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Interaction between velocity fluctuations and equivalence ratio fluctuations during thermoacoustic oscillations in a partially premixed swirl combustor

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Abstract

The combined effects of velocity fluctuations (VF) and equivalence ratio fluctuations (ERF) on thermoacoustic flame oscillations are studied experimentally in a gas turbine model combustor. The analysis is based on time-resolved simultaneous measurements of flow field, flame structure and fuel distribution using combined PIV, OH-PLIF and tracer-PLIF at a rate of 10 kHz. In order to separate the effects of VF and ERF, the combustor has been operated in two configurations: a technically (i.e. partially) premixed (TP) configuration where both ERF and VF occur, and a perfectly premixed (PP) configuration where only VF are present. A particular operating condition is selected where the VF are similar for both premixing modes. The corresponding fluctuations of heat release, by contrast, exhibit considerably different spatial patterns for the two modes. In particular, periodic widening and narrowing as well as extinction and re-ignition of the flame base, and a convective motion of the flame zone are observed in the TP flame but not in the PP case. An evaluation of periodic variations of flux rates and heat release shows that the feedback loop of the TP flame includes an additional convective delay of 50°. The time-resolved measurements reveal that this delay leads to a coincidence of fuel-lean unburned gas and high velocity that induces local flame extinction and narrowing of the flame base. When the equivalence ratio later increases, the flame base re-ignites and a widened zone of increased heat release forms that is convected downstream. For the PP case, by contrast, reaction at the flame base is stable and accordingly the flame responds earlier to VF compared to the TP case. The results show that interacting VF and ERF have a strong and complex impact on the thermoacoustic response of turbulent swirl flames, and this impact depends largely on their time-delay.

Keywords: Thermoacoustic instability; Turbulent swirl flames; Flow-chemistry interaction; Gas turbine combustion; High-speed laser diagnostics

1. Introduction

For modern, lean, low-emission gas turbine (GT) combustors, the prevalent susceptibility to

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thermoacoustic pressure pulsations [1] poses a major problem for the development of combustors with improved emissions and operational flexibility. The feedback loop of these thermoacoustic instabilities is determined by highly complex, multiscale transient interactions of acoustics, turbulent flow, mixing and reaction [2], which are difficult to model even with expensive modern CFD tools. The design of improved combustors therefore requires further basic understanding of these interactions based on detailed experimental data.

For a closed feedback loop, it is necessary that the acoustic oscillations excite a varying heat release of the flame. It is widely established [3–6] that this mainly takes place in two ways, namely through velocity fluctuations (VF) and equivalence ratio fluctuations (ERF) (other effects, such as entropy waves, are neglected in this work). VF lead to a varying flux of unburned gas into the flame zone, and subsequently to changes of, e.g., flame surface density, vorticity or strain rate [7]. ERF are caused by fluctuations of velocity or pressure at the point of fuel injection [8–10], which induce local inhomogeneities of fuel-air mixture propagating into the combustion chamber. This leads to a varying equivalence ratio of the unburned gas entering the flame zone, and hence variations of heating value, flame speed and flame surface density [11]. In GT burners with perfect premixing (PP), where fuel and air are mixed far upstream of the flame, only VF can be present. In order to avoid safety risks such as auto-ignition or flashback, however, most burners are operated in a partially premixed or technically premixed (TP) mode, where fuel is injected shortly upstream of the burner nozzle, and thus both ERF and VF occur.

A number of studies has shown that VF and ERF cannot be treated separately, but interact in various ways. Comparing results from PP and TP operation of a combustor, it was found that ERF, often depending on their convective time lag, can either enhance or dampen the flame response to VF [5–7,9]. It was further observed that non-linear effects of the TP flame response, such as saturation at high amplitude, depend on the phase difference between VF and ERF [4]. Cosic et al. [6] concluded that an increase of VF enhances fuel-air mixing and thus causes saturation of the flame response. The phenomena reported in these works are the result of intricate interactions amongst flow field, mixing and flame propagation taking place on a wide range of spatial and temporal scales, which are not well understood to date. Elucidating these mechanisms requires time-resolved multi-parameter diagnostics that was not available in previous works.

The aim of this work is to study the mechanisms of transient interactions between VF and ERF in a GT-typical turbulent swirl flame, and relate them to the observed global flame oscillation. For this purpose, the work employs a combustor that can be operated both in PP [13–15] and TP [12,15] mode. Flow field, flame structure and fuel distribution are measured simultaneously in a 2D domain using combined time-resolved stereo-PIV, OH-PLIF and tracer-PLIF. In order to separate the effects of VF and ERF, measurements are performed in both PP and TP mode at a specific condition where the respective VF are nearly equal. The respective patterns of heat release variation, on the other hand, exhibit pronounced differences between the two modes. These differences are then traced back to the transient combined effects of VF and ERF seen in the time-resolved measurements like, e.g., local flame extinction or changes of local flame speed. Furthermore, the combined measurements of velocity field and fuel distribution are used for a quantitative analysis of oscillating fluxes of unburned fuel and air and their role in the global feedback cycle.

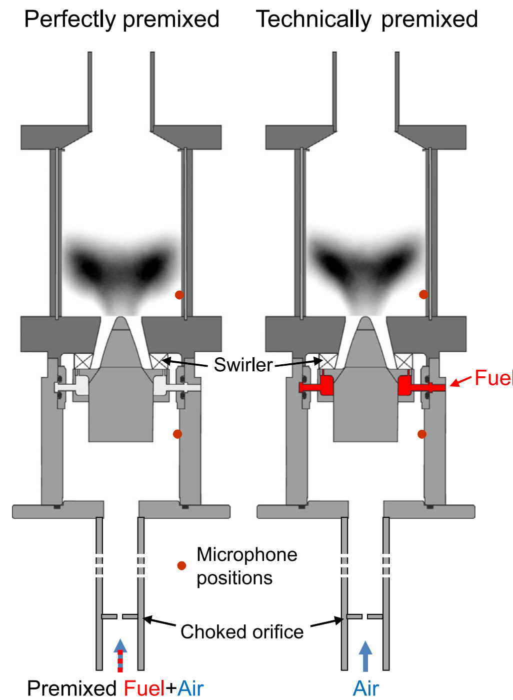

Fig. 1. Geometry of gas turbine model combustor for PP (left) and TP (right) configuration. OH-CL images of flame shape are shown for P_{th}=15 kW and ϕ=0.8.

2. Experimental setup

2.1. Combustor and operating condition

The schematics of the two versions of the gas turbine model combustor are shown in Fig. 1. The burner is derived from a design by Turbomeca and has been investigated experimentally (e.g., [12–15]) and numerically (e.g., [16–18]) within and after the