International Journal of Heat and Mass Transfer 121 (2018) 1089–1098

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effects of co-flow and equivalence ratio on flickering in partially premixed flame

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ARTICLE INFO

Article history:
Received 20 May 2017
Received in revised form 30 August 2017
Accepted 16 January 2018

Keywords:
Flickering flame
Co-flow
Equivalence ratio
POD analysis
Flame visualization

ABSTRACT

The effects of air co-flow and equivalence ratio on flickering of a partially premixed flame of methane/air were experimentally studied for various combinations of burner diameters, fuel/co-flow velocities, and equivalence ratios of methane/air fuel. A scaling law was proposed by introducing the corrections made to the Froude number, equivalence ratio, and co-flow velocity ratio to describe the flickering characteristics of the flame in the co-flow. It is found that the corrected Strouhal number of the partially premixed flame increases with an increase in the co-flow at higher equivalence ratios with a frequency jump, whereas the value is still higher without the frequency jump at lower equivalence ratios. The oscillation amplitude weakens with an increase in the corrected co-flow velocity ratio at high equivalence ratios, which reduces at low equivalence ratios. The corrected critical co-flow velocity ratio used to suppress the flickering is found to be independent of the equivalence ratio in this scaling law. The proper orthogonal decomposition (POD) analysis of the flame indicates that the random flickering motion at high equivalence ratios is weakened and the fluctuating energy distribution of the lower POD modes is modified when the equivalence ratio is low. These changes in the flame structure are due to the disappearance of the clip-off flame in the partially premixed flickering flame at low equivalence ratios in the co-flow.

1. Introduction

The flame-flickering phenomenon in a flame is a fundamental topic of interest in the study of combustion, which has been analyzed largely based on the experiments on the diffusion flame. However, the physics behind the flame-flickering phenomenon still remains unclear because of its complexity of the phenomenon [1,2]. Previous studies [3–16] on the flame-flickering phenomenon in the diffusion flame show that the flickering motion is due to the Kelvin–Helmholtz and Rayleigh–Taylor instabilities in the shear layer along the interface of the high-temperature flame and the surrounding low-temperature fluid of different densities [4–9]. Because of the instability in the shear layer with density variations [12–14], a periodic motion of the flame occurs and leads to large-scale vortices [3,6], thereby oscillating the entire flow field. The detailed studies on the flickering flame have been reported in literature, which cover the visualization and measurements of temperature and velocity field [17–22] and numerical simulations of the flame [23–25]. These studies contribute to better understanding the physical mechanism of the flickering diffusion flame.

In the past, the scaling law of the flickering frequency of the flame [4] has been studied largely based on the experiments on diffusion flames, which cover the effect of fuel types, flow rates, burner sizes, burner configurations. These experimental results are well correlated using the Strouhal number St (= fd/U) of the flickering frequency and Froude number Fr(= U_f^2/gd), which are expressed by St $\sim$ Fr$^{-0.57}$ in a wide range of Froude numbers. It should be mentioned that this relationship is independent of the fuel types, flow rates, burner sizes, and burner configurations. Furthermore, the numerical simulation suggests that the relationship is robust even under the influence of gravity, radiation and co-flow [26]. The flame flickering occurs also in the premixed flame. However, the mechanism of flickering is somewhat different from that of the diffusion flame due to the complexity of the premixed-flame nature, such as the propagation of flame front with intrinsic burning velocity and flashback. The flickering frequency of the premixed flame was studied under the different gravitational levels, and the effects of flow velocities, pressures and equivalence ratios were examined experimentally [27], while the empirical correlations of the flickering frequency St in the premixed flame were given by the function of Richardson number Ri (=$(\Delta T/T_0)gd/U_f^2$) and Reynolds number Re (=$U_f d/\nu$), where ΔT is the temperature difference of flame and surrounding air, T_0 is the surrounding

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.01.072
0017-9310/

Nomenclature

d	burner diameter
E_k	fluctuating energy of POD mode
Fr	Froude number ($=U_f^2/gd$)
f	frequency
f_d	appearance rate of clip-off flame
f_f	frequency at maximum oscillation amplitude
g	gravitational acceleration
H_0	height of steady flame
H_m	mean flame height
H_{rms}	RMS oscillation amplitude of flame height
I_0, I_1, I_2	0th, 1st and 2nd POD modes
$\overline{I_0}, \overline{I_1}, \overline{I_2}$	dimensionless POD modes
i	local intensity
Q	fuel flow rate
t	time
St	Strouhal number ($= f_f\, d/U_f$)
$\overline{S_t}$	corrected Strouhal number ($=StFr^{0.57}$)
U_c	co-flow velocity
U_f	fuel velocity of methane and air
U_r	co-flow velocity ratio ($=U_c/U_f$)
$\overline{U_r}$	corrected co-flow velocity ratio ($=Ur\ Fr^{0.37}/c$)
U_{rc}	critical co-flow velocity ratio to suppress flickering
x, y, z	coordinates (See Fig. 1)

Greek letters

Λ	total fluctuating energy ($=\Sigma\lambda_k$)
$\Lambda_{Ur=0}$	total fluctuating energy at $U_r = 0$
λ_k	eigenvalue of POD mode

temperature, U_f is the fuel velocity and ν is the kinematic viscosity [28–30]. Furthermore, the modified Richardson number was proposed to better correlate with the experimental data [31]. On the other hand, the partially premixed flame is other type of flame configuration [26,32–34], which is a flame studied in the present experiment. This flame is formed by mixing air into fuel stream prior to the reaction zone, where additional air is available for complete combustion. The flickering frequency of the partially premixed flame follows the empirical formula $\mathrm{St} \sim \mathrm{Fr}^{-0.57}$ [26] in agreement with the diffusion flame. This formula can be rewritten as $\mathrm{St} \sim \mathrm{Ri}^{0.57}$ using the relationship $\mathrm{Fr} \sim \mathrm{Ri}^{-1}$ [32]. It should be mentioned that the partially premixed flame has been attracted attention in the industrial burners and furnaces due to the fundamental relevance to flame liftoff and stabilization.

The oscillation amplitude of the flickering flame can be suppressed by including the co-flowing air parallel to the flame, whereas the flickering can be fully suppressed only by increasing the co-flow velocity to the same level of the fuel velocity in the diffusion flame [35,36]. The co-flow effect on the partially premixed flame is studied experimentally using a flame-visualization technique [37,38]. The result shows that the oscillation amplitude was suppressed with an increase in the co-flow velocity similar to that in the diffusion flame. However, the co-flow effect on the partially premixed flame could not be quantitatively compared with the diffusion flame because of the limited amount of experimental data for the partially premixed flame in literature. It should be mentioned that the co-flow effect on the flickering diffusion flame was studied experimentally for various combinations of burner diameters and fuel/co-flow velocities [39], and the result indicates that the oscillation amplitude and flickering frequency of the diffusion flame in the co-flow were characterized using the Froude number and co-flow velocity ratio.

The objective of this study is to analyze the flickering characteristics of a partially premixed flame of methane/air in air co-flow using an image-processing technique and proper orthogonal decomposition (POD) analysis. The experiments are conducted systematically using three burner diameters and different combinations of equivalence ratios and co-flow velocity ratios, which help in understanding the characteristics of the flickering partially premixed flame in the co-flow and the effects of equivalence ratio and co-flow velocity ratio on the suppression mechanism of the flickering.

2. Experimental apparatus and procedure

2.1. Experimental setup

Fig. 1 shows the experimental setup employed to study the flickering partially premixed flame of various fuel/burner tube equivalence ratios $\varphi = 1$, 3 and 10 in the co-flow. It should be mentioned that $\varphi = 1$ is the case of complete combustion, while $\varphi = 3$ and 10 corresponds to incomplete combustion. The premixed fuel flowing through the mixing chamber is supplied to a burner with a pipe of circular cross section of length 500 mm. Three burners with different diameters are selected for the experiment: 11.4, 17.4, and 24 mm. The temperature of the methane/air and the surrounding air temperature is approximately 290 K. The premixed flame with an equivalence ratio higher than 5 was visible because of the soot emitting from the flame, whereas the flame with an equivalence ratio lower than 3 was not visible. Hence, all the flames were visualized using a flame-reaction technique with the help of a sodium-chloride solution, which was supplied to the flame in the form of a mist with a diameter of 1 µm generated using an ultrasonic humidifier. Note that the flame boundary of the visualized flame was detected through a band-pass filter of sodium D-line. The mass flow rate of the mist was controlled using a DC voltage power supply of variable output. When the mist is supplied to the flame, the color of the flame becomes orange in the high-temperature flame. The mass flow rate of the mist was set to 0.2 mg/s, which is sufficiently low to avoid affecting the temperature of the flame. The

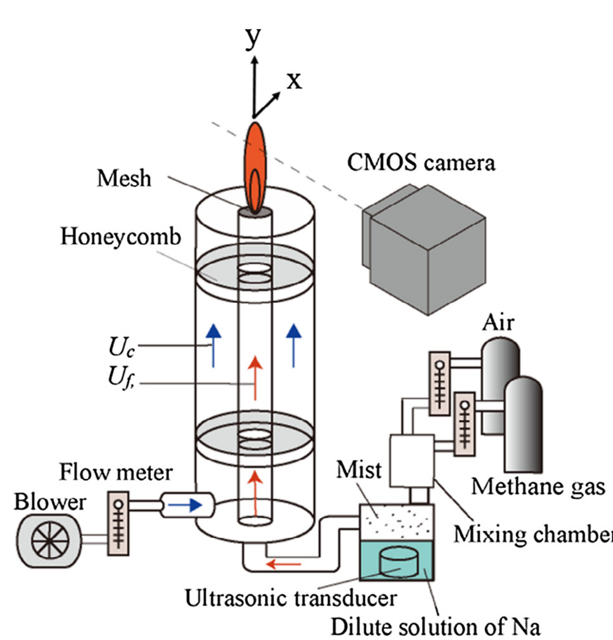

Fig. 1. Experimental setup.