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Mixing and reaction progress in a confined swirl flame undergoing thermo-acoustic oscillations studied with laser Raman scattering

W. Meier *, C. Dem, C.M. Arndt

Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Verbrennungstechnik, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany

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ABSTRACT

A gas turbine model combustor for partially premixed flames was equipped with an optically accessible combustion chamber and operated with methane and air at atmospheric pressure, with a global equivalence ratio of 0.7 and a thermal power of 25 kW. At these conditions the combustor exhibited thermo-acoustic oscillations with a frequency of approximately 400 Hz. The flame behavior and its cyclic variations were investigated by laser Raman scattering for the simultaneous determination of the major species concentrations, temperature and mixture fraction. Additional information of the mean flow field and the flame shape was provided by particle image velocimetry and OH* chemiluminescence imaging, respectively. Previously published results of phase-correlated mean values of this flame showed that the instability was sustained by the mechanism known as equivalence ratio fluctuations with convective delay. The current paper is focused on the characterization of the thermo-chemical state of the flame during the oscillation cycle. The mixture fraction varies considerably with spatial location and with the phase of the pressure oscillation and strong effects of turbulence–chemistry interaction are prevailing in the region close to burner mouth. Further, the effect of locally rich mixtures and elevated temperature on the local CO concentration level is shown.

1. Introduction

The performance of gas turbines (GT) for power generation and propulsion is often limited by the occurrence of thermo-acoustic instabilities which arise from the interaction of the flame dynamics with the acoustic modes of the combustion system [1,2]. Due to the complex coupling of flame stabilization, heat release, flow field and acoustic modes, a detailed understanding of the underlying mechanisms presents a difficult task, and a reliable prediction of frequencies and amplitudes of thermo-acoustic instabilities remains challenging. Periodic variations in heat release can stem from oscillations of the fuel stream entering the combustion chamber, equivalence ratio fluctuations or oscillations in flame area [1]. The varying thermal expansion associated with the heat release oscillations affects the pressure in the combustor which in turn influences the flow field. The relation between the time scales of the flow field variation and the acoustic modes of the system play a crucial role for the feedback mechanism of the thermo-acoustic instability. Another important aspect of the feedback mechanism concerns the response of the flame to variations of the flow field and chemical composition. The region where the flame can stabilize and the burning rate depend strongly on local strain rates and the composition and temperature of the reactants. Therefore, knowledge of the structure, flow field and thermo-chemical state of the flame as well as of their spatio-temporal fluctuations is essential for the understanding of the mechanisms leading to self-sustaining thermo-acoustic oscillations.

On the experimental side, good progress in this field has been achieved by the use of optically accessible GT model combustors and the application of optical and laser-based techniques, see e.g. Refs. [3,4] and the citations therein. Therefore, the Karlsruhe Institute of Technology (KIT) and the German Aerospace Center (DLR) have co-operatively designed and set up a GT model combustor with an optical combustion chamber for the investigation of thermo-acoustic combustion instabilities [5–7].

One of the target flames investigated was a partially premixed methane/air flame with an overall equivalence ratio of $\phi = 0.7$ and a thermal power of 25 kW. It exhibited thermo-acoustic instabilities at a frequency around 400 Hz which coincided with an acoustic resonance of the plenum length. The flame and the phase-dependent variations during an oscillation cycle were previously studied by OH* chemiluminescence imaging for the investigation of the cyclic variation of the heat release and overall flame characterization, stereoscopic particle image velocimetry (PIV)

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* Corresponding author.
E-mail address: wolfgang.meier@dlr.de (W. Meier).

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for the measurement of the flow field and by laser Raman scattering for the simultaneous determination of the major species concentrations, temperature and mixture fraction. The phase-correlated mean values from those measurements showed that the pressure variations in the combustion chamber modulated the flow field and equivalence ratio. Mixtures with alternating high and low fuel content were periodically formed in the burner nozzle near the fuel injection which then convected downstream toward the flame zone, where they caused a periodic variation of the heat release rate [7]. The reason for the varying fuel/air mixture in the nozzle was the different response (impedance) of the fuel and air supply lines to pressure variations. Arndt et al. [7] showed that the feedback loop of the self-sustaining combustion oscillation was closed by the coincidence of the convection time of the fuel-rich mixtures to the flame zone and the period of the acoustic resonance frequency. Thus, the instability was sustained by the mechanism known as equivalence ratio fluctuations with convective delay [8–12].

In the current paper, the focus is on mixing and reaction progress as well as on effects of turbulence–chemistry interaction in the same flame. The results are mainly based on single-shot laser Raman measurements which enabled the determination of the joint probability density functions of the concentrations of CH_4, O_2, N_2, CO_2, CO, H_2O and H_2, the mixture fraction and temperature. In addition, the mean flow field measured by particle image velocimetry, mean 2D distributions of OH* chemiluminescence, mixture fraction and temperature are shown to yield a general overview of the flame.

2. Experimental

2.1. Combustor

Fig. 1 shows a schematic of the combustor. The burner consists of an inner nozzle (diameter $D = 15$ mm) and a concentric annular nozzle (ID = 15.2 mm, OD = 24 mm), which are supplied with dry air at room temperature from two separate plenums. Both flows are swirled in the same direction by individual radial swirl generators. The theoretical swirl number is $S_o = 1.06$ for the outer swirler and $S_i = 0.73$ for the inner swirler. Methane is supplied to the inner nozzle through 60 holes with a diameter of 0.5 mm, arranged on a circumference at the wall 12 mm below the nozzle exit. Thus, the flow from the inner nozzle is partially premixed before entering the combustion chamber and reaching the flame zone. The flames are enclosed by a square combustion chamber (inner dimension 89 mm × 89 mm cross section, 112 mm high) comprised of four fused silica plates which are held by steel frames. The frames are mounted to four posts in the corners and to the bottom and top of the combustion chamber. The resulting optical access to the flame is 73 mm wide and 112 mm high on each side. The origin of the coordinate system for all measurements is the center of the nozzle exit ($h = 0$, $r = 0$). The exit of the upright combustion chamber is conically shaped leading to a short central exhaust pipe with an inner diameter of 50 mm. Two of the four posts are equipped with ports for the installation of microphone probes. The lower part of the combustor contains the air plenums and supply lines. The housing is squared with inner dimensions of 90 mm × 90 mm. It has two tubes (ID = 72 mm) on the side for the air supplies. A defined acoustic boundary is achieved by sonic orifices located approximately 200 mm upstream of the inlet into the vertical plenum section. A round tube (ID = 50 mm) along the axis of the confinement forms the inner boundary of the inner plenum. It contains the fuel tube (ID = 4 mm) that terminates into a small plenum for the fuel distribution at the nozzle. The inner air plenum has a height of 380 mm, a round cross section with an ID of 50 mm and an OD of 76 mm at its upper half and a square 90 mm × 90 mm cross section at its lower half. The outer air plenum has a height of 200 mm, an ID of 80 mm and an outer boundary of 90 mm × 90 mm. Ports for microphone probes enable the registration of acoustic oscillations in the plenums as indicated in Fig. 1.

The flow rates were metered by electromechanical mass flow meters (Brooks type 5851S for CH_4 and type SLA5853S for each air flow) and additionally controlled by calibration-standard Coriolis mass flow meters (Siemens SITRANS F C MASS 2100 DI 3 for CH_4, Siemens SITRANS F C MASS 2100 DI 15 for each air flow) with an accuracy of approx. 1.5%.

The burner was operated with 451 and 282 g/min of air in the outer and inner plenum, respectively, and 30 g/min of CH_4. The corresponding thermal power was 25 kW and the global

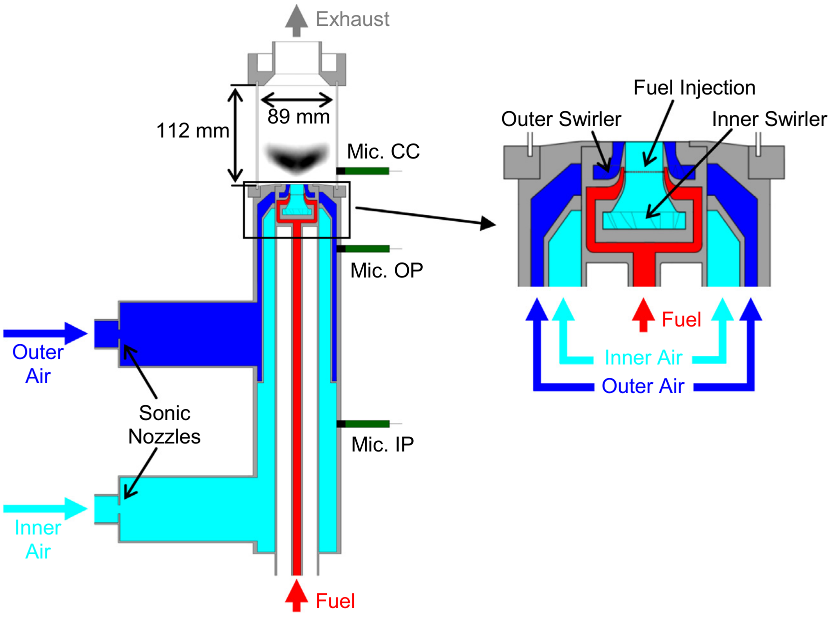

Fig. 1. Schematic of the combustor.