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Computational study of flame characteristics of a turbulent piloted jet burner with inhomogeneous inlets

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Abstract

Recent experimental studies of a piloted turbulent jet burner at Sydney and Sandia with inhomogeneous mixture composition at the inlet have revealed that the flame stability of a partially premixed flame can be significantly increased with a tailored mixture fraction profile at the burner exit. In the present work, large-eddy simulations of this burner are performed with three different levels of mixture inhomogeneity. A multi-regime flamelet model is employed, which accounts for the range of combustion modes found in these flames. The results of the simulations are validated against experimental data for the case with the highest blowoff velocity. Good agreement is observed for velocity, mixture fraction, and temperature fields. The simulations with the multi-regime model provide detailed data of the prevalent combustion regime as well as the heat release. The location of heat release and differences in the combustion modes are analyzed for three cases with different mixture inhomogeneities. The progress variable source term is split up into the individual contributions of the combustion regimes. Substantial differences are found for the contributions of premixed and non-premixed combustion in the different flames as well as the location of the heat release. These results are used to explain the respective flame stabilities. For the inhomogeneous case, which features substantially increased flame stability, hot pilot gases are in contact with reactive mixture directly at the nozzle. Therefore a predominantly premixed zone of strong heat release develops at the jet exit and stabilizes the flame. For both other cases, the heat release at the nozzle is lower leading to smaller blowoff velocities. For the non-premixed case, this is due to air shielding the pilot from the reactive mixture. For the premixed case, the homogeneous mixture issuing from the jet is above the flammability limit and consequently the heat release is diffusion dominated.

Keywords: Turbulent combustion; Partially premixed combustion; Inhomogeneous jet; Large-eddy simulation

1. Introduction

The governing physics of combustion processes in the premixed and the non-premixed regime are substantially different. Since diffusion and

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convection time scales are rate controlling for non-premixed combustion, transport and chemistry time scales are of the same order magnitude in premixed combustion [1,2]. Combustion models, therefore, should consider the peculiarities of the microphysics governing the respective combustion regime. In many practical devices the fuel/air mixture is inhomogeneous and both combustion regimes significantly contribute to the combustion process [3]. For example, Rosenberg et al. [4] measured the ratio of the combustion regimes of a swirl flame in a gas turbine model combustor. In this nominally non-premixed configuration, both regimes contribute equally to the combustion process near the injector and the application of a single combustion model for premixed or non-premixed combustion is no longer accurate. Similar findings were observed by Luo et al. [5] in the DNS of swirl-stabilized turbulent combustion of liquid fuels. Other examples for partially premixed combustion include diesel [6] and gasoline direct injection engines [7].

Different approaches to model partially premixed combustion have been presented over the recent years. Many depend on an indicator, which identifies the mode of combustion and evaluates the relative importance of the regimes. Yamashita et al. [8] introduced the flame index for that matter, which was used by Fiorina et al. [9]. Knudsen and Pitsch [10] developed a multi-regime flamelet combustion model, which determines a budget of the progress variable source term to locally determine a regime indicator.

An experimental setup, where the mixture inhomogeneity at the inlet is varied, has been studied extensively by Meares et al. [11,12] and Barlow et al. [13] in terms of flame stability of partially premixed flames. The investigation revealed that the blowoff velocity as a measure for the stability can be increased significantly with a tailored mixture inhomogeneity. Barlow et al. [13] also performed additional 1D laminar flame calculations in order to provide further insights into the mechanisms leading to improved flame stability. In the vicinity of the nozzle, substantial differences in the combustion regime were found for different levels of inhomogeneity. The present paper aims at analyzing these stabilization mechanisms with results of turbulent 3D large-eddy simulations (LES). A multi-regime combustion model is applied to three configurations with different mixture inhomogeneities. Detailed, localized data are shown for the prevalent combustion regime as well as the heat release. This information is used to understand the experimental findings and to illuminate the origin of the different blowoff velocities.

The work is structured as follows: Section 2 presents the experimental configuration and Section 3 gives a brief introduction of the employed multi-regime model. The numerical setup is described in Section 4. In Section 5, simulation results are presented and validated against experimental data of velocity, mixture fraction, and temperature. Section 6 contains the analysis of the flame characteristics of the three different cases.

2. Experimental setup

The investigated burner is a modified version of the well-known piloted jet burner from the University of Sydney [14,15]. While the original burner consists of two concentric pipes to form the jet and the pilot, the modified version, shown in Fig. 1a, has an additional pipe within the jet, which can be recessed to vary the degree of premixing of fuel and air in the central jet. The distance between this additional pipe and the jet exit is referred to as recession length L_r. The fuel/air mixture is completely homogeneous for the fully receded pipe ($L_r = 300$ mm) and entirely non-premixed when the inner pipe exit is flush with the central jet corresponding to $L_r = 0$ mm. For all cases, the global equivalence ratio of the central jet is equal and above the rich flammability limit.

The experimental studies revealed that flame stability in this configuration is a function of the recession length or rather the mixture inhomogeneity at the inlet. The experimentally observed flame stability, measured as blowoff velocity, is plotted in Fig. 1b. Interestingly, the flame stability is significantly increased at intermediate recession lengths, with the inhomogeneity providing optimal flame characteristics. For the configurations studied in this paper, fuel and air are issued from the central pipe and the annulus, respectively. At a recession length $L_r = 0$ mm fuel and air are completely separated at the jet exit. On the other end, the central pipe is fully recessed ($L_r = 300$ mm). The mixture of fuel and air is then nearly homogeneous. For all cases, the volumetric air/fuel ratio is $V_A/V_F = 2$ and the global mixture of the jet is thus above the rich flammability limit.

Experiments for this burner have been performed both at the University of Sydney [11,12] and Sandia Livermore National Laboratories [13] using different experimental equipment. The two setups differ in pilot gas composition, fuel, and measured quantities. The Sydney setup uses a 3-gas pilot (C_2H_2/H_2/air) with an adiabatic temperature of 2480 K and compressed natural gas (CNG) as fuel. Experimental data of flow velocities are only available for this case. The Sandia setup uses a 5-gas pilot ($C_2H_2/H_2/CO_2/N_2$/air) tailored to meet the adiabatic equilibrium temperature of a stoichiometric CH_4/air mixture (2226 K). It is operated with pure methane as fuel and experimental data are available for mixture fraction, temperature, and different species mass fractions. The studied configurations are listed in Table 1 and shown in Fig. 1 in relation to the blowoff