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Experimental study of industrial gas turbine flames including quantification of pressure influence on flow field, fuel/air premixing and flame shape

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ABSTRACT

A commercial swirl burner for industrial gas turbine combustors was equipped with an optically accessible combustion chamber and installed in a high-pressure test-rig. Several premixed natural gas/air flames at pressures between 3 and 6 bar and thermal powers of up to 1 MW were studied by using a variety of measurement techniques. These include particle image velocimetry (PIV) for the investigation of the flow field, one-dimensional laser Raman scattering for the determination of the joint probability density functions of major species concentrations, mixture fraction and temperature, planar laser induced fluorescence (PLIF) of OH for the visualization of the flame front, chemiluminescence measurements of OH^* for determining the lift-off height and size of the flame and acoustic recordings. The results give insights into important flame properties like the flow field structure, the premixing quality and the turbulence–flame interaction as well as their dependency on operating parameters like pressure, inflow velocity and equivalence ratio. The 1D Raman measurements yielded information about the gradients and variation of the mixture fraction and the quality of the fuel/air mixing, as well as the reaction progress. The OH PLIF images showed that the flame was located between the inflow of fresh gas and the recirculated combustion products. The flame front structures varied significantly with Reynolds number from wrinkled flame fronts to fragmented and strongly corrugated flame fronts. All results are combined in one database that can be used for the validation of numerical simulations.

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1. Introduction

The understanding of combustion in gas turbines (GTs) has been strongly improved by the combined and mutually supporting effort of experimental studies in GT model combustors and numerical simulations using advanced methods like Large Eddy Simulation (LES) [1,2]. In particular, GT model combustors with optically accessible combustion chambers which facilitate the application of laser and optical measurement techniques enabled a deeper insight into the complex interaction between flow field, combustion and acoustic modes of the system. Among the main advantages of these techniques is their ability to non-intrusively measure instantaneous two-dimensional distributions of various quantities, to image short-lived combustion radicals and heat release rates, to measure several quantities simultaneously and to capture the temporal development using high-speed imaging techniques [3–6]. Main research topics in GT combustion have been thermo-acoustic instabilities, coherent flow structures, flame stabilization, pollutant emissions, effects of mixing and turbulence–chemistry interaction, fuel flexibility, flashback and the potential of new combustion systems. Many laser-based studies in GT (model) combustors addressed these topics, for example, the dynamics of swirl flames by using particle image velocimetry (PIV) for the characterization of the flow field or planar laser-induced fluorescence (PLIF) for the measurement of the flame front, often in combination with chemiluminescence imaging [7–11]. PLIF was also applied to investigate the mechanisms of flame stabilization [12–14]. The role of equivalence ratio fluctuations and effects of unmixedness in lean premixed flames were investigated by Schürmans et al. [15] using chemiluminescence and infrared absorption measurements and by Meier et al. [16] using laser Raman scattering. Further examples of similar studies are given in the tables of the papers by Palis et al. [17] and Dhanuka et al. [18].

The cited investigations and some more have been performed at atmospheric pressure. At elevated pressure, the experimental complexity and costs increase drastically. In high-pressure test-rigs optical access is limited, laser and signal beams must pass through

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several windows (pressure housing and combustion chamber), windows degrade from the high heat load to the glass surface and the pressure broadening of spectral lines often leads to signal decrease. Thus, fewer studies using optical and laser based techniques have been reported at high-pressure GT conditions. However, such investigations are important because increased pressure changes the physical and chemical quantities in the flame, like Reynolds number, viscosity, reaction rate related quantities like flame speed, ignition delay time or pollutant formation and, in general, all effects of turbulence–chemistry interaction. For example, Griebel et al. measured the influence of pressure and turbulence on the flame speed of premixed turbulent flames [19], Lückerath et al. studied flame stabilization in a staged GT model combustor [20], Strakey et al. and Fleck et al. investigated the impact of hydrogen in GT combustors [21,22], the role of coherent structures was studied by Janus et al. [23], mixing and reaction progress by Ax et al. [24] and new burner concepts were investigated with coherent anti-Stokes Raman spectroscopy (CARS) by Lammel et al. [25] and Thariyan et al. [26].

One of the targets of the experimental studies was the generation of validation data for numerical simulations. Here, significant improvements for the prediction of GT combustion have been achieved with Large Eddy Simulation (LES) [27–38]. LES is a powerful and promising modeling technique particularly for highly swirling and unsteady flows. For gas turbine combustion chambers, particular attention is given to development of the flow field, coherent structures, flame front and thermo-acoustic instabilities. In studies of industrial geometries, [27,29,30,39,40], the LES formulation was completed considering reduced chemistry (2-, or 3-step). Good agreement was generally obtained for the velocity and scalar fields with over-prediction of temperature and species in most cases. The use of reduced chemistry did not exploit the full potential of the LES method to capture the turbulence and chemistry interaction of industrial flows. The major objective of industrial LES studies appears to aim at capturing more turbulent features, rather than additional chemistry. This was most likely dictated by the lack of detailed experimental data for the species composition.

This paper presents results from optical and laser-based measurements performed in an optically accessible combustion chamber equipped with an original Siemens Industrial Turbomachinery, Lincoln dry low emissions (SITL DLE) combustor. The burner and combustion chamber were installed in the high-pressure test rig HBK-S at DLR in Stuttgart and operated with natural gas and preheated air at pressures up to 6 bar. Particle image velocimetry (PIV) was applied to measure the flow field, 1D laser Raman scattering for the simultaneous determination of the major species concentrations, mixture fraction and temperature, PLIF of OH and chemiluminescence imaging for the visualization of flame structures, as well as chemical analysis of the exhaust gas composition. A particular challenge was the application of single shot 1D laser Raman scattering under GT conditions in flames with thermal powers of up to 1 MW. With this technique, it was for the first time possible to quantify spatial mixture fraction gradients and effects of unmixedness in an industrial GT combustor under realistic operating conditions. The combustion parameters that were varied within the investigations were the pressure in the combustion chamber, pressure drop at the burner (and thus flow velocity) and the equivalence ratio. A comparable data set from a high-pressure GT flame comprising flow velocities, flame structures and joint probability density functions of major species concentrations, temperature and mixture fraction has not been documented before. The main goals of the measurements were a better understanding of the mixing and reaction progress, flow field structures and unsteady combustion processes as well as the establishment of a comprehensive experimental database for the validation of numerical simulations. It is envisioned that this database may serve as a "standard" test case for the comparison of the performance of different computational fluid dynamic (CFD) codes.

2. Experimental setup and measurement techniques

2.1. Burner, combustor and test rig

The studied burner was an original-sized industrial GT burner from Siemens. It is the smallest commercial version of the company's DLE combustor family which is installed in the small and medium sized turbo-machines SGT-100 to 400 as a retrofit solution [41] and as the standard equipment in the current product line [42,43]. The fields of application of these engines cover both the production of electrical and mechanical power in a range between 4.9 and 15 MW. The burner is built up of a radial swirler with 12 rectangular channels (see Fig. 1). Each channel has multiple small holes for the injection of fuel that mixes with the air flow. Downstream of the swirler the air–fuel mixture flows through a ~46 mm long tube in which the largest part of the premixing takes place. The exit diameter of this "burner nozzle" is 86 mm. The pilot burner is only used for part load operation in the commercial gas turbine [44]. In the present work, it was used for the flame ignition and switched off after the startup procedure. The development of the DLE combustion system in Lincoln started in the mid-nineties [45,46]. It aims for a fast mixing of fuel and air prior to the combustion in order to generate a uniform flame temperature distribution and hence low NO_x emissions [47–49]. Experimental [50,51] as well as numerical studies [52] were performed to analyze such emissions and to validate a novel NO_x prediction method [53]. Further experimental work was focused on finding correlations between acoustic oscillations and the flame behavior [54] as well as the wall heat transfer [55]. In recent experiments the DLE

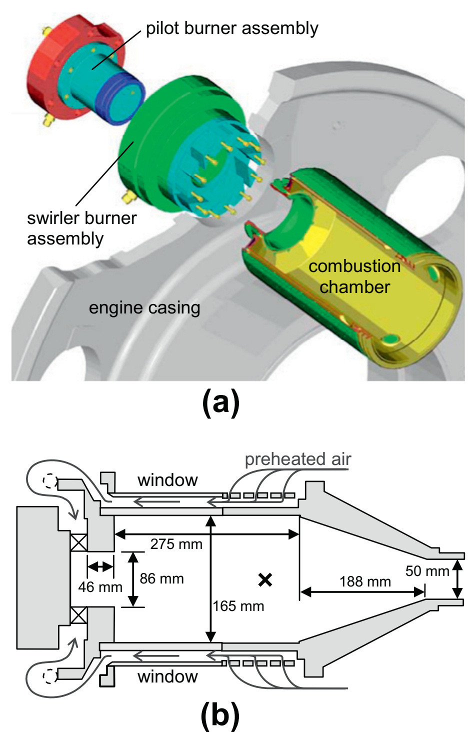

Fig. 1. The industrial burner with the commercial cylindrical combustion chamber (a) and with the optically accessible combustion chamber (b) (based on [65]). A cross marks the location of the acoustic probe. Two dashed circles represent the perforated ring tube used for particle seeding.

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