Combustion and Flame 162 (2015) 86–99

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Shear flow instabilities in swirl-stabilized combustors and their impact on the amplitude dependent flame response: A linear stability analysis

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ARTICLE INFO

Article history:
Received 26 September 2013
Received in revised form 20 January 2014
Accepted 15 July 2014
Available online 20 August 2014

Keywords:
Swirl flame
Hydrodynamic instability
Flame describing function
Linear stability analysis

ABSTRACT

The hydrodynamic instabilities in the flow field of a swirl-stabilized combustor are investigated theoretically. These instabilities give rise to large-scale flow structures that interact with the flame front causing unsteady heat release rate fluctuations. The streamwise growth of these coherent structures depends on the receptivity of the shear layer, which can be predicted numerically by means of linear stability analysis. This analysis is applied to the reacting flow field of a perfectly premixed swirl-stabilized combustor that is subjected to strong axial forcing mimicking thermoacoustic oscillations. The linear stability analysis reveals a clear correlation between the shear layer receptivity and the measured amplitude dependent flame transfer function. The stability analysis based on the natural flow predicts the distinctive frequency dependent flame response to low amplitude forcing. At these conditions, the flow reveals strong spatial amplification near the nozzle, causing the inlet perturbations to be significantly amplified before they reach the flame. At higher forcing amplitudes, the flow instabilities saturate, which manifests in a saturation of the flame response. The saturation of the shear layers predicted from the linear stability analysis is compared to phase-locked measurements of the forced flow field revealing good qualitative agreement. The analysis of the mean flow stability offers a powerful analytical tool to investigate the impact of shear flow instabilities on the flame describing function.

1. Introduction

This work focuses on the role of shear flow instabilities in the coupling between the acoustic field and the flame in modern lean premixed combustors. These combustion systems are highly susceptible to thermoacoustic instabilities that are driven by a constructive interference of pressure and heat release rate fluctuations [1–3]. The associated limit-cycle oscillations have a detrimental effect on the combustion process and on the engine life time [4]. The flow field in the combustor closes the feedback loop converting acoustic perturbations emanated from the flame into flow fluctuations that, in turn, propagate into the flame and induce heat release rate fluctuations.

The linear stability of a combustion system is determined by the flame's response to low amplitude acoustic perturbations. This is typically quantified by the flame transfer function (FTF) that relates inflow perturbations to the global heat release rate fluctuations. It is valid for the low amplitude (linear) regime, where the heat release rate fluctuations increase linearly with increasing perturbation amplitude. At unstable conditions, the oscillation amplitudes increase and nonlinearities in the flame response become effective. This is expressed by the amplitude dependent transfer function also called the flame describing function (FDF) [5,6]. The nonlinearities captured by the FDF determine the limit-cycle amplitude of the instability.

Up to date, there is no rigorous method available that allows for predicting the FDF for a given combustion system revealing no other option than costly experimental assessment. This calls for a better understanding of the physics buried in the FTF and the FDF in order to develop new models that require less empirical input to predict thermoacoustic instabilities.

The difficulties in predicting the FDF stem from the multiple mechanisms that determine the flame's response to acoustic perturbations. In technically premixed flames, equivalence ratio fluctuations can cause significant heat release rate fluctuations. At perfectly premixed conditions, the fluctuations in the flow field are the main driver of the unsteady heat release. Moreover, the flame-front itself features inherent nonlinear dynamics that interfere with the flow dynamics thereby affecting the FDF [7].

Flow–flame interactions and their impact on the heat release rate fluctuations have been extensively studied within the last

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http://dx.doi.org/10.1016/j.combustflame.2014.07.012

decade [8–12]. Two main mechanisms have been identified, the vortex–flame interactions and the swirl number fluctuations. The first is the consequence of shear layer instabilities that cause the formation of large-scale (coherent) flow structures that propagate into the flame front. The vortex–flame interactions alter the instantaneous heat release rate fluctuations in several ways, such as flame roll-up [13], mixing of burned and unburned gas and subsequent flame reignition [14]. The intensity of the vortex–flame interaction and its impact on the FTF depends on the underlying flow instability. Helical (skew-symmetric) coherent structures prevalent in natural swirling jets, although affecting the flame locally [14], do not contribute to the global heat release rate fluctuations [15]. In contrast, the axisymmetric Kelvin–Helmholtz-type instability that couples with plane acoustic waves, significantly affects the global heat release rate fluctuations. Thereby, the gain in the FTF depends on the growth of the vortical structures, their lifetime before impinging the flame, and thus, on the flame shape [11,13,16,17]. Swirl number fluctuations are generated by the interference of vorticity waves generated in the swirler and plane acoustic waves. This may lead to oscillations of the opening angle of the annular swirling jet and, consequently, of the flame [18]. The oscillations of the flame angle may interfere with the roll-up of the flame tip (vortex–flame interactions) thereby affecting the FTF [17].

All the previous work mentioned here focuses on the dynamics of the flame and how they are affected by the fluctuating flow field. In this study we focus on the generation of these flow fluctuations rather then on how they actually interact with the flame. Our focus lies on the underlying hydrodynamic instabilities that lead to the formation of the coherent flow structures before they interact with the flame. We adopt an analytic approach to predict the flow response to the incoming acoustic perturbations.

The adopted approach is based on the linearized Navier–Stokes equations in conjunction with a normal mode perturbation ansatz, leading to the well-known Orr–Sommerfeld eigenvalue problem [19,20]. Equipped with an eddy viscosity model, this method provides an analytic framework for the formation of coherent structures in turbulent shear flows of various kinds. Fundamental research on elementary flow configurations such as the mixing layer or the axisymmetric jet revealed that coherent flow structures are driven by an inherent flow instability and their characteristics (frequency, wavenumber, and amplitude) are well modeled by linear eigenmodes of the Orr–Sommerfeld operator [21–24].

Within the framework of linear hydrodynamic stability analysis there are different methods applicable to different types of instabilities. A global stability analysis, utilizing a two- or three-dimensional perturbation ansatz, predicts weather the entire flow field is unstable to a single flow-inherent oscillatory mode [25,26]. Examples for global instabilities are the precessing vortex core of a strongly swirling jet [27–29] or the *von Kármán vortex street* encountered in the cylinder wake [30,31]. Internal resonance in the flow field triggers these global instabilities that then manifest in stable limit-cycle oscillations. Globally stable flows can still be convectively unstable. These flows act as amplifiers allowing a wide range of perturbation modes to be amplified in downstream direction [24,32]. The overall growth of these instabilities depends on the spatial growthrates of the flow field that is traversed by the perturbation. These growth rates are conveniently derived from a local spatial stability analysis utilizing a one-dimensional perturbation ansatz. Examples for convectively unstable flows are the mixing layer or the cold axisymmetric jet [21,23].

Although, shear flow instabilities have been extensively studied within the last four decades, the established theoretical concepts have only recently entered the focus of the combustion dynamics community. O'Connor and Lieuwen [12] emphasize the importance of flow instabilities as the link between acoustic waves and flame oscillations. Within the same group, the destabilizing effect of density inhomogeneities on a bluff-body-stabilized flame was investigated employing an local linear stability approach [33]. This methodology was used recently within our group to reveal the impact of combustion on the formation of a precessing vortex core [29,34].

The flow considered in this work is globally stable and a local spatial stability analysis is adopted, providing the spatial growth rates and the overall amplification of the inlet perturbations for a given combustor flow field. We apply the analysis to a perfectly-premixed swirl-stabilized flame that is forced axially mimicking thermoacoustic oscillations. The FDF is obtained for a wide range of frequencies and amplitudes and correlated with the results from the linear stability analysis. Connections are drawn between the amplification occurring in the shear layers and the global heat release rate fluctuations.

The goal of this work is to demonstrate this analytic approach on an realistic combustor flow. The correlations between the FDF and the results from the stability analysis must remain qualitative as the vortex–flame interactions explained above are not resolved by this approach. In order to *quantitatively* predict the heat release rate fluctuations, the flame dynamic must be derived from a flame-front tracking equation (e.g. the *G*-equation [35,36]) utilizing the flow field derived from the stability analysis. This (initiative) study is understood as a first step towards an analytical model for a FDF based on hydrodynamic linear stability analysis.

The present manuscript is organized in the following way: The reader is first introduced to the concept of linear stability analysis applied to a turbulent flow in Section 2. The combustion test rig, the measurement techniques, and the considered operating condition are outlined in Section 3. The flame response to inlet perturbations quantified by the FDF is discussed in Section 4. Based on the experimental observation, a working hypothesis is formulated in Section 5, which relates the observed flame response to the shear flow instability. The results of the linear stability analysis of the natural and forced combustor flow are presented in Section 6. The theoretical results are correlated with the experimental observations in Section 7 and the working hypothesis is validated. The study is concluded in Section 8.

2. Theoretical principal and approach

Local linear stability analysis is employed to model the large-scale flow structures encountered in the combustor subjected to acoustic forcing. For the sake of simplicity, the combustor flow is assumed to be isothermal. Generally, a non-uniform density/temperature field in the combustor affects the growth rates of the instabilities [37,38]. This is crucial for self-excited instabilities like the precessing vortex core, where the growth rates in flow regions driving the internal resonance must be accurately predicted. As demonstrated by Oberleithner et al. [29], significant changes of the density field, induced by a reattachment of the flame, cause a complete suppression of the precessing vortex core. However, for convectively unstable flows as investigated here, inaccuracies in the predicted growth rates are not expected to qualitatively alter the results as these instabilities are externally driven and remain unstable over a wide range of parameters. Moreover, in the present investigation, the flame shape changes only weakly with increasing forcing amplitude, and hence, the stability analysis of the different forcing cases should be, at the least, qualitatively correct. The main theoretical approach is in line with the analysis applied to the isothermal unconfined swirling jet reported in Ref. [28] and is, therefore, only briefly described here.