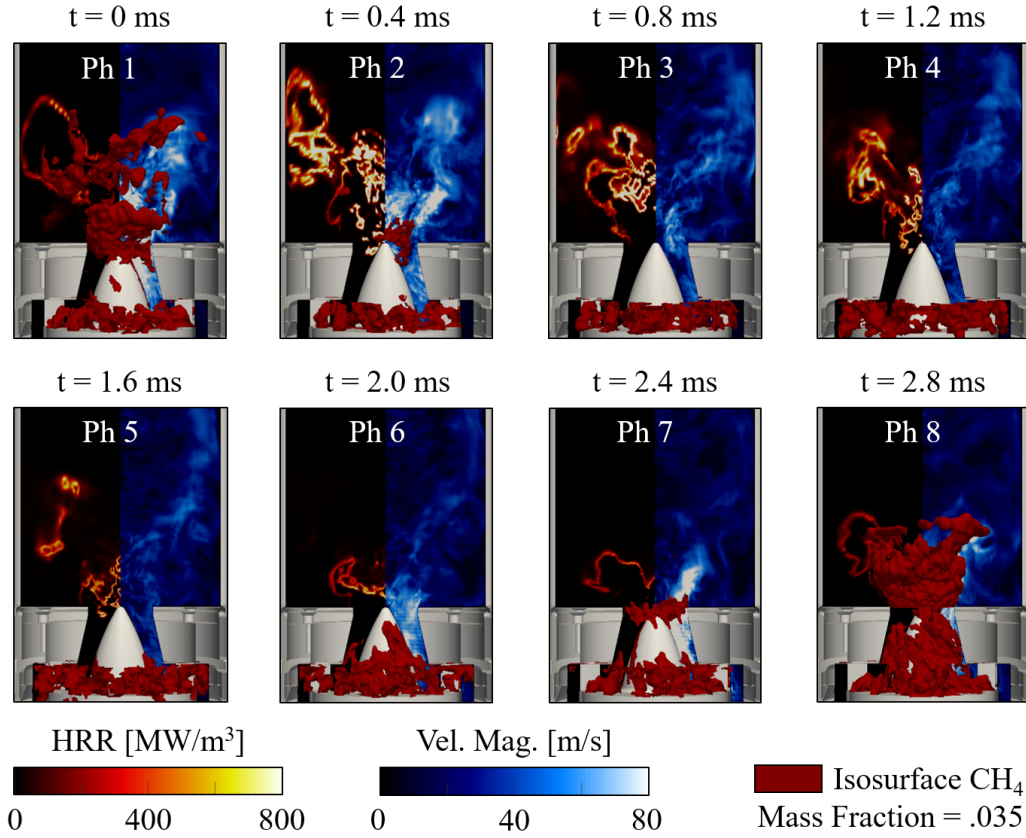


Figure 6: Phase-resolved temporal evolution of the heat release rate (HRR), velocity magnitude and CH_4 mass fraction for one full oscillation cycle.

to their high acoustic impedance. This leads to fuel accumulation inside the swirler during phases 4 and 5, raising the equivalence ratio of the local mixture. Minor flame flashback occurs as the heat release rapidly decreases followed by a reduction of the local pressure. A phase difference of about 80° between the recorded pressure signals in the combustion chamber and air plenum is determined at this point, similar to the shift reported in the experiments [15]. This pressure drop in turn generates an increased mass flow rate within the swirler from Ph 6 and 7 while the integrated heat release rate reaches its minimum. The high equivalence ratio mixture finally exits the burner nozzle at Ph 8 pushing the flame front downstream and closing the feedback loop as the heat release rate begins to increase again.

In summary, fluctuations of the mixture mass flow rate due to a periodically varying pressure drop between the air plenum and combustion chamber can be identified as the dominant driver of the oscillation. This mechanism is superimposed by equivalence ratio fluctuations [6, 21, 34] in the local mixture entering the reaction zone as a result of fuel accumulation inside the swirler at one specific period of the oscillation cycle.

Conclusions

Self-excited thermo-acoustic instabilities in the PRECCINSTA gas turbine model combustor have been investigated using a novel fully compressible LES-*pdf* approach comprising the Eulerian stochastic fields method. Comparisons with available measurement data revealed good agreement for the predicted time-averaged velocity and temperature field. Small deviations in the mean profiles were attributed to higher flame angle oscillations in the simulation as a result of swirl number fluctuations induced by stronger acoustic perturbations. These are thought to be caused by an overestimated pressure oscillation amplitude compared to the original experiment where acoustic damping from the vibrating combustion chamber walls was reported.

Excellent agreement was achieved in reproducing the dynamic behaviour of the combustor. Recorded signals of the fluctuating heat release rate and pressure in the combustion chamber were in phase and showed growth rates equal to zero indicating a thermo-acoustic limit-cycle oscillation. PSD analysis of the pressure fluctuations revealed a dominant frequency of 300 Hz, identified as the thermo-acoustic mode, as well as its first harmonic at 600 Hz closely matching the respective experimental values. The amplitude of these two modes was further found to be in very good agreement with measurements obtained using stiff combustion chamber side walls to suppress acoustic damping. Finally, a phase-resolved analysis of the oscillation cycle was carried out to identify its underlying coupling mechanisms. A periodically changing pressure drop between the air plenum and combustion chamber due to acoustic wave propagation led to a fluctuating mixture mass flow rate entering the reaction zone. The mixture further showed local equivalence ratio variations caused by fuel accumulation inside the swirler at one specific period of the cycle. The superposition of these two effects enhanced the unsteadiness of the heat release rate, which in turn generated acoustic wave propagation closing the feedback loop.

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