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Experiments on dynamical motion of buoyancy-induced flame instability under different oxygen concentration in ambient gas

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ABSTRACT

We experimentally investigated the dynamical motion of buoyancy-induced flame instability under different oxygen concentrations in ambient gas for a non-premixed flame, focusing on how the oscillation frequency and amplitude of the flame tip change with oxygen concentration in ambient gas. The oscillation frequency of flame tip f_t increases monotonically with increasing oxygen concentration in ambient gas X_o, while the oscillation amplitude at flame tip A_m drastically decreases with increasing X_o. The change in the oscillation frequency for different oxygen concentrations can be clearly explained by the use of the theoretical equation proposed by Cetegen and Ahmed [B.M. Cetegen, T.A. Ahmed, Experiments on the periodic instability of buoyant plumes and pool fires, Combustion and Flame 93 (1993) 157–184]. As the flame tip location decreases with increasing X_o, the magnitude of the periodic fluctuation of the interface between hot combustion products and ambient gas becomes small at the flame tip. This leads to a remarkable decrease in the oscillation amplitude of the flame tip in a high oxygen concentration environment.

1. Introduction

Buoyancy has substantial impact on flame dynamics, the flame stabilization limit, and pollutant emission. Therefore, an in-depth understanding of flame instability resulting from buoyancy-induced natural convection is of scientific and practical importance to combustion and fire research today. Thus far, many aspects of flame oscillations/buoyancy interaction for non-premixed flames originating from circular nozzles have been described in details in a number of recent studies [1–8]. One of the important findings in these studies is that large-scale toroidal vortices associated with hydrodynamic shear layer instability of the interface between hot combustion products and cold ambient air are very significant in initiating the flame oscillation. As the large-scale toroidal vortex develops and moves in the downstream direction, it interacts with the flame front to create periodic oscillation at the flame tip manifested as *flame flickering* with a low frequency (approximately 10 Hz). The frequency of toroidal vortices derived from the convection velocity corresponds with that of the flame oscillation and is significantly affected by physical parameters such as flow velocities [2], [6], gravitational levels [5], burner diameters [2], [6], [8] and sub-atmospheric pressures [6].

The density difference between the combustion products and ambient gas is also one of the important factors affecting the buoyancy-induced hydrodynamic shear layer instability mechanism. Its effect will appear when a large change in temperature of the hot combustion products occurs under different proportions of oxidizer. Therefore, in addition to the physical parameters noted above, the oxygen concentration in ambient gas should be considered as a significant parameter.

Knowledge of these parameters is significant in the field of fire suppression. Fire suppression methods alternative to use of the fire extinguishing agent CF_3Br (Halon 1301) are required because the Halon production has been banned [9], [10]. The inert gas fire extinguishment system (e.g., formation of a reduced oxygen concentration environment) is coming into wide use as an alternative fire suppression method [11]. A better understanding of how the oxygen composition influences flame motion would provide a baseline for controlling the performance of inert gas. The effect of various agents (e.g., CF_3Br, CF_3H) on flow velocity and temperature distributions of flame oscillation has been numerically investigated for non-premixed flames in normal and microgravity [12]. However, the effect of oxygen concentration on fundamental characteristics of flame oscillation under a wide range of oxygen concentration in ambient gas has yet not been experimentally investigated.

The objective of the present study is to experimentally investigate the dynamical motion of buoyancy-induced flame instability,

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focusing on how the oxygen concentration in ambient gas affects the oscillation frequency and amplitude. The obtained results will provide more comprehensive insight into the buoyancy-induced flame instability mechanism.

2. Experimental apparatus and method

A schematic diagram of our experimental configuration is shown in Fig. 1. The burner used in this study was the so-called *cup burner*, and consisted of an inner cup burner and an outer chimney. The inner cup burner was constructed from straight sections of stainless-steel tube with a diameter of $d_i = 10$ mm. It was positioned inside a Pyrex glass chimney with a diameter $d_o = 200$ mm. A damping screen, glass beads, and honeycomb were set at the bottom of the chimney so that the uniformity of oxidizer/inert gas flow inside the outer chimney could be achieved. Methane (CH_4) was used as the gaseous fuel and supplied through the inner cup burner. The bulk flow velocity of gaseous fuel V_f (=volumetric flow rate/cross-sectional area of the inner cup burner) and oxidizer/inert gas V_o(=volumetric flow rate/cross-sectional area of the outer chimney) were held at 0.08 and 0.008 m/s, respectively. Nitrogen gas (N_2) was used as the inert gas for the current experiments, and the oxygen concentration in oxidizer/inert gas X_o (=volume percentage of oxygen in the oxidizer/inert) was varied from 18% (low oxygen concentration environment) to 50% (high oxygen concentration environment).

We used a beam deflection technique based on the Schlieren principle to measure the oscillation frequency at the flame tip f_t (Hz) in a manner similar to that reported in previous studies [13], [14]. The light source was a 5 mW He–Ne laser, and a pinhole ($\phi_0 = 1.0$ mm) was placed in front of the laser to form an 1 mm laser beam diameter. A plano-convex lens with 1000 mm focal length was used to focus the beam onto a Schlieren stop placed at the focus. The Schlieren stop was a circular opaque spot glued to a transparent plastic sheet. A focusing lens (AF Nikon, 35–105 mm, f: 3.5–4.5) and a photodiode (Hamamatusu, Model: H55-338) were placed behind the circular opaque stop to detect the change in light intensity caused by the laser beam deflection induced by flame motions. The obtained time series from the photodiode was acquired using a LabVIEW system (National Instrument). After acquiring the time series data, FFT analysis was implemented by MATLAB programming in an attempt to evaluate the oscillation frequency. The sampling frequency of the obtained time series was 1 kHz, and the data number N was 10,000. Measurements were made at the flame tip location along the centerline of the burner tube. Fig. 2 shows time variation in deviation from mean value of output voltage ΔI (V) and the frequency spectrum for $X_o = 21\%$. The dominant peak generated by buoyancy-induced

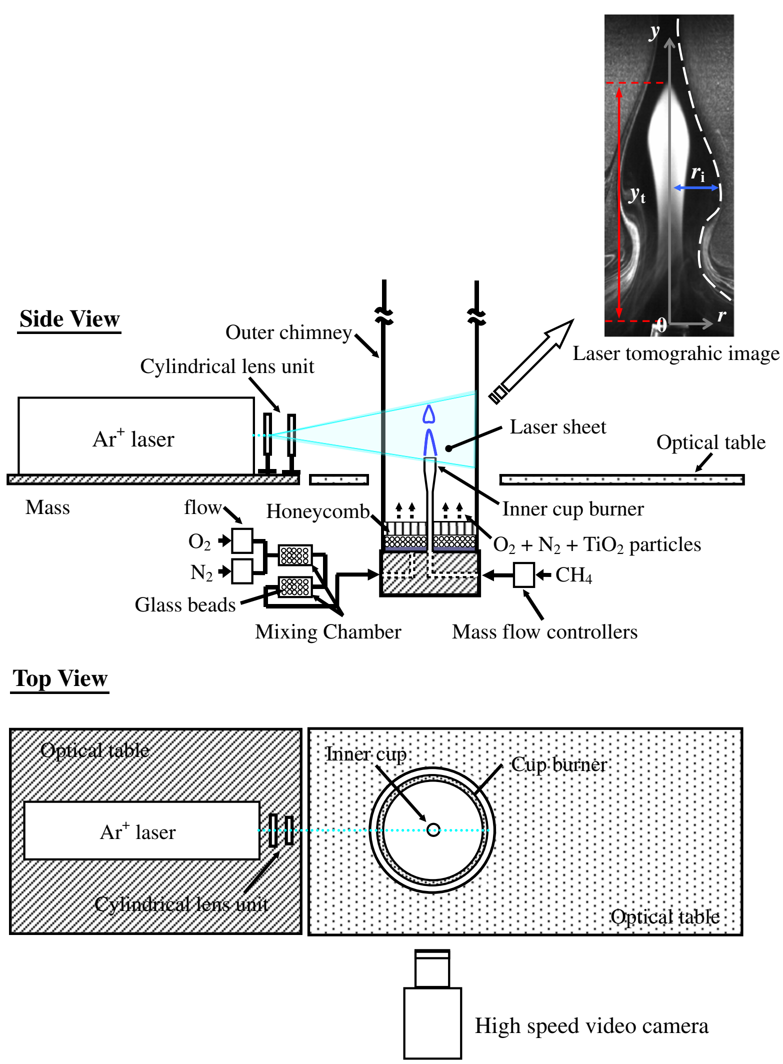

Fig. 1. Schematic diagram of experimental configuration.