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An experimental study on the high frequency oscillatory combustion in tubular flame burners

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ABSTRACT

In this study, high frequency oscillatory combustion in tubular flame burner was experimentally investigated using large scale 8- and 12-in. diameter tubular flame burners. The conditions for the high frequency oscillatory combustion were determined, and the pressure fluctuations were measured, on which spectral analyses were made. The results showed that a smooth laminar tubular flame could be established, however, high frequency combustion sound was emitted from the 8- and 12-in. burners when the air flow rates exceeded 650 and 1200 m^3/h, respectively. Pressure fluctuation measurements and spectral analyses showed that high frequency pressure fluctuations occurred simultaneously during the high frequency oscillation. The flame images were also obtained with a high speed video camera. The flame surface was found to be notably corrugated and the symmetry was broken during the oscillation. By assuming that the tubular flame burner is a simple tube, the natural frequencies of the burners were determined using the fundamental theory of the acoustic resonance in a cylindrical cavity, and the experimental peak frequencies in the spectra were compared with the natural frequencies. As a result, it was found that the high frequency oscillations in both the burners were identified as the tangential/radial mode acoustic resonant oscillations. It was further found that the tangential first mode of oscillation, which had an asymmetric structure, preceded the higher modes of oscillation which indicated that the mode dominated the occurrence of the high frequency oscillation. To verify the occurrence of the tangential first mode oscillation, the pressure fluctuations were measured with two pressure sensors installed at opposed locations. The results showed that the phase of the oscillation was 180° difference, and the asymmetric structure confirmed the occurrence of the tangential first mode of oscillation.

1. Introduction

A tubular flame has been extensively studied from a fundamental viewpoint for the past three decades [1–3]. Because of symmetry of temperature distribution, the conductive heat loss behind the flame is negligible, and hence, the flame gives a wide stable flame range from the lean to rich flammability limits [2–4]. Furthermore, the flame consists of an inner burned gas region of low density and an outer unburned gas region of high density, and hence, the flame is aerodynamically stable according to the Rayleigh stability criterion [5], when the flame is formed in a rotating vortex flow.

Recently, these advantages have received keen interest from a practical viewpoint. A proto-type tubular flame burner has been developed for 0.1 MW heat output which has 100 mm (4-in.) inner diameter and 1000 mm long, and a homogeneous propane/air or methane/air mixture is tangentially injected from the closed end of the tube [6,7]. It has been shown that a laminar flame of large flame area up to 0.3 m^2 can be formed. Under a constant flow rate of the unburned gas, the flame diameter reaches the maximum while the flame length reaches the minimum around the stoichiometry. It has been also confirmed that the adiabatic flame temperature as well as the chemical equilibrium compositions are achieved in the burned gas region [8].

Up to now, a variety of tubular flame burners have been developed [3,9–13]. Using the technical merit of wide flammable range, a tubular flame burner to burn blast furnace gas (BFG), which has a lower heating value just 4 MJ/m^3(stp) and is about one twentieth that of propane, has been developed [10,11], and a tubular flame burner to burn biomass powder has been developed as well [11]. A tubular flame burner is utilized for stabilizing a

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flame in a high speed stream [12] or for heating the head of a Stirling Engine [11]. Recently, a tubular flame has been installed in a super-heated steam generator [13].

On the other hand, to meet increasing demands for larger heat outputs, large scale tubular flame burners for 1.0–2.0 MW are being developed. During the development, it has turned out that high frequency oscillatory combustion occurs under the high heat output conditions.

The occurrence of combustion driven oscillations has long been a subject of interest (e.g., [14–19]) because it can result in system performance degradation and, in the worst case, system failure due to structural damage [18,19]. Thus, the oscillatory combustions have been extensively studied with variety of combustors. Examples of the recent studies on the high frequency oscillatory combustion are Refs. [20–23]. In a series of study [20–22], a self-excited transverse acoustic mode of oscillatory combustion in a cylindrical combustor was investigated experimentally and theoretically with a swirl stabilized turbulent flame. It was verified that the onset of the instability was due to the balance between system damping and permanently driving potential. And furthermore, it was found that the instability was driven in the region of high pressure gradients, not in the region of high acoustic pressure amplitude. On the other hand, in Ref. [23], the experiments were conducted with VHAM (Very High Amplitude Modulator) and with coaxial methane/liquid oxygen injectors in a rectangle combustion chamber. It was found that the flame structure as well as the spray characteristics can modified by the acoustic modulations.

Compared to such combustion systems used by other researches, the tubular flame burners are unique in that the burner itself is simple in configuration, and in addition, the flame has a thin laminar flame front structure [1–3], and hence, the heat release zone is limited in a narrow space in the radial direction because the flame is laminar and, further limited in a finite space in the axial direction corresponding to the flame length. Therefore, the location as well as the moment of the excitation of the high frequency oscillation, and hence, the mechanism responsible for the instabilities can be easily identified.

Then, in this study, high frequency oscillatory combustion in the tubular flame burner has been experimentally investigated using large scale 8- and 12-in. diameter burners which correspond to 1.0 and 2.0 MW heat outputs, respectively. The conditions for oscillatory combustion were determined under various air flow rate conditions, and the pressure fluctuations during the oscillation were measured with pressure sensors, and then, spectral analyses were made on the results. The modes of oscillatory combustion were identified by comparing the experimentally obtained spectral peak frequencies with the natural frequencies of the burners, which were calculated based on the fundamental theory of the acoustic resonance in a cylindrical cavity. The high frequency oscillatory combustion studied here may yield useful insights on understanding the occurrence of the high frequency combustion oscillations in general combustion systems, in which volumetric combustion of high intensity occurs in turbulent flows.

2. Experimental

Figure 1 shows a schematic of the tubular flame burners. In this study, two tubular flame burners of 8- (Fig. 1A) and 12- (Fig. 1B) inches in diameter were used. The inner diameter and length were 208 and 500 mm for the 8-in. burner, and 306 and 700 mm for the 12-in. burner, respectively. A combustible mixture was injected from two rectangular tangential slits (Fig. 1 tangential slit), which was 10 mm wide and 300 mm long for the 8-in. burner, and 15 mm wide and 300 mm long for the 12-in. burner. According to the

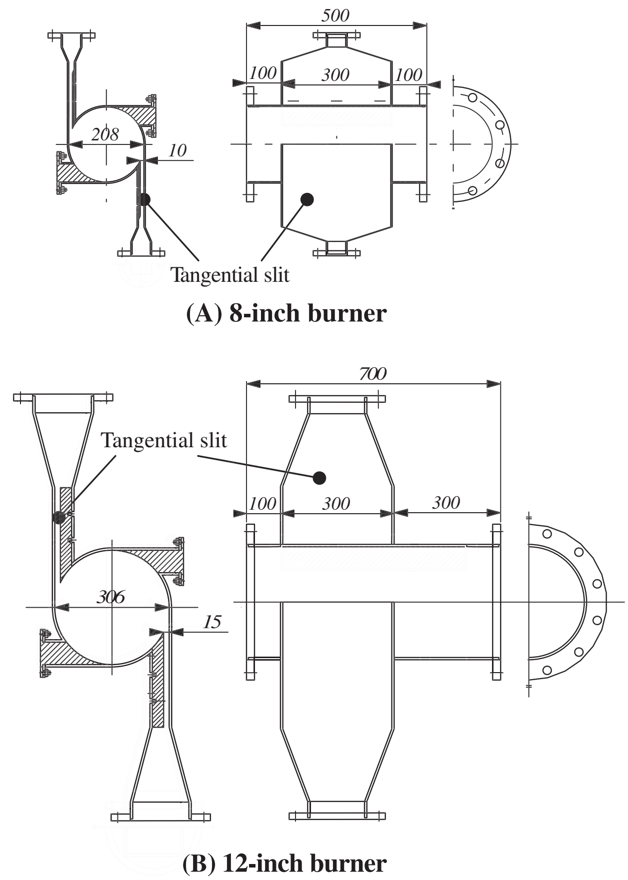

Fig. 1. Schematics of the tubular flame burners (A: 8-in. burner and B: 12-in. burner).

simple calculation [24], the swirl numbers (*S*), which is a measure of the degree of rotational motion, are 5.0 and 8.2 for the 8- and 12-in. burners, respectively.

Figure 2 shows a schematic of the experimental apparatus. One end of the burner was closed with a quartz plate (Fig. 2, quartz window 1), through which a tubular flame could be observed (see Fig. 2(A)). As shown in Fig. 2(A), a laminar tubular flame front can be established in the burner of which inner region is filled by the burned gas while the outer region is covered by the unburned gas.

At the other end of the burner, a combustion tube of stainless steel was connected with flanges (Fig. 2, combustion tube). The inner diameter and the total length of the combustion tube were 208 and 1300 mm for the 8-in. burner, and 306 and 1400 mm for the 12-in. burner, respectively. The total length of the burner and the combustion tubes were 1800 and 2100 mm for the 8- and 12-in. burner. To permit viewing, two rectangular quartz windows were installed on one of the 8-in. combustion tube (Fig. 2, quartz window 2), while, on the 12-in. burner, instead of the combustion tubes, a quartz tube of 306 mm inner diameter and 1500 mm length was connected. The flames were photographed with a conventional video camera (Panasonic, NV-GS400). In Fig. 2(B), the image of the tubular flame established inside the burner is depicted. A tubular flame front is established near the tangential inlets (Tubular flame in Fig. 2(B)), however, the visible tubular flame front ends when the whole unburned mixture is consumed (at “End of the visible flame” in Fig. 2(B)), and the axially downstream region of the flame is filled with the burned gas.