Experimental Thermal and Fluid Science 54 (2014) 1–11

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Flow visualization and mixing in a rapidly mixed type tubular flame burner

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ARTICLE INFO

Article history:
Received 20 October 2013
Received in revised form 21 December 2013
Accepted 19 January 2014
Available online 31 January 2014

Keywords:
Tubular flame
Flow visualization
Mixing
PIV

ABSTRACT

To fundamentally investigate the flow structure and mixing in the inherently safe combustion of rapidly mixed type tubular flame, flow visualization and velocity measurements are conducted using a Particle Image Velocimetry (PIV) system. Four optically accessible quartz made burners with four tangential slits of rectangular shape have been designed, from two of which a seeded flow is parallel injected into the burner while the non-seeded flow is injected from the other two. The slit width is 2 mm and by varying the slit length, the swirl number varies from 0.34 to 0.69, 1.37 and 2.75. Flow visualizations in a cross section perpendicular to the tube axis as well as in a plane containing the tube axis, and the corresponding velocity distributions have been examined. In the burner of low swirl number of 0.34, the mixing around the exit of the injection slit and that around the inner wall downstream of the slit is poor; a recirculation reverse flow is not observed. However, with an increase of the swirl number and the flow rate, mixing is much enhanced and a recirculation reverse flow occurs in the burners of swirl number larger than 0.69. Furthermore, with an increase of the swirl number, the radial position where the circumferential velocity takes its maximum shifts outward. Around the exit of the slit, the mixing layer thickness along circumference is inversely proportional to the square root of the mean injection velocity regardless of the swirl number.

1. Introduction

In case of flame flashback and explosion hazards in the premixed combustion with high burning velocity, such as the pure oxygen combustion [1], an inherently safe technique of rapidly mixed type tubular flame combustion in which the fuel and the oxidizer are individually injected into the burner [2], has received keen interest. The primary objective of this paper is to fundamentally investigate the characteristics of flow structure and mixing in a series of rapidly mixed type tubular flame burners with various swirl numbers.

At first, the tubular flame burner and some of its merits are briefly introduced. As a new type of flame, the tubular flame combustion has been extensively investigated through a variety of burners, including the non-rotating type and the swirl type. The non-rotating type tubular flame is usually established in a counter-flow type tubular flame burner, in which a combustible mixture is injected inward directly [3,4] or through a porous wall [5–7], resulting in a non-rotating axisymmetric flow field inside the burner. The swirl type tubular flame, which could be achieved by tangentially injecting fresh gas into a two-side or one-side open tube, can be stably established between the lean and rich flammability limits and also up to very large injection velocities of several decades of m/s [6,7]. Owing to its special structure, this type of flame has excellent flame characteristics such as negligible heat loss, aerodynamic stability and thermodynamic stability [5,7]. Various applications have been proposed and demonstrated for determining the flammability limits [6–8], stabilizing a flame in a high speed flow [9], and obtaining a uniform and large-area laminar flame to heat iron slab or to reduce steel sheet surface [10,11].

In the rapidly mixed type tubular flame combustion, after being separately injected into the burner, the fuel and the oxidizer are rapidly mixed in a strong centrifugal force field in a tube, and after ignition the combustion with a laminar, tubular like stretched flame can be established [2]. Since there is no supply line of combustible pre-mixture, flame flashback will never occur. A large amount of studies have been made for the rapidly mixed type tubular flame of air/fuel combustion. Under various swirl numbers the flame characteristics have been discussed from the flame structure and inflammability, and it has been pointed out that, to get the same flame appearance as that of the premixed fuel/air combustion, the swirl number should be no less than 5 and injection velocity higher than 20 m/s [2]. Various applications have been summarized in a recent review [12]. From the fundamental point of view, the flame characteristics including the flame appearances,

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http://dx.doi.org/10.1016/j.expthermflusci.2014.01.009
0894-1777/

extinction limits and stability under various oxygen mole fractions have been investigated by Shi et al. [13,14]. To quantify the establishment of stable tubular flame combustion, the mixing between the oxidizer stream and the fuel stream around the injection slit has been visualized in three burners of different slit widths and under various injection velocity ratios of the oxidizer stream to the fuel stream [14]. The mixing layer thickness has been analyzed to yield the Damköhler number, which has proved to be a good measure for the success/failure of the tubular flame combustion [13,14].

On the other hand, the mixing of fuel and oxidizer has a great influence on the overall performance of combustion in various kinds of combustors, say, the air breathing engine [15,16], fluidized bed combustor [17,18] and jet burner [19–21]. Extensive research has been carried out on the mixing of fuel and oxidizer in shear or mixing layers formed between two reactant streams in the planar, the curved and the rotating flow conditions. In the planar mixing layer, to study the fundamental processes of mixing as well as chemistry, the flow configuration has been measured by various methods including LDV [22], OH LIF/soot LII technique [23] and PIV system [24]. The effects of curvature on the turbulent mixing layer have been investigated experimentally [25] and computationally [26]. Particularly, swirl is widely utilized to enhance fuel/air mixing, prolong residence time and generate the recirculation zone for flame stabilization, which forms an integral part of many combustion and propulsion systems. Chen and Driscoll [27] have investigated the role of the recirculation vortex in improving fuel/air mixing within swirling flames, in which the effect of swirl on flame length was investigated in detail. The effects of fuel/air mixing on flame structures and NO_x emissions in a swirling flame have been analyzed in swirl burners [28] and jet flames [29]. Through introducing swirling air, a liquid film combustor with a double chamber has been designed to compare with a central porous fuel inlet delivery, both of which help to describe the limits and the potential of liquid fuel/film miniature combustors [30]. Most of these studies are based on the turbulent mixing in the swirling flow, while in the current study the mixing in the stretched, swirling and laminar flow field is addressed. In the rapidly mixed type tubular flame burner, usually the Reynolds number based on the injection slit varies from a few thousand to the order of ten thousand. It is reasonable to expect that the combustion is turbulent. However, in the intense rotating environment, the turbulence is impeded, resulting in laminarization of the turbulent flames [31,32].

As for the mixing layer in the swirling flow, with a swirl generator, Wood et al. [33] investigated the detailed structure of a swirling turbulent mixing layer; the influences of a swirl on the flow and mixing characteristics of acoustically excited swirling double concentric jets were experimentally studied by Jufar et al. [34]. Through flow visualization, Ito et al. [35] investigated the flow structure in developing liquid shear mixing layer; Chua et al. [36] discussed mixing enhancement of a square jet with mixing tabs; based on flow visualization and velocity distribution, the flow features in the rotating disk have been investigated in detail by Wu [37]. It is seen that the flow visualization is very helpful to analyze the mixing problem. Thus, in this study, through flow visualization and velocity distribution, the flow structure and the mixing layer are experimentally investigated.

A series of optically accessible tubular flame burners with the same slit width but different slit lengths have been made. The swirl number, which is the ratio of axial flux of angular momentum to the axial flux of linear momentum [38], in this study is defined based on the input and exit parameters assuming an isothermal flow and a uniform exit axial velocity profile, as given by Eq. (1) in the next section. This definition has a unique physical meaning in the rapidly mixed type tubular flame burner, which addresses how long periphery distance the flow makes during the period when the flow proceeds a distance of the slit length, i.e., how extent the fuel and oxidizer streams are overlapped in geometry [39].

The swirl number varies from 0.34 to 0.69, 1.37 and 2.75, which plays an important role in determining the occurrence of a reverse flow. Though it is general accepted that when the swirl number exceeds 0.6 a reverse flow is induced [40], a number of swirl numbers exist and not all acquire the critical value of 0.6. For instance, Toh et al. [41] experimentally obtained a higher critical value of 0.94 in the axial plus tangential swirling jet, while Al-Abdeli and Masri [42,43] addressed the significance of other flow parameters such as the axial velocity or its Reynolds number on the formation of downstream recirculation zone.

The flow fields in the swirl type tubular flame burner were characterized by determining the tangential and axial velocity profiles in the weak swirl burners with swirl numbers of 0.21 and 0.78 [44]. To discuss the influences of fuel/oxidizer mixing on the flame characteristics in the strong swirl tubular flame burners, flow visualizations in a cross section perpendicular to the tube axis have been discussed to yield the mixing time and the Damköhler number [13,14]. It is stated that mixing of fuel and oxidizer plays a significant role in the establishment of tubular flame combustion, especially those under high oxygen mole fractions [14]. To obtain a general relation in terms of the mixing layer thickness estimation around the exit of the injection slit, and a full understanding of the mixing downstream of the slit, in the present study, (1) burners with weak to strong swirl intensities are used; (2) besides the flow visualizations in a cross section perpendicular to the tube axis, those in a plane containing the tube axis have been discussed; and (3) corresponding tangential and axial velocity distributions are discussed in detail.

2. Experimental setup

Schematic drawings of the tubular flame burners used in this study are shown in Fig. 1. The burners were made by quartz for visualization, which had four rectangular tangential slits (left picture). The width (W) of the slit is 2 mm while the lengths (L) are 64, 32, 16 and 8 mm, respectively. The burners are open on two sides with inner diameter of 16 mm and total length (L^*) of 160 and 120 mm (only for L = 8 mm).

To clarify the effects of swirl intensity on the flow structure and mixing, a set of burners were used. Table 1 lists the detailed parameters of the configuration. By varying the length of the injection slit, i.e., the cross section area, flows with different intensities of rotation can be obtained. Here the swirl number is defined based on geometry, given by the following equation,

$$S_w = \frac{\pi D_e D_0}{4A_T} \quad (1)$$

in which D_e is the exit throat diameter, D_0 is the diameter of a swirl burner, and A_T is the tangential slit area [38]. In this study, D_0 is the combustion tube diameter, D_e is approximately determined by

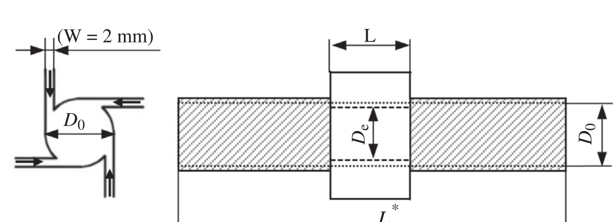

Fig. 1. Schematic of the rapidly mixed type tubular flame burners (quartz made, two-side open).