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Dynamics and mechanisms of pressure, heat release rate, and fuel spray coupling during intermittent thermoacoustic oscillations in a model aeronautical combustor at elevated pressure

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ABSTRACT

Dynamics of thermoacoustics oscillations occurring in a liquid fueled aeronautical gas turbine model combustor burning Jet A fuel were investigated experimentally at a pressure of approximately 10 bar. Data was acquired using 5 kHz repetition-rate stereoscopic particle image velocimetry (S-PIV) for both gas phase and fuel droplet velocities, 10 kHz repetition-rate OH^* chemiluminescence (CL), and a variety of pressure transducers. Methods for addressing challenges in the application of PIV at these conditions are presented. Analysis of the pressure and CL data showed two coexisting thermoacoustic modes at Strouhal numbers of $St \approx 0.3$ and 0.8, both of which exhibited intermittent changes in the oscillation amplitudes. The spatial distribution of the transient pressure-heat release rate coupling, i.e., Rayleigh index, demonstrated repeated dynamics during intermittent oscillations. Specifically, different combustor regions added and/or removed energy from the oscillations at different times. For the tested experimental conditions, the gas phase velocity did not feature any detectable coherent oscillations. However, the fuel droplet velocities in the immediate vicinity of the combustor dump plane exhibited oscillations with a similar intermittent spectral signature as the pressure and CL, indicating coupling through oscillations in the fuel. To further investigate the fuel coupling, the laser scattering signal from the fuel droplets was evaluated. Coherent oscillations in the fuel droplet scattering persisted over the entire length of the fuel spray, which is consistent with an oscillating fuel supply being convected by a non-oscillating air supply for the conditions studied here. The amplitude of the total fuel droplet scattering oscillations was linearly correlated with that of the pressure oscillations. As the pressure amplitude increased, the droplet and pressure oscillation cycles became more coherently out-of-phase, which is hypothesized to lead to the observed intermittent behavior.

1. Introduction

Thermoacoustic oscillations can lead to thermal and mechanical fatigue, efficiency reduction, and emissions increases of gas turbine engines. Ongoing developments in the theory and practical approaches to mitigating thermoacoustic oscillations has been described by several review papers [1–6]. Broadly, experimental studies of thermoacoustic oscillations can be divided into those in which the oscillations are forced in order to measure the flame response to known perturbations [7–11], or those in which oscillations are self-excited and a myriad of perturbation coupling pathways are available [11–19]. The latter often focus on systems and conditions in which the oscillations have reached a steady limit cycle, specifically, the amplitude and frequency of the oscillations are relatively constant in time. The studies of self-excited limit cycle oscillations have been performed for both atmospheric flames [11–15], and recently at elevated pressures [16–19]. Although limit cycle oscillations quite commonly occur in both atmospheric and elevated pressure test rigs, several recent studies have demonstrated that self-excited oscillations may have an intermittent behavior, in which the amplitude and/or frequency of the oscillations vary in time while the system operates at a fixed condition [20–32]. Although these studies provide substantial insight regarding characteristics and underlying mechanisms associated with intermittent thermoacoustic oscillations, they were performed for premixed flames operating at atmospheric conditions. The present

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study focuses on the experimental characterization of intermittent thermoacoustic coupling in a model aeronautical gas turbine combustor burning partially premixed liquid fuel at elevated pressure.

Intermittent thermoacoustic oscillations have been studied in various atmospheric pressure configurations that replicate features of single combustor industrial burners [20–31] and annular gas turbine combustors [32]. Several approaches have been utilized to study intermittent thermoacoustic oscillations. Boudy et al. [20,21] performed an experiment with a variable length reactant manifold feeding a grid-stabilized laminar premixed flame. By varying the manifold length, they observed two types of thermoacoustic oscillations with time-varying amplitudes. For a particular manifold length [20], they observed a low-amplitude steady limit cycle that, after some time, spontaneously changed to a higher amplitude oscillation at a lower frequency; this behavior was associated with a spontaneous mode switch. Using the same setup but with a different manifold length, they described a condition at which the oscillation amplitude repeatedly increased and decreased, and the pressure power spectrum showed several important frequencies [21]. This type of thermoacoustic oscillations was referred to as a galloping limit-cycle. They also utilized the Flame Describing Functions (FDF) and showed that, for a fixed manifold length, the modes of oscillations described earlier can be predicted, confirming their experimental observations [20]. For a flame configuration similar to that of Boudy et al. [20,21], several research groups utilized dynamical system theory in order to characterize intermittent thermoacoustic oscillations by means of recurrence plots [26,27], bifurcation analysis [28], entropy methods [33], and complex network analysis [29]. Using dynamical system modeling, it was shown that reduced order dynamical models with impulsive forcing captures the intermittent behavior of thermoacoustic oscillations [30].

For annular combustors operating at atmospheric condition, Worth and Dawson [32] observed a limit-cycle thermoacoustic oscillation with constant frequency but time-varying amplitude. Compared to single-nozzle combustors, changes in the oscillations amplitude of annular combustors were linked to switching between standing and spinning modes inside the annulus. Using a Van der Pol oscillator model along with stochastic forcing, Bothien et al. [31] showed that the mode switching in this type of combustor is associated with combustion noise.

Here, the focus is on the mechanisms driving longitudinal instability modes in a single-element combustor that exhibited intermittent amplitude oscillations at fixed frequencies. Specifically, the aim is to understand the causes of transient coupling between pressure (p) and heat release rate ($\dot{q}$) oscillations. The description of coupling between heat release rate and pressure was first presented by Rayleigh [34]. The principles of this coupling can be expressed in the simplified transport equation for acoustic energy ($\mathcal{E}$), given by Candel [1]

$$\frac{\partial}{\partial t}\mathcal{E}(\vec{x},t)+\vec{\nabla}\cdot[p'(\vec{x},t)\vec{u}'(\vec{x},t)]=\frac{\gamma-1}{\gamma\,\overline{p}(x)}\left[p'(\vec{x},t)\dot{q}'(\vec{x},t)\right]+D \quad (1)$$

where $(\cdot)'$ represents fluctuations of a variable relative to the corresponding temporally-averaged value, $(\bar{\cdot})$. In Eq. (1), the second term on the left represents the flux, the first term on the right is the source/sink of acoustic energy due to coupled heat release and pressure fluctuations, and D is the dissipation of the acoustic energy.

Constant amplitude limit-cycle oscillations arise through a balance between the thermoacoustic flux, source due to $p'-\dot{q}'$ coupling, and dissipation term in Eq. (1). For constant amplitude limit-cycle oscillations at a fixed angular frequency (ω), the instantaneous $p'-\dot{q}'$ coupling term varies at a frequency of 2ω and has a net effect on the acoustic energy, given by the temporal integral over this interval, viz.

$$\theta(\vec{x},t)\overset{\propto}{\approx}\frac{\omega}{\pi}\int_{t-\pi/2\omega}^{t+\pi/2\omega}p'(\vec{x},\tau)\dot{q}'(\vec{x},\tau)\,\mathrm{d}\tau, \quad (2)$$

where t is time, and τ is an integration variable. The pre-factor of the $p'-\dot{q}'$ term in Eq. (1) is neglected in Eq. (2) since it is nearly constant and does not affect the nature of the thermoacoustic coupling. The resultant value of θ, often referred to as the Rayleigh gain or Rayleigh index, is positive (source) for local pressure and heat-release-rate oscillations having a phase shift of $|\Delta\phi_{pq}(\vec{x},t)|<\pi/2$, and negative (sink) for $\pi/2<|\Delta\phi_{pq}(\vec{x},t)|\le\pi$. The spatial integral of $\theta(\vec{x})$ over the combustor domain yields the total thermoacoustic source through $p'-\dot{q}'$ coupling.

For perfectly premixed flames, pressure oscillations can cause oscillations in the flow rate of the fuel/air mixture, which in turn leads to phenomena such as periodic vortex shedding or deformation of coherent helical vortex structures [35–38]. This leads to fluctuations in the heat release rate through fluctuations in the flame surface area. Compared to perfectly premixed flames, flames in engineering applications generally are partially-premixed or technically premixed; the thermoacoustic oscillations can be coupled through air and/or fuel streams, as well as through entropy waves [39–42]. The latter takes place due to flow acceleration at the exit of the combustor and discharge to the turbine, is different from the $p'-\dot{q}'$ mechanism described above, and is not expected to be significant for the present investigation. The focus here is on the $p'-\dot{q}'$ coupling mechanism through pressure-induced oscillations in the fuel and air flow rates.

A challenging aspect of analyzing the spatial distribution of $p'-\dot{q}'$ coupling is estimating the spatial distribution of the heat release rate, which is mainly achieved using Planar Laser Induced Fluorescence (PLIF) of OH, CH, HCO, or combined OH and CH_2O, or through chemiluminescence measurements [15,43–45]. The former two PLIF techniques are related to the heat release rate through the flame surface area (which applies to premixed flames with spatially and temporally fixed fuel/air equivalence ratio), whereas the latter two provide more direct measures of the heat release rate through the relationship between these species concentrations and the fuel oxidation pathway. Past experimental investigations, show that PLIF of HCO is relatively difficult mainly due to low concentrations and accessibility of appropriate excitation wavelengths. Recent studies have demonstrated single-shot HCO PLIF in turbulent methane/air flames at atmospheric pressure using pulsed alexandrite lasers, which also highlighted challenges with spectral interferences [44,46]. As an alternative, it has been demonstrated that heat release rate in low carbon fuels can be inferred from the product of OH and CH_2O, which are more readily accessible via PLIF, due to their role in the formation of HCO [45,47,48]. Although PLIF measurements have shown adequacy for heat release rate measurements of atmospheric flames, performing this technique at elevated pressures is challenging. This is mainly due to broadening of spectral absorption lines, self-absorption of fluorescence by the gas between the source and detector (signal trapping), and complexities in relating the detected signal to quantitative species concentrations [49–51]. In addition to these challenges, the adequacy of the aforementioned PLIF techniques as heat release metrics is not established for the larger hydrocarbons found in liquid fuels [44,52].

Chemiluminescence-based heat release measurements rely on the link between the concentration of electronically excited hydroxyl (OH^*) or methylidyne (CH^*) and exothermic reactions; spontaneous emissions from these species provide a marker of the heat release rate [53–55]. However, the relationship between chemiluminescence emissions and heat release rate is influenced by the local fuel/air equivalence ratio variation, local turbulence intensity, signal trapping (similar to PLIF), and background noise