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Reexamination on methane/oxygen combustion in a rapidly mixed type tubular flame burner

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ABSTRACT

To fundamentally elucidate the requirement for an inherently safe technique of rapidly mixed type tubular flame combustion, experiments have been made to investigate (1) the mixing process of fuel and oxidizer, and (2) the appearances of methane flames under various oxygen mole fractions. Three optically accessible quartz burners of different slit widths were made for measuring the mixing layer thickness with a PIV system. Under various rates of flow of the oxidizer to the fuel, a boundary layer type flow is recognized to dominate the mixing of fuel and oxidizer around the exit of the injection slit, namely the mixing layer thickness is inversely proportional to the square root of mean injection velocity. Using two stainless steel burners, combustion tests were conducted with the oxidizers of oxygen/air mixtures. To quantitatively investigate the requirement for tubular flame establishment, the Damköhler number, which is the ratio of characteristic mixing time to characteristic chemical reaction time, has been discussed in detail. The mixing time was calculated according to estimated mixing layer thickness, while the chemical reaction time was computed with the Chemkin code. The Damköhler number has proved to be a useful measure for success/failure of tubular flame combustion. When the Damköhler number is larger than unity, chemical reaction starts before complete fuel/air mixing and the tubular flame fails to be established; when the Damköhler number is much smaller than unity, the fuel and the oxidizer are completely mixed before the onset of reaction, resulting in successful tubular flame combustion. The results confirm our hypothesis in a previous study. Furthermore, based on the concept of Damköhler number, the minimum flow rate to achieve the tubular flame combustion could be estimated.

1. Introduction

Energy consumption rates will keep a steady increase as a result of economic growth, social modernization and expanding populations in the world. The rise in fossil fuel consumption, especially those with high carbon content such as coal, oil and other heavy hydrocarbons, known as the major energy resources in the long term, has led to increasing emissions of carbon dioxide which is believed to be responsible for global warming [1]. Consequently, energy saving and carbon dioxide capture and sequestration (CCS) have become two most important topics in combustion.

Recently pure oxygen combustion and oxygen-enriched air combustion have received keen interest owing to their high efficiencies, which prompt both energy security and environmental security [2–6]. Particularly, pure oxygen combustion is one promising approach for low-cost CCS combined with reduction of NO_x emissions [2,5]. Pure oxygen and oxygen-enriched air combustion provide a number of technical advantages, such as increased flame temperature, thermal efficiency, flame stability and heat transfer, however, due to high burning velocity, destructive flame flashback even detonation may frequently occur if the combustion is conducted in a premixed mode [2,7]. Hence a very safe combustion technique is indispensable for the premixed type pure oxygen or oxygen-enriched air combustion.

In our recent study [8], an inherently safe technique of rapidly mixed type tubular flame combustion [9] has been first applied to investigate the characteristics of the methane/oxygen flame. Though the tubular flame combustion has been extensively studied through a variety of burners [9–14], and various applications have also been proposed [15–17], the oxidizer is limited to air or diluted air. For the oxidizer of pure oxygen discussed in Ref. [8], it is found that a stable tubular flame, which has excellent flame characteristics such as negligible heat loss, aerodynamic stability and thermodynamic stability [10,12], is only established at lean conditions. Diffusion flames were observed to be anchored at the exits of the fuel slits which restrained the mixing of fuel and oxidizer, resulting in a failure of tubular flame combustion. The Damköhler number (D_a), defined as the ratio of characteristic mixing time (τ_m) to characteristic chemical reaction time (τ_r), has been adopted to quantify

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the requirement for tubular flame establishment. To obtain a successful methane/oxygen tubular flame, the Damköhler number based on the boundary layer type flow should be much smaller than unity [8].

To substantiate our hypothesis on the estimation of mixing layer thickness, i.e., the thickness is inversely proportion to the square root of the injection velocity, in the present study three optically accessible tubular flame burners have been made to fundamentally investigate the mixing process of fuel and oxidizer around the exit of the tangential slit. With the same and different injection flow rates between the fuel and the oxidizer streams, flow visualizations obtained with a PIV system have been analyzed to yield a general estimation of the mixing layer thickness. In addition, two stainless steel burners of different slit widths have been designed to carry out the combustion tests under various oxygen mole fractions in the oxidizer. A stable tubular flame could be achieved from lean to rich inflammability when the oxygen mole fraction is less than about 0.4, above which a tubular flame is failed to be established at large equivalence ratios due to unsuccessful mixing of fuel and oxidizer resulting from diffusion flames anchored around the tangential slits. To address the effects of mixing on the flame characteristics, three cases, with the oxygen mole fractions in the oxidizer of 0.684, 0.842 and 1.0, have been examined, respectively. In addition, corresponding Damköhler numbers are calculated to investigate the quantitative requirement for the successful tubular flame combustion under the conditions of high oxygen mole fractions in the oxidizer, which further confirmed the concept of the Damköhler number smaller than unity. Furthermore, based on the Damköhler number calculations, the flow rates of the reactants for the establishment of tubular flame combustion are estimated.

2. Experimental and numerical methods

Schematic drawings of the tubular flame burners used in this study are shown in Fig. 1. To obtain flow visualizations inside the tubular flame burner, three optically accessible quartz burners have been made (Fig. 1a). Each burner has four tangential slits (left picture). From the two opposed slits, seeded air is parallel injected into the burner, while from the other two opposed slits non-seeded air is injected. The length of the slit is 8 mm while the widths (W) are 3, 2 and 1 mm. The burners are open on two sides with inner diameter of 16 mm and total length of 120 mm.

For combustion tests, two stainless steel burners were designed (Fig. 1b), for which the slit length and the inner diameter were the same as those of quartz burners while the slit widths were $W = 1$ and 2 mm, respectively. To permit viewing and photographing the flame, a round quartz window was installed at the closed end of the burner. To conduct the flame, a quartz tube of 100 mm in length was connected downstream of the slits. Oxygen was gradually added into the air stream and injected into the burner from two horizontal tangential slits (denoted as oxidizer slits); while the fuel (methane) was individually injected from another two vertical slits (denoted as fuel slits). The fuel and the oxidizer were rapidly mixed in a strong centrifugal force field in the combustion tube, and then the mixture exited from the open side of the quartz tube, where it was ignited by a torch at the exit, resulting in safe combustion without flame flashback.

The mixing process was examined through flow visualizations recorded by a PIV system, as shown in Fig. 2. Dry air metered by an orifice flow meter was supplied as the flow gas. Magnesium oxide (MgO) particles with a few microns in diameter were seeded into one stream through a particle seeder, and then the seeded

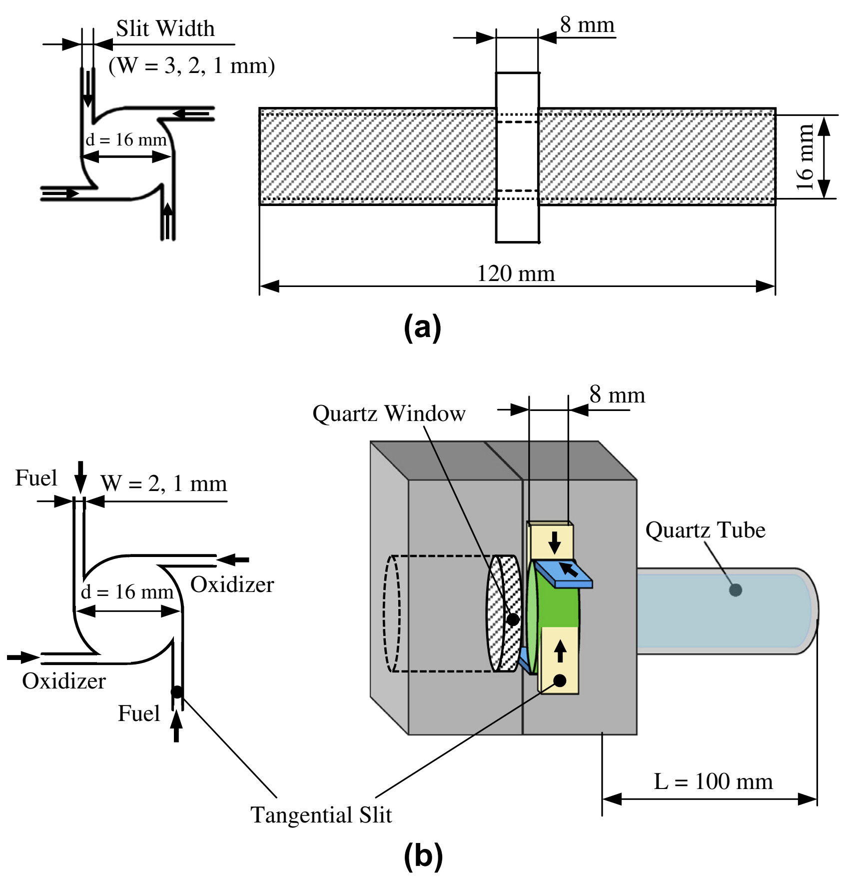

Fig. 1. Schematics of the rapidly mixed type tubular flame burner ((a) quartz burners for mixing process analysis, two-side open; (b) stainless steel burners for combustion tests, one-side open).