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Effect of fuel nozzle geometry and airflow swirl on the coherent structures of partially premixed methane flame under flashback conditions

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ABSTRACT

The effect of fuel nozzle geometry and swirling airflow on the flashback and its relationship with the coherent structures of partially premixed methane flame is investigated experimentally. Particle image velocimetry (PIV) and laser Doppler velocimetry (LDV) are used to document flow characteristics, and Schlieren imaging technique is used to study flame appearance and vortex shedding frequency downstream of the burner exit. Proper orthogonal decomposition (POD) technique is applied to capture the coherent structures, along with phase averaging of the linear superposition of the first four POD modes. Seven different fuel nozzle geometries and two swirl number (S = 0.79 and 1.15) are tested. The nozzles are categorized into three groups, with each has similar equivalent diameter; namely, a symmetric nozzle (used as a reference), nozzles with polygonal orifices (group A), and angled multi-orifice nozzles (group B). The results of the flow field inside the mixing tube show that the strength of coherent structures and flashback propensity increase with the swirling airflow Reynolds number, swirl number, nozzle bluff body area, and the number of the peripheral angled orifices of the fuel (central) nozzle. On the other hand, the results of flame appearance outside of the mixing tube indicate that methane flame experiences symmetric vortex shedding at high swirl number and low Reynolds number, while it experiences PVC near blowout conditions at low swirl number and high Reynolds number. Furthermore, the frequency of coherent structures is found to depend on the swirling airflow Reynolds number, swirl number, and fuel nozzle geometry. Additionally, the flashback's mean region inside the mixing tube is found directly proportional to the strength and frequency of the coherent structures.

1. Introduction

Partially premixed flames (PPFs) were used in several combustion applications such as internal combustion engines, gas turbines and industrial burners. For instance, the presence of lean and rich pockets along the stoichiometric mixture fraction line in a triple flame were reported to improve the PPFs stability compared to their counterparts' non-premixed and premixed flames [1–3]. Moreover, it was reported that emissions characteristics of PPFs can be comparable to those of premixed flames [4]. However, these flames require stabilization mechanisms, such as concentric flow conical nozzles (CFCN) [1,3], coflows [1], or pilot flames [5]. Other stabilization mechanisms, such as swirl and bluff body, were also adopted. Swirl was recently used with PPFs [6] since it enhances mass and heat transfer which in turn improves combustion and thermal efficiency [7]. However, the use of swirl may increase flashback propensity due to increased flame speed [8]. Furthermore, swirling flames are more prone to combustion instabilities as a result of the coupling between precessing vortex core (PVC) or vortex shedding and heat release [9]. Bluff body was used to stabilize flames at high flow velocities [10]. However, when using a bluff body in the direction of a flow, vortex shedding as coherent structures becomes the main driver of combustion instabilities. Furthermore, PPFs burners with a very short mixing length were used as an alternative to lean premixed flame to avoid combustion instabilities [11]. However, decreasing the mixing length may result in an increase in gas emissions [11]. Other studies reported that the optimum emissions characteristics and flame stability can be achieved using a longer mixing length [3,4]. However, the induced inhomogeneity and unmixedness of PPFs can generate thermoacoustic instabilities when using longer mixing lengths [12].

Flashback, as a consequence of combustion instabilities, can occur due to the interaction between acoustic modes and heat release fluctuations. Flashback can cause severe damage and overheating to burners and combustion chamber parts. In addition, flashback increases pollutant emissions [13] where a possible coupling may occur between acoustics and flashback [14]. Combustion instabilities are considered as a complex phenomenon since they are three-dimensional and time-

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dependent in nature. It was found that hydrodynamic instabilities, equivalence ratio fluctuations, flame surface variations, and oscillatory fuel atomization and vaporization are the main driving mechanisms of combustion instabilities [15].

Coherent structures, such as vortex shedding and PVC due to hydrodynamic instabilities, can be considered as a source of periodic heat release [15,16]. Vortex shedding can cause wrinkling which can significantly contribute to flame surface variation [15] and, hence, cause heat release fluctuations. Heat release fluctuations are considered as a major source of acoustics motion in a combustion chamber [15]. Acoustic modes can modulate fuel/air mass flow rate leading to equivalence ratio fluctuations and consequently cause combustion instabilities [15]. Coherent structures and their influence on flame blowout and flashback have recently been the subject of several studies (e.g., [17]). It was found that the coupling between combustion chamber acoustics, coherent structures and heat release can cause combustion instabilities. Several studies investigated flame stability and blowoff mechanism of axisymmetric bluff body burners [18–21]. Unlike the 2D slender bluff body which shows BVK street, axisymmetric bluff body exhibits helical or symmetric modes of vortex shedding. Conversion from symmetric to helical mode was found to occur at high Reynolds number [22]. Furthermore, depending on the flow conditions, the same burner configuration can exhibit either vortex shedding or PVC.

Controlled mixing should enhance flame stability and lower NO_x emissions. Combustor and burner geometries play a key role in the stability of combustion since it significantly affect flame structure and acoustics [15,23]. Injecting the fuel through a central orifice of a bluff body was adopted in several studies with the aim to enhance mixing in the wake region [18,24]. Implementing a recession for an axisymmetric bluff body inside a confinement with an optimum inner diameter was found to significantly enhance flame stability [18]. For instance, using a concentric central recessed tube inside an outer tube to discharge premixed fuel-air was found to eliminate coherent structures by promoting inhomogeneity of the mixture [17,25]. For example, Galley et al. [26] reported that, when injecting fuel axially from a central recessed tube, mixing was not sufficient over short distances. However, improving the mixing upstream of a flame may lead to upstream flame propagation [26]. Despite the importance of using central axial fuel injection to mitigate coherent structures and avoid flashback, increasing the momentum of the axial injection beyond a certain limit can increase the flashback propensity by enhancing macroscopic mixing [27]. In addition, central fuel injection may promote the flashback through wall boundary layer mechanism. Despite the fact that flashback propensity can be increased due to the presence of PVC or vortex shedding [28,29], only a few published studies investigated the relationship between flashback and flow coherent structures.

Motivated by the aforementioned literature review, the present study aims to investigate the effects of the geometry of fuel orifice through an axisymmetric bluff body and swirling airflow strength on the upstream propagation of methane PPFs. The objective is to provide a passive technique for controlling the flashback by altering the coherent structures behavior inside the mixing tube. To achieve the objective of this study, turbulent flow field upstream of the flame under flashback conditions is examined.

2. Experimental setup and methodology

2.1. Burner and test conditions

The burner consists mainly of an interchangeable central nozzle and a co-axial annulus with a swirl generator, both discharging into a mixing tube, as schematically shown in Fig. 1. Two swirl generators with different vanes angle (50° and 60°) which correspond to a swirl number of 0.79 and 1.15, respectively, are tested. The swirl number is calculated based on the vanes angle (e.g., [26]). The mixing tube is made from fused silica with a length of 117 mm, which provides a mixing length of 111 mm, which is the distance between the tip of the central nozzle and the mixing tube exit. The mixing tube inner and outer diameters are 24 and 28 mm, respectively. It was found that further increase in the inner diameter of the mixing tube causes flame attachment to the central nozzle since the effect of the mixing tube's wall becomes weak. On the other hand, decreasing the inner diameter of the mixing tube was found to significantly reduce flame stability by increasing the mean bulk velocity at the same equivalence ratio. Seven central (fuel) nozzles with the same outer diameter (d_o = 12 mm) and categorized into two groups and one reference nozzle are used. Table 1 provides a summary of these nozzles. A single-orifice nozzle (N1) is used as a reference. Group A includes a square nozzle (N2), an equilateral nozzle, and a rectangulair nozzle with aspect ratio of 2:1. The equivalent diameter of group A nozzles is assumed to be constant since it varies within ± 5%. Group B includes a four-orifice nozzle (N5), a six-orifice nozzle (N6), and a seven-orifice nozzle (N7). Their peripheral orifices are inclined by an angle β_p with respect to the centerline of the mixing tube. It should be mentioned that the bluff solid area (solid area without orifices) of group B is higher than that of group A, with N1 has the highest. This allows to also study the effect of the central nozzle's bluff solid area. The equivalent diameter is determined as $D_e = \sqrt{4A/\pi}$ where D_e is the diameter of a circle having a cross-sectional area, A, equivalent/similar to that of a non-circular orifice (rectangle, triangle or square) or a multi-orifice nozzle. Note that for a multi-orifice nozzle (group B), $A = A_c + nA_p$, where A_c is the area of the central orifice, A_p is the area of a single peripheral orifice, and n is the number of the peripheral orifices. The swirling airflow emerges from the annulus, which is a cylinder surrounding the central nozzle. The flow discharging from the central nozzle is a premixed air/methane and its mixing with swirling airflow starts right at the exit of the central nozzle. The central nozzle flowrate is kept constant (22 LPM and 4.6 LPM for air and 17.4 LPM for fuel) at both swirl numbers, and the swirling airflow rate at low and high swirl numbers are 535 and 215 LPM, respectively. These flow rates are selected such that the flame is maintained upstream of the mixing tube exit (in flashback conditions) but still not attached to the central nozzle. The equivalence ratio at low and high swirl number are 0.30 and 0.75, respectively. At low swirl number, the flame does not experience flashback before blowout, except with N7, and thus nozzles N1 through N6 are excluded from the experiments at this swirl number. Reynolds number ($Re_D = DV_j/\nu$) is calculated based on the inner diameter of mixing tube (D) and the bulk flow mean velocity (V_j), where ν is the kinematic viscosity of the air-methane mixture. The inlet axial turbulence intensity is 0.31 and 0.3 at low and high Reynolds numbers, respectively. Test conditions are given in Table 2.

2.2. Particle Image Velocimetry (PIV)

Particle Image Velocimetry (PIV) was used to document the flow field inside the mixing tube. A schematic diagram of PIV arrangement is shown in Fig. 1. It consisted of a Nd:Yag laser with a maximum pulse energy of 135 mJ at 10 Hz, a double-frame FlowSence EO 4 M CCD camera with a full resolution of 2048 × 2048 pixel^2, and DynamicStudio software. The physical size of the CCD sensor was 15.2 × 15.2 mm^2, and the f-number of the lens was adjusted at f/2.8 to limit the depth of field. A 45° protected silver 2-in. square mirror with an air cooling fan was placed 1 m above the quartz tube in order to project 1 mm thickness laser sheet through the quartz tube's centreline. The premixed flow from the central nozzle was seeded with incense particles with an average diameter of approximately 1 µm. Seeding only the flow from the central nozzle was found adequate since the measurements' field of view was located farther away from the central nozzle. This distance allowed both the central and swirling airflow to mix inside the mixing tube prior to reaching the PIV measurement region (ROI). Note that incense particles disappeared in the flame zone, and consequently an in-house developed Matlab code was used to remove velocity vectors in the flame zone from the velocity vector fields,