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Experimental and numerical investigation of the influence of thermal boundary conditions on premixed swirling flame stabilization

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ABSTRACT

This paper focuses on the experimental and numerical investigation of the shape taken by confined turbulent CH_4/H_2/air premixed flames stabilized over a bluff-body swirling injector. Two configurations, which correspond to two levels of H_2 enrichment in the CH_4/H_2 fuel blend, are investigated. Experiments show that high H_2 concentrations promote M flame shapes, whereas V flame shapes are observed for lower values of H_2 enrichment. In both cases, non-reacting and reacting flow Large Eddy Simulation (LES) calculations were performed. Numerical results are compared with detailed velocimetry measurements under non-reacting and reacting conditions, OH-laser induced fluorescence and OH^* chemiluminescence measurements. All temperatures of solid walls of the experimental setup including the combustor dump plane, the injector central rod tip, the combustor sidewalls and the quartz windows were also characterized. Assuming a fully adiabatic combustion chamber, LES always predicts an M flame shape and does not capture the V to M shape transition observed in the experiments when the hydrogen concentration in the fuel blend is increased. By accounting for non-adiabaticity using measured thermal boundary conditions, simulations predict the correct flame stabilization for both V and M flames and show a good agreement with experiments in terms of flame shape. Key features that need to be included in non-adiabatic simulations are finally stressed out.

1. Introduction

In many combustors operating in the lean premixed combustion regime, the flame is stabilized by a swirling flow. By promoting recirculation zones composed of burnt gases, flame stabilization is enhanced over a wide range of operating conditions [1]. The flow structure in a combustor equipped with a swirling injector is very complex [2] and either M or V flame shapes can be observed. The shape taken by the flame then affects the temperature field in the burnt gases at the outlet of the combustion chamber and pollutant emissions. Experiments and simulations indicate that the topology of swirling flames is highly sensitive to fuel composition [3–5] and heat transfer to the combustion chamber walls [6–10]. Simulations of the stabilization regimes of these flames are very challenging as numerous physical phenomena such as the combustion chemistry, flame interactions with turbulence, and heat losses have to be taken into account.

In this way, modeling efforts are continuously conducted to improve the description of detailed chemistry effects in turbulent combustion simulations [11]. In particular, Large Eddy Simulations (LES) turbulent combustion models based on tabulated chemistry have been recently improved by several groups to account for the influence of heat transfer on the flame stabilization process [12–14]. These numerical strategies have been targeted on the same Turbulent Stratified Flame (TSF) experiments conducted at the Technical University of Darmstadt (TUD) [15]. A joined comparative study between simulations and experimental data shows that while each adiabatic computations predict a flame anchored on the burner lip, all non-adiabatic simulations agree on a flame lift-off of one half pilot diameter [16]. These last results lead to a better agreement with experimental measurements of temperature and species concentrations [16]. However, being unconfined and non-swirled, the TSF configuration validates only partially the ability of a turbulent combustion model to capture flame stabilization process in a gas turbine like combustor. To achieve the validation,

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complementary experimental configurations, more representative of combustion chamber with a swirling flow are required.

Tay Wo Chong et al. [8] analyzed numerically the influence of heat losses on the shape taken by the flame in a confined swirled non-adiabatic combustor. They accounted for heat losses in Reynolds Averaged Navier-Stokes (RANS) simulations to reproduce the V flame shape observed through chemiluminescence imaging experiments. However, as accurate measurements of the thermal boundary conditions and flame shape were not available in this study, the comparisons between simulations and experiments remained qualitative. Proch et al. [9] modeled the effects of heat losses in a model gas turbine combustor where it was shown that non-adiabatic computations allow a better prediction of the flame shape and length in comparisons to adiabatic simulations. In this study, the wall temperatures were not measured and a fixed temperature of $T = 1000$ K was imposed for all the combustor walls. In [7], Nogenmyr et al. imposed realistic measured temperature profiles in the non-adiabatic LES of a reduced-scale confined burner. However, temperature measurements were not realized on the same burner geometry and with the same fuel as in the simulation.

The objective of the present work is first to propose a configuration which challenges the ability of turbulent combustion model to capture swirled premixed flame stabilization mechanisms in a confined geometry. The combustion chamber recently studied experimentally at the EM2C laboratory is retained for that purpose [6]. It was shown that the V to M flame shape transitions observed in this experiment are controlled by heat losses and fuel composition. As boundary conditions (inlet velocity profiles and wall temperatures) were characterized in this combustor [6], the resulting experimental database is a useful benchmark target for turbulent combustion model validation. The second objective is to test the suitability of the model F-TACLES (Filtered Tabulated Chemistry for LES) [17], recently developed to account for the impact of heat losses on detailed chemistry [14,18], to capture such complex flame stabilization mechanisms.

The article is organized as follows. The experimental configuration is first presented. The diagnostics and the numerical strategies along with the investigated operated conditions are secondly described. Two configurations, which correspond to two levels of H_2 enrichment in the fuel blend, are investigated. Experiments show that high H_2 concentrations promote M flame shapes, whereas V flame shapes are observed for lower values of H_2 enrichment. An analysis is then carried out to examine the ability of F-TACLES to capture both V and M flame stabilization processes.

2. Experimental setup

2.1. Geometry

The experimental setup presented in Fig. 1 was used in [6] for the study of the impact of heat losses on the shape of confined swirling flames. The burner, fed by mixtures of methane (CH_4), hydrogen (H_2) and air, includes a cylindrical injection tube with a 14 mm exit diameter. The flow is put in rotation by a radial swirling vane located upstream of the injection tube. The radial swirler features 12 blades with an angle $\theta = 35^\circ$ and a 4 mm span. The swirl number $S^{PIV} = 0.33$ has been measured at the burner outlet using Particle Image Velocimetry (PIV) in longitudinal and transversal planes under non-reacting conditions. A 6 mm diameter central rod installed on the burner axis helps anchoring the flame at the injection unit outlet 2 mm above the combustor dump plane. The mixture enters the burner through a plenum and subsequently passes through a set of grid/honeycomb/grid arrangement before entering a water-cooled convergent nozzle to reach a nearly uniform top hat velocity profile at the entrance of the swirler. The flame is stabilized in the combustion chamber featuring four 250 mm (height) × 92 mm (width) × 12 mm (thickness) quartz windows. The windows are maintained using four vertical steel-bars not sketched in Fig. 1. To prevent ambient air intrusion at the combustor outlet, a convergent exhaust, featuring a 53% reduction of its section, is added on the top of the chamber to accelerate the outgoing flow.

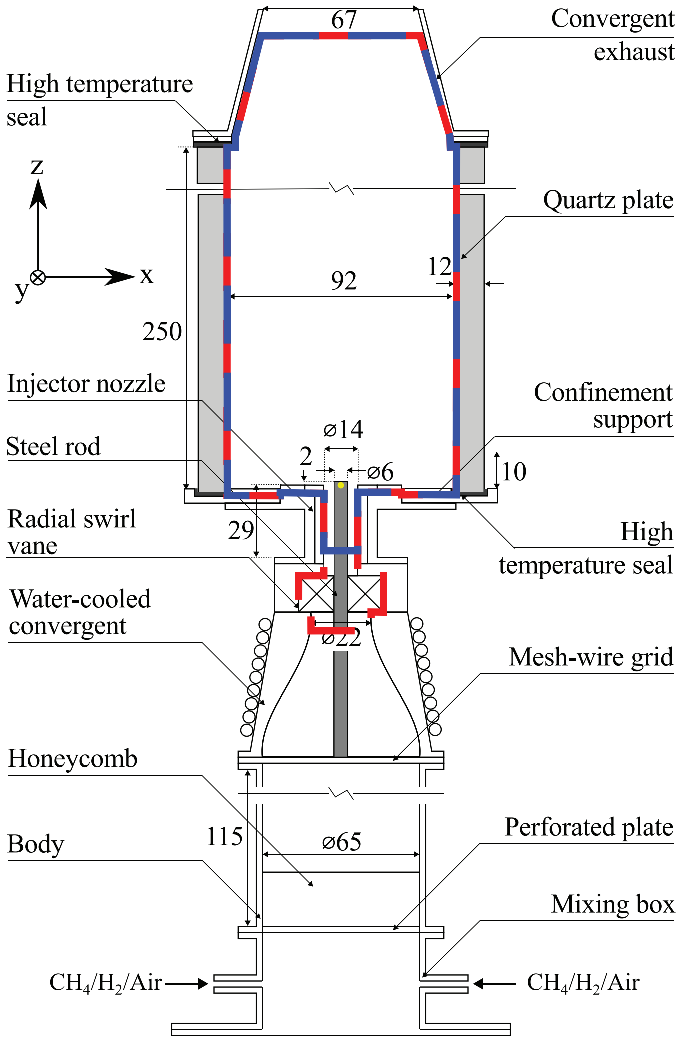

Fig. 1. Schematic of the test-rig. Dimensions are in mm. The reference computational domain for both non-reacting and reacting cases is delimited by the blue dashed line. The red dashed line represents the preliminary computational domain used to extract the velocity boundary conditions for the reference domain. The yellow dot at the tip of the central rod indicates the origin of the numerical frames. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. Operating conditions

Experiments in [6] show that flame stabilization is strongly influenced by heat losses at the combustor wall. In addition, transitions between V and M flame shapes are observed when increasing the H_2 concentration in the CH_4/H_2 fuel blend. Two fuel compositions of $\{X^{fuel}_{H_2} = 0.6; X^{fuel}_{CH_4} = 0.4\}$ and $\{X^{fuel}_{H_2} = 0.9; X^{fuel}_{CH_4} = 0.1\}$ are retained for this study, where $X^{fuel}_{H_2}$ and $X^{fuel}_{CH_4}$ denote the volumetric concentration of H_2 and CH_4 in the fuel. For all cases, the flame power is $P = 4$ kW and the equivalence ratio is set to $\phi = 0.7$. The mass flows of the different dry gases injected are regulated by thermal mass flow controllers. The mixture composition and bulk