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Autoignition flame dynamics in sequential combustors

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ABSTRACT

This numerical study investigates the linear and non-linear flame dynamics in the second stage of a sequential combustor, with methane fuel injection into vitiated hot gas. It focuses on the heat release rate response of the sequential flame to entropy waves. The response is shown to be very sensitive to small changes in operating condition and excitation amplitude. One-dimensional (1-D) flame simulations were performed to identify transitions between three combustion regimes: autoignition, flame propagation and flame propagation assisted by autoignition. Three-dimensional (3-D) large eddy simulations (LES) were performed for two configurations: one that includes the fuel injector and the mixing section, and one with a perfectly premixed inlet. An analytically reduced chemistry (ARC) mechanism, which allows to account for autoignition chemistry, was used in combination with the dynamic thickened flame (DTF) model. For certain conditions, local autoignition events occur upstream of the flame in the advected “hot” streamwise strata that result from the inlet modulation. These auto-ignited kernels get convected downstream and impinge on the stabilized flame front leading to a sudden increase of heat release rate followed by an abrupt decrease due to flame front merging. This is identified as the driving mechanism for the onset of non-linear flame response characterised by high transfer function gains. In particular, this work shows that the gain of the flame describing function increases beyond a certain threshold of the excitation amplitude.

1. Introduction

The demand for pollutant emission reduction, higher efficiency, increased operational and fuel flexibility pushes the research and development of novel gas turbine combustor architectures forward. An important technology step change is the development of constant pressure sequential combustion systems [1] or axial staging concepts [2]. In these combustors the second-stage fuel is injected into the vitiated hot gas flowing from the first stage to a stabilized second flame. Recently, an increasing number of studies dealing with the second stage combustion process have been published. One can refer to previous experimental work [3–10] and numerical studies [11–13]. Knowledge about reheat-type flame dynamics is very limited [14–16]. None of these studies treat the non-linear aspects of flame response nor the flame's driving mechanism. Both are addressed in the present paper.

Thermoacoustic stability is one of the main challenges in gas turbine combustor engineering, especially at lean conditions [17]. Thermoacoustic instabilities result from a constructive interaction between the acoustic pressure and the unsteady heat release rate from the flame [18]. These instabilities can lead to high level acoustic pressure oscillations [19] that are detrimental to the mechanical components. Thermoacoustic dynamics have been investigated in countless research works. For example, the following studies deal with the effect of: the mean flow on flame dynamics [20–22], azimuthal modes encountered in axisymmetric chambers [23–26], stochastic aspects of the acoustic-flame coupling [27–29], intrinsic thermoacoustic instabilities [30–32] and the active control of flame dynamics using plasma actuation [33].

Coherent oscillations of the flame heat release rate can be generated by various perturbations, such as bulk pressure [15,34], acoustic velocity [35–37], acoustically triggered equivalence ratio fluctuations [38,39] or acoustically triggered temperature fluctuations [40,41]. The link between these perturbations and the heat release rate response is given in terms of the frequency response of the flame or also referred to as the flame transfer function (FTF). Examples of FTFs are shown in Fig. 1. Two similar boundary conditions (BC1 and BC2) are investigated for different types of perturbation: velocity u', equivalence ratio ϕ' and temperature T' (from left to right). The FTFs relate the respective perturbation inputs to the heat release rate $\dot{Q}'$ outputs. Here the reader should pay attention to the change in FTF gain for temperature fluctuations. This change is highlighted by red arrows, and is significantly more pronounced than for the other types of perturbations. This dy-

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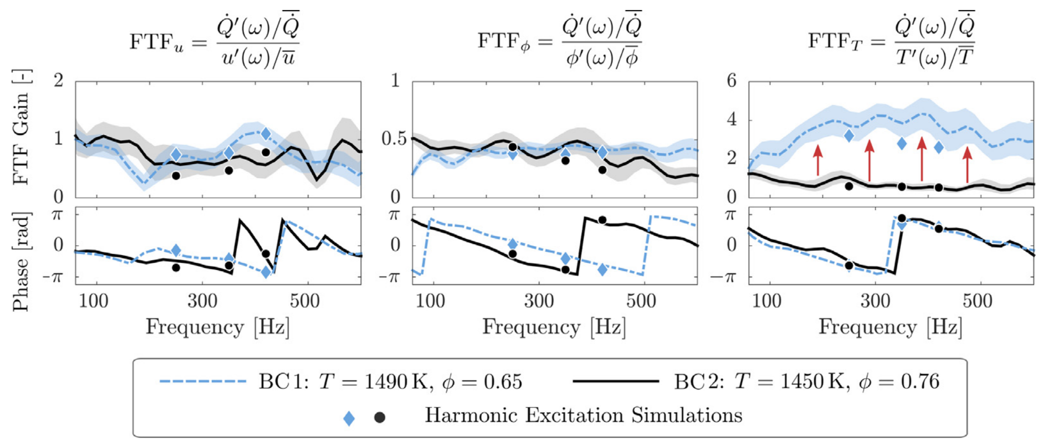

Fig. 1. Flame transfer functions (FTFs) relating input perturbations and heat release rate fluctuation $\dot{Q}'$ outputs. FTFs from left to right for: velocity u', equivalence ratio ϕ' and temperature T' perturbations. Two similar boundary conditions are compared: BC1 with mean inlet temperature 1490 K and $\phi = 0.65$ (dashed lines). BC2 with mean inlet temperature 1450 K and $\phi = 0.76$ (solid lines). Results derived for perfectly premixed (see Section 6) sequential combustor using broadband (lines) and harmonic excitation simulations (symbols). Excitation amplitudes with respect to mean values from left to right: 2.4%, 3.6% and 2.4%. Light patches show 85% confidence interval.

namic behavior has a strong influence on the thermoacoustic stability of a combustion system [19]. The FTFs were derived for the perfectly premixed burner that is investigated in Section 6. Temperature fluctuations, also known as entropy waves, result from unsteady heat release. As first described in [42], these hot spots convect with the flow and generate acoustic waves due to an acceleration [43–45], for example, at the turbine inlet [46]. These generated acoustic waves are also known as indirect combustion noise [47,48] and play an important role for the thermoacoustic dynamics [49–51]. One can refer to experimental [52,53] and modeling [54] studies investigating the influence of dispersion and dissipation of entropy waves. Recently, a new approach to measure temperature fluctuations up to 100 Hz was presented in [55].

For a sequential combustor, however, a different mechanism can be of similar importance for the thermoacoustic stability: entropy waves originating from the first stage get convected downstream and interact with the second flame. These temperature fluctuations are generated, for example, due to unsteady combustion in the first stage flame, and can lead to strong heat release rate modulation of the second stage autoignition flame, even for low excitation amplitudes. An example demonstrating the strong influence of the hot gas temperature on the autoignition position is the well-documented experimental Cabra flame configuration [56] with a cold methane–air jet that is injected into a hot vitiated coflow. Autoignition is the main stabilization mechanism as shown, for example, in [57] and the hot gas temperature is the dominant parameter significantly influencing the liftoff height of the flame, as seen for instance in [56,58]. This example indicates that variations of upstream temperatures can significantly alter the flame stabilization position. Therefore, it is expected that coherent temperature fluctuations in sequential combustors, which feature similar turbulence chemistry interactions, play a key role in the flame dynamics.

This numerical work investigates flame dynamics due to entropy waves of a sequential combustor flame and focuses on the following goals: (i) determine the linear and non-linear heat release rate response to temperature fluctuations, (ii) identify the driving mechanisms inducing the start of non-linear flame dynamics and (iii) investigate the impact of varying burner operating conditions on (i) and (ii).

This paper is structured as follows. Sections 2 and 3 introduce the sequential burner configuration, and the methodology that was used to perform large eddy simulation (LES) with system identification (SI). Section 4 identifies the dominant combustion regimes for the operating conditions considered in this study. In Section 5, the flame dynamics are compared for two operating conditions with varying inlet hot gas temperatures. This section also investigates the driving mechanism for the non-linear heat release rate response. Based on these results, Section 6 investigates the onset of the non-linear flame response in a simplified perfectly premixed domain. This is done for varying excitation amplitudes and different inlet temperatures. Finally, these findings are applied to the more complex technically premixed case in Section 7.

2. ETH sequential burner

The second stage of the ETH sequential burner at atmospheric pressure is investigated in the present study. Throughout the paper, the burner as it is shown in Fig. 2, is called "technically premixed case". As shown in the sketch of Fig. 2a, a cold methane–air jet is injected as a cross flow into a main hot gas stream that is composed of lean methane–air flame products diluted with air. Injection takes place 180 mm upstream of the combustion chamber. The jet, which is injected through a circular inlet with a diameter of $d_{\mathrm{jet}} = 2.6\,\mathrm{mm}$, consists of 10% air and 90% methane at $T_{\mathrm{jet}} = 320\,\mathrm{K}$. Hot gas and jet velocities of $u_{\mathrm{HG}} = 60\,\mathrm{m/s}$ and $u_{\mathrm{jet}} = 200\,\mathrm{m/s}$ give a momentum ratio of $J = (\rho_{\mathrm{jet}}\, u_{\mathrm{jet}}^2)/(\rho_{\mathrm{HG}}\, u_{\mathrm{HG}}^2) = 29$. The mixing section and combustion chamber have square cross sections with 40 mm and 100 mm respectively. For the purpose of this study, a pure jet in cross flow configuration does not sufficiently mix fuel and hot gas. Hence, 2 vortex generators (VGs) are used to improve the mixing between the two streams. The axial distance between VGs tip and the fuel injection center is 15.5 mm. The width (x-direction) of each VG is 15 mm at the most upstream position; the height and length are 20 mm and 30 mm. The x-distance between the VGs tips is 31 mm.

Two different cross flow temperatures were investigated: $T_{\mathrm{HG},1} = 1350\,\mathrm{K}$ and $T_{\mathrm{HG},2} = 1450\,\mathrm{K}$. The cross flow is a mixture of burnt products flowing from the first stage, which is operated at $\phi = 0.75$, and additional fresh air with a mass flow of approximately 11 g/s. This part of the combustor is not simulated in the present study. Only main species were considered and the effect on autoignition of minor species such as NO [59] was neglected. Therefore, the hot gas inlet has the following composition: $Y_{N_2} = 0.7405$, $Y_{O_2} = 0.1355$, $Y_{H_2O} = 0.056$ and $Y_{CO_2} = 0.068$. The fuel injection is acoustically stiff ensuring constant fuel mass flow delivery. The global equivalence ratio of the second stage is fixed at $\phi = 0.76$. Hot gas and fuel mass flows are set to 23 g/s and 0.66 g/s (thermal power: 33 kW).

The ignition sequence does not necessitate external heat source: the mixture auto-ignites and the recirculation zones