Flickering Behavior of Premixed Flame Confined in a Tube

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1 Introduction

A large number of experimental and theoretical studies have investigated the flame flicker in diffusion flame. It has been known that the flickering frequency ranges from 10 to 20 Hz for a wide variety of burner sizes, flow rates, and compositions. Employing a linear stability analysis, Buckmaster and Peters[1] showed that a modified Kelvin-Helmholtz type instability exists in diffusion flames, predicting a low frequency oscillation around 17 Hz. As experimental studies, Hamins[2] and Sato[3] measured the flickering frequency and correlated Strouhal number and Richardson number. They showed that the two parameters have power law dependence showing the role of buoyancy-induced velocity field on the flickering frequency.

Although the flame flicker is familiar phenomenon in diffusion flame, it is also reported that there exists flame flicker and the flickering frequency ranges from 10 Hz to 20 Hz in premixed flame. Kostiuk[4] obtained an empirical relationship among Strouhal number, Richardson number and Reynolds number.

In the previous studies, both the diffusion and premixed flames were open to ambient air so that buoyancy driven Kelvin-Helmholtz type instability occurred due to the velocity difference between the ambient air and the hot products which were accelerated by the buoyancy force. But the flickering phenomena exist also in the premixed flame confined by a tube, where the outside disturbance does not exist. The flickering frequency and flickering wavelength were measured. From the results, the generation mechanism of flickering phenomena and correlation between Richardson number and dimensionless wavelength of flickering curvature were studied. It is also interesting that the flickering frequency has wider range from 10 Hz to 40 Hz compared to previous studies.

2 Experimental setup and method

Figure 1 shows the experimental setup used in this study. Methane gas was used as fuel and air was used as oxidizer. Methane flame behaviors were investigated varying the mean velocity from 25 to 55 cm/s and the equivalence ratio from 0.56 to 0.62. Premixed gas passes through a honeycomb and a contraction nozzle for making laminar flow and uniform axial velocity field. Inverted conical flame is attached to the hydrogen pilot flame and surrounded by a quartz tube of 50 mm diameter and 220 mm length. The hydrogen pilot flame acts only as a flame anchor because the hydrogen flow rate was 20 cc/min corresponding to enthalpy of combustion 139 J/min, which is very small compared to the enthalpy of combustion of premixed mixture(for example, 130 kJ/min at the mean velocity 30 cm/s and equivalence ratio 0.6). To measure the flickering frequency, a photo-multiplier tube(R212, Hamamatsu) was installed near the flickering part of the flame and connected to an oscilloscope(DL 1640E, Yokogawa). To measure the flickering wavelength, successive images were recorded at the rate of 250 frames/second. using an intensified high-speed camera(FASTCAM Ultima APX, Photron Ltd.). Finally, the measurement system was synchronized by a delay generator(Model 555, BNC).

3 Flame-generated vorticity

Lee[5] solved the velocity field analytically by a large activation energy asymptotics in an inclined planar flame. The positive x direction is taken to point to the burned region and the y axis is set tangentially on the planar active sheet. The dimensional space variable x and y is normalized by the flame thickness $d=\rho D_{th}/\rho_u u_L$ (density ρ, thermal diffusivity D_{th} with subscripts u referring to unburned gas) and the tangential velocity v is normalized by the burning velocity u_L. Then the dimensionless momentum equation in tangential direction becomes

$$Pr\frac{d^2v^*}{dx^{*2}}-\frac{dv^*}{dx^*}=\frac{g_y d}{u_L^{\,2}}\left(1-\rho^*\right) \qquad (1)$$

where Pr, g_y, γ is Prandtl number $Pr=\mu/\rho D_{th}$(viscosity μ), gravitational acceleration in tangential direction $g_y=g\cos\phi$(flame angle ϕ), and thermal expansion parameter $\gamma=1-T_u/T_f$ (gas temperature T with subscripts f referring to flame) respectively. As a result of velocity analysis, distribution of the dimensionless vorticity ω^* normal to the active sheet is obtained as follows.

$$\omega^*=\frac{dv^*}{dx^*}=\begin{cases}\dfrac{g_y d}{u_L^{\,2}}\gamma\left[1+\dfrac{1}{Pr}\displaystyle\int_{x^*}^{0}\dfrac{e^{(1-1/Pr)z}}{1-\gamma+\gamma e^z}dz\right]e^{x^*/Pr} & \left(x^*<0\right)\\[2ex] \dfrac{g_y d}{u_L^{\,2}}\gamma & \left(x^*>0\right)\end{cases} \qquad (2)$$

Equation (1) shows that dimensionless buoyancy force has an important role in tangential velocity field and the value at the active sheet is equal to dimensionless vorticity value $\Omega^* = g_y d\gamma/u_L^2$(thermal expansion parameter $\gamma=1-\rho_f/\rho_u$ with subscripts f referring to flame) at the active sheet. The dimensionless vorticity Ω^* resembles the Richardson number in the previous studies[2, 3, 4] in the view that Ω^* is the ratio of momentum force $\rho_u u_L^2 A$(unit flame area A) at normal direction to the active sheet and buoyancy force $g_y(\rho_u-\rho_f)dA$ at tangential direction, although nozzle diameter and exit velocity were replaced by flame thickness and burning velocity respectively. In summary, an inclined flame induces tangential velocity difference across the flame, thus vorticity generation, although the original flow is irrotational. Likewise on previous studies, buoyancy driven Kelvin-Helmholtz type instability or flame generated vorticity is the cause of the flickering phenomena.

4 Experimental results and discussion

Figure 2 shows representative flickering shapes of methane flame according to equivalence ratio ϕ at mean velocity U=0.40 m/s. It shows that the wavelength of the flame curvature decreases as the equivalence ratio increases. Figure 3(a) shows variation of the flickering frequency f according to the mean velocity and the equivalence ratio. It is expected that the flickering frequency increases as the mean velocity increases because the flame curvature is advected at the phase velocity which is a little different from tangential velocity according to the Lewis number of mixtures[5]. From images taken by intensified high-speed camera, the flickering wavelength was measured as follows. The flame surface was extracted by image analysis and the surface was deformed in axial or radial direction and rotated finally. Then the flame surface points were fitted by a function of sinusoidal function times exponential function.

$$y = a \cdot \exp(bx) \cdot \sin(cx + d) + f \qquad (3)$$

From the fitted results, the wavelength is obtained by restoring the length $c/2\pi$ to the original length before the deformation process. The fitting was conducted at the early stage of the flame curvature evolution where the amplitude is small so that the wavelength may not be influenced by nonlinear effect.

Figure 3(b) shows variation of the flickering wavelength according to the mean velocity and the equivalence ratio. It shows that the flickering wavelength has strong dependence on the equivalence ratio and certain amount of dependence on the mean velocity too. To consider effects of momentum force and buoyancy force, the Richardson number *Ri* was calculated using equation (2). The burning velocity u_L and the flame temperature T_f were calculated from u_L = $U\sin\phi$ and CHEMKIN software respectively. The flickering wavelength λ was normalized by flame thickness d. Figure 4 shows the dimensionless wavelength λ^* according to the Richardson number Ri. From the results, an empirical equation is obtained as follows.

$$\lambda^* = 62.63 Ri^{-0.247} \qquad (4)$$

Equation (4) tells us that Richardson number controls the dimensionless wavelength. But it should be noted that the Richardson number used in this equation includes flame property like burning velocity and flame thickness not burner geometry like nozzle diameter and nozzle exit velocity.

5 Concluding remarks

Flickering behavior of premixed flame confined in a tube were studied. An inclined flame induces tangential velocity difference across the flame, thus vorticity generation, although the original flow is irrotational. This buoyancy driven Kelvin-Helmholtz type instability causes the flickering phenomena. From the measurement of frequency and wavelength of flickering flame, an empirical equation between the nondimensional vorticity, or Richardson number and the nondimensional curvature wavelength of flickering flame.

6 Acknowledgements

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7 References

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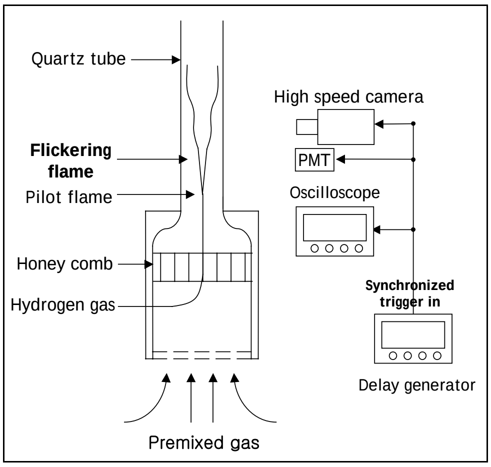

Fig. 1 Schematic diagram of the experimental setup

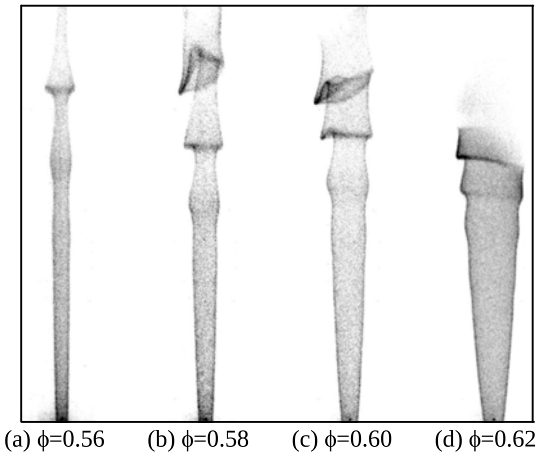

Fig. 2 Flickering shapes of methane flame according to the equivalence ratio ϕ (mean velocity U : 0.40 m/s)

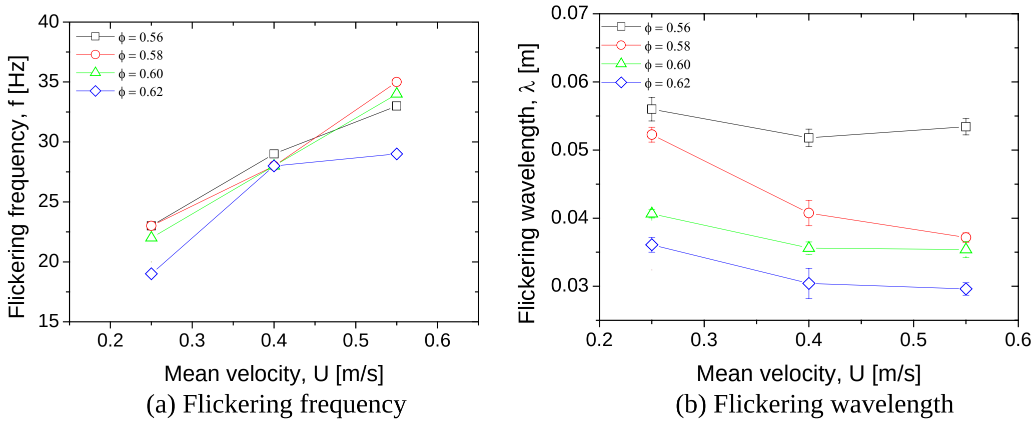

Fig. 3 Flickering frequency f and wavelength λ according to mean velocity U and equivalence ratio ϕ

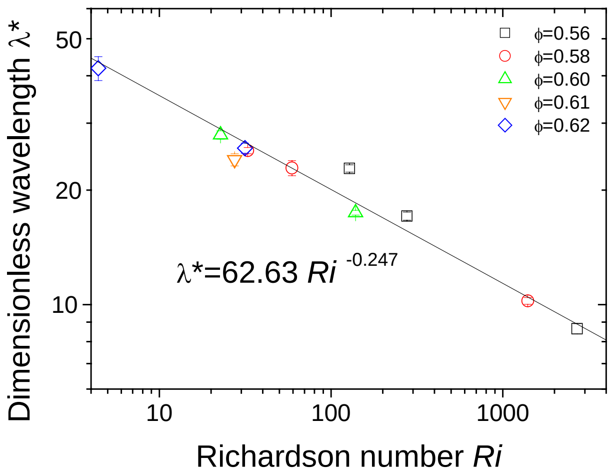

Fig. 4 Dimensionless wavelength λ* according to Richardson number