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Conical quarl swirl stabilized non-premixed flames: flame and flow field interaction

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Abstract

The flame-flow field interaction is studied in non-premixed methane swirl flames stabilized in quartz quarl via simultaneous measurements of the flow field using a stereo PIV and OH-PLIF at 5 KHz repetition rate. Under the same swirl intensity, two flames with different fuel jet velocity were investigated. The time-averaged flow field shows a unique flow pattern at the quarl exit, where two recirculation vortices are formed; a strong recirculation zone formed far from the quarl exit and a larger recirculation zone extending inside the quarl. However, the instantaneous images show that, the flow pattern near the quarl exit plays a vital role in the spatial location and structure of the reaction zone. In the low fuel jet velocity flame, a pair of vortical structures, located precisely at the corners of the quarl exit, cause the flame to roll up into the central region of low speed flow, where the flame sheet then tracks the axial velocity fluctuations. The vorticity field reveals a vortical structure surrounding the reaction zones, which reside on a layer of low compressive strain adjacent to that vortical structure. In the high fuel jet velocity flame, initially a laminar flame sheet resides at the inner shear layer of the main jet, along the interface between incoming fresh gas and high temperature recirculating gas. Further downstream, vortex breakdown alters the flame sheet path toward the central flame region. The lower reaction zones show good correlation to the regions of maximum vorticity and track the regions of low compressive strain associated with the inner shear layer of the jet flow. In both flames the reactions zones conform the passage of the large structure while remaining inside the low speed regions or at the inner shear layer.

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Keywords: Conical swirl stabilized; non-premixed flames; PIV/OH-PLIF

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1. Introduction

Non-premixed swirling flames are used extensively in practical combustion systems, particularly gas turbines, furnaces and boilers [1-2]. The quarl geometry has significant effects on the swirling flame structure and emission characteristics. Different aspects of swirling combustion have been studied, including the swirling flow features [3-4], flame stability and enhancement of flame blowout limits by the use of swirl [5-6], and flow field and emission pollutants, in particularly nitrogen oxide [7-8]. Although most of these studies have been conducted on burners using a diverging quarl, there is little information on the effect of the quarl on the flame-flow interaction.

In contrast to the diverging quarl swirling flame, many free or confined swirl flame studies have been conducted using straight-exit burners. For example, using intrusive measuring techniques, detailed measurements of gas species and temperature in a non-premixed swirling flame are presented in [9]. Also, the effect of the fuel injection pattern and fuel–air mixing on NOx formation in swirling non-premixed flame were investigated [10]. The effect of fuel injection pattern on near flow field of a confined swirl flame was investigated in [11]. They observed intermittent fuel penetration into the recirculated hot products with a central sooting luminous plume in the case of axial fuel injection, whereas this phenomenon was totally absent in the case of radial injection.

Laser based diagnostics have been employed in the swirling flame of a gas turbine model combustor [12-15] without attention to the effects of the quarl geometry on the flame structure. Using OH-PLIF measurements, under pressures ranging from 2 to 6 bar, the general features of the reaction zone of a gas turbine model combustor were reported [12]. The application of the simultaneous PIV and OH-PLIF measurements on this model yielded physical insight into various relevant combustion phenomena, such as the presence of a helical processing vortex core (PVC) in the inner shear layer of the swirling jet [13]. The coupling between the PVC and the thermo-acoustic pulsation in a noisy swirling flame have been addressed by analysing OH-PLIF/PIV measurements [14]. Recently, the interaction of flow, fuel-air mixing and reaction in a turbulent swirling flame have been investigated using simultaneous PIV and acetone/OH-PLIF measurements [15]. A periodic changes in the composition of the unburned mixture between pure air and well-mixed fuel-air is induced at the flame root by the formation of PVC have been addressed [15]. Considering the complex interplay between flow field, chemical reactions, and quarl geometry, the necessity to delineate the role of the quarl on the flame–flow field interaction specifically, and to contribute to a better understanding of the combustion process in the swirl quarl stabilized flames in general, is clear. Simultaneous high speed OH-PLIF/PIV imaging was applied to non-premixed swirling flames stabilized in a diverging quarl at a 5 KHz repetition rate to gain this understanding

2. Experimental apparatus

Figure 1a shows a sketch of the burner. The swirling flow around a central fuel tube (d_f = 4.4 mm) was generated via four tangential air inlets to the outer air tube (d_A =27 mm). The tangential air streams mixed with axial air upstream of the burner. The swirling flame was stabilized in a quartz quarl of a half cone angle of 15° and a length of 40 mm. The exit planes of the two concentric tubes, fuel (methane) and air, was located at the inlet plane of the quarl (Z = 0 mm). The geometrical swirl number, $S_g = (\pi\, r_o\, d_A/2A_t)/\ [m_\theta/\ (m_\theta + m_A)]^2$, is used to define the swirl intensity [5], where m_θ and m_A are the tangential and axial air flow rates respectively, A_t is the total area of the four tangential air inlets, d_A is the diameter of the air tube, and r_o is the air tube radius at the location of the tangent inputs. At S_g= 12, two flames with different fuel jet velocity (V_f) were studied, namely flame F_A with V_f= 4.4 m/s and flame F_B with V_f = 8.8 m/s. Simultaneous PIV/OH-PLIF measurements were conducted for the region just above the quarl exit at 5 KHz repetition rate. However, the field of view for OH measurements was extended to cover the entire quarl region, ending at the same height as the PIV field of view, see Fig. 1a for the respective field of views.

A schematic of the measuring techniques used for the simultaneous stereoscopic PIV and OH-PLIF is shown in Fig. 1b. Two counter propagating laser beams were formed into overlapping sheets and crossed the vertical plan of the burner. The stereoscopic PIV system consisted of a dual cavity, diode-pumped, solid-state Nd:YLF laser (LDY 300 Series) and two high-speed CMOS cameras (LaVision, Image Pro HS 4M, HSS5) with 105 mm/f4 objective lens (Nikon UV Micro-Nikkor) equipped with a 527 nm band pass filter. The two cameras were located at both sides of the OH-PLIF ICCD camera at an angle of ± 15° to acquire the stereoscopic particle images. The laser was capable