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Impact of confinement on flowfield of swirl flow burners

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HIGHLIGHTS

- Investigated the flowfield of swirl burner under unconfined and confined conditions.
- Velocities were measured under both reacting and non-reacting conditions.
- Unconfined non-reacting case showed central recirculation as opposed to reacting case.
- Confinement enhanced recirculation under non-reacting and reacting conditions.
- Increasing Reynolds' number enhanced recirculation and increased turbulence.

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ABSTRACT

Swirlers are commonly used in gas turbine combustors as they provide recirculation zones and reduce axial velocity for enhanced flame stability. Swirl provides hot gas recirculation zone at front end of the combustor for enhanced mixing between hot reactive species and the freshly introduced mixture. In this paper, the impact of confinement on a swirl assisted combustion was investigated with focus on the flowfield under unconfined and confined conditions. The features of the flowfield were characterized under both isothermal and reacting conditions. Experimental results showed that for the unconfined cases, the flowfield exhibited the traditional central toroidal recirculation zone. Upon confinement, this zone shortened and also widened with increased velocity fluctuations across the combustor. Increase in the Reynolds number further enhanced the recirculation zone and increased the velocity magnitudes and turbulence. For reacting conditions, minimal recirculation was noticed for the unconfined flame. The recirculation zone was significantly enlarged upon confinement (compared to the non-reacting case) and with increase in Reynolds number. In general, the fluctuating velocity was found to be higher in the confined case compared to the unconfined case, and even higher at increased Reynolds number.

1. Introduction

Gas turbine (both stationary and for aviation) widely uses swirling flow for controlled mixing of air, fuel and reactive species with the goal to enhance flame stability and control pollutants emission. These significant benefits along with swirl deployment in other engineering applications have stimulated many studies, both experimental and numerical, to characterize swirling flow under different conditions (confinement, aspect ratio, operating conditions, etc.).

Swirling flows have been commonly used for furnaces and gas turbines among others. Characteristics of swirling flow generated by simple swirlers have been reviewed and investigated by multiple researchers [1–3]. These reviews have provided different methods of generating swirl in the system, the parameters that affect the size of the recirculation zone, and flow structure produced by different swirlers. Most of the discussed results were obtained using intrusive instrumentation and therefore the true detailed flow structure was not obtained.

Multiple research groups performed subsequent studies using non-intrusive diagnostics [4–10]. Cheen et al. [4] investigated confined and unconfined annular swirling jet flows with different Reynolds' number ($Re \sim 60$–6000) and Swirl numbers (with S of 0–0.6). They classified the recirculation zone into seven different categories based on *Re* and S. They concluded that the behavior of these seven categories were the same for both confined and unconfined configuration with the exception of one regime (called attachment regime) [4]. Mongia et al. has performed an extensive review covering research performed on swirl cup burners (at GE, University of Cincinnati, and the University of California Irvine), and provided a benchmark Laser Doppler Velocimetry (LDV) data

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for modeling, and outlined some empirical design rules [5]. In one of the subsequent publication, Cai et al. outlined the impact of confinement on the flowfield, where smaller confinement has the strongest impact on the flowfield, while larger confinement looked similar to that of the unconfined case [6]. It is worth noting that these measurements were performed under non-reacting conditions. Archer and Gupta [7] outlined the role of confinement under fuel lean combustion using a double concentric swirl burner. They concluded that confinement decreases both the central recirculation zone and strength and increases the turbulence level. In addition, confinement decreased axial velocity magnitude under non-reacting condition [7]. Fu et al. [8] also studied a counter rotating radial swirler under non-reacting condition. They outlined the clear impact of confinement on mean and turbulent flowfield, wherein their results showed recirculation zone for the confined case was almost twice that of the unconfined case, which was contradictory to what outlined by Archer and Gupta [7], however, this difference can be attributed to the much higher *Re* number utilized by Fu et al. (~60,000 [8] vs. 8000 [7]), as well as the different swirl geometry.

More recently, low swirl burners have been proposed in contrast to high swirl burners due to their benefits in terms of reduced emissions [9,10], stabilization of planar flames without heat losses or boundary effect [11], and low pressure drop. In another study, Cheng et al. investigated the flowfield of low swirl injector [12]. They outlined the difference between unconfined and confined cases under reacting and non-reacting conditions with methane and hydrogen as the fuel with confinement ratios of 3 and 2.44:1. They demonstrated that enclosure increases the central recirculation zone under non-reacting conditions. On the other hand, for methane flames, enclosure had minimal effect at the 3:1 confinement ratio; however, the smaller confinement did not generate central flow recirculation [12]. Other researchers examined the flowfield, temperatures, and species distribution within swirl flames [13–16].

From the previous summary, one can see that confinement has an effect for some cases but not others, depending on Reynolds' number, swirl geometry, and whether the experiments were performed under isothermal (non-reacting) or combustion (reacting) conditions. In this paper, the impact of confinement on a swirl burner flowfield is examined with focus on low-intermediate swirl configuration that will help resolve some of the discrepancies found in the literature on general flowfield from different swirl burners and to quantify the role of confinement and combustion on the changes in flow behavior. It is noteworthy that the literature mainly discuses confinements that are larger compared to the one discussed here as explained in the experimental setup. Another goal here is to characterize the swirl burner for further numerical and experimental studies under swirl and distributed combustion conditions [17]. For these purposes, experiments are performed under both non-reacting and reacting conditions to outline the impact of heat release on the flowfield. The flowfield measurements have been further analyzed to obtain turbulence characteristics, such as, velocity fluctuations and turbulence kinetic energy. These quantities play an important role in characterizing the flowfield as well as the turbulent Reynolds' number calculation.

2. Experimental facility

2.1. Experimental setup

The experiments were performed using a swirl burner under different configurations. Details of the swirl burner can be found elsewhere [18]. For all the cases reported here, methane was used as the fuel. A laminar flow controller with an accuracy of ±0.8% of the reading and ±0.2% of full scale was used to control the air flow rates, leading to an overall accuracy of about 1.5% of the reading. Methane and seeding air flow rates were controlled through gravimetric flow controllers with an accuracy of 1.5% of full scale. Fuel was injected at the center of the swirler in a non-premixed configuration. Fig. 1 shows the flow configuration of the swirl while Fig. 2 shows a schematic diagram of the facility and the diagnostic tools used. For this swirler, the contraction ratio, defined as the contraction diameter over the burner diameter (D_c/D_b), was 0.3636. The Swirl number (S) can be calculated using the equation $S = 2/3 [(1 - (d_h/d)^3)/(1 - (d_h/d)^2)]\tan\Phi$, where d is the swirler diameter, d_h is the swirl hub diameter, Φ is the swirl angle. For the shown configuration, $d_h/d = 0.5$, and $\Phi = 45$, yielding a swirl number $S = 0.77$. If one considers the conical shape after the swirler where the hub diameter goes to zero, the approximation of Gupta et al. [3] can be followed, where swirl number S can be approximated to $S = 2/3\tan\Phi$, Φ is the swirl angle. This yields a swirl number $S = 0.66$. The swirl burner was confined using a quartz cylinder with a diameter ratio (D_q/D_b) of 1.7, where D_q is the quartz diameter and D_b is the burner diameter, leading to an area ratio of 2.9. This is significantly smaller than values reported in the literature (4 by Archer and Gupta [7] and Fu et al. [8], 6 and 9.9 by Cheng and Littlejohn [12], and 12.25 by Nogenmyr et al. [19]). It is to be noted that both the confinement ratio and swirl configuration used here are different than those cited in the above investigations.

It is noteworthy that the swirl number here was calculated based on the geometrical configuration used along with relations given in the literature [2,3]. Change in any of the geometrical parameters or swirl configurations (even for the same vane angle) can yield different swirl number and strength. However, the experiments and analysis presented in this paper are useful for this class of swirlers as well as their close configurations.

2.2. Particle image velocimetry

Particle image velocimetry (PIV) system was used here to obtain the flowfield. The camera was located at a distance of 0.5 m away from the laser plane. The camera view covered an area of about 7 cm × 6 cm. Portion of the air supplied to the combustor was diverted to a fluidized bed seeder, where the seeding particles were picked up by the air and then combined with the main airflow line, see Fig. 2. The portion of air diverted was about 10% and the flow rates of the main air and seeding air were controlled to reach the desired total air flow for all the experimental conditions examined. The seeding particles used were Alumina Oxide with a nominal particle diameter of 2 μm. The laser sheet beam had a thickness of about 1 mm and was used to illuminate the seed particles in the flow. Table 1 summarizes the different parameters used in the PIV system.

For data processing, PIVLab was used [20]. For each data set, four passes were performed with interrogation window size of 48, 36, 24, and 12 pixels with 50% overlap. High reflection regions

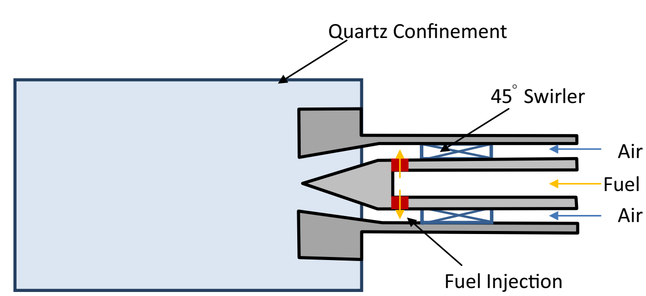

Fig. 1. Schematic of the swirl configuration with 45° swirl vane angle.