FLICKERING CHARACTERISTICS OF PREMIXED FLAME WITHOUT INTERACTION WITH AMBIENT AIR

Young Tae Guahk[1], Dae Geun Lee[3], Gwang Chul Oh[3], Hyun Dong Shin[1]

[1] KAIST, Korea, [2] KIER, Korea, [3] KATI, Korea
Corresponding e-mail: guahk@kaist.ac.kr

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. Buckmaster and Peters reported that a buoyancy driven Kelvin-Helmholtz(KH) type instability causes flickering phenomena via buoyancy-induced velocity field surrounding jet flow and predicted a low frequency oscillation around 17 Hz using a viscous stability analysis with the infinite candle model - an ideal plane diffusion flame in which the flow field is induced solely by buoyancy.

The previous researches in diffusion and premixed flames investigated buoyancy driven KH instability in the shear layer between the buoyant hot products and the ambient air. But Kostiuk and Cheng showed that the even the geometry of flames could affect the flickering phenomena significantly and which inspired us to investigate the buoyancy driven KH instability in flame front not in the shear layer. For the purpose, the flame should have geometry which induces large buoyancy driven KH instability without the effect of the buoyancy driven KH instability in the shear layer. In the present research, the flame with the shape of long inverted cone was selected so that buoyancy driven KH instability could be generated easily through large baroclinic torque due to near perpendicularity between the direction of the density gradient and the buoyancy force.

The overall objective of the present research is to understand the effect of boundary conditions (i.e. whether or not there is interaction with ambient air) on flickering features and to find out dominant parameter of flickering phenomena without interaction with ambient air in premixed flames of inverted cone shape. Burning velocity and flame angle were measured for flame-generated vorticity expressed also as modified Richardson number Ri* and flickering wavelength was measured. Finally, the empirical relation between Ri* and St was obtained and it was shown that the flickering phenomena of inverted cone shape without interaction with ambient air can be explained by buoyancy driven KH instability.

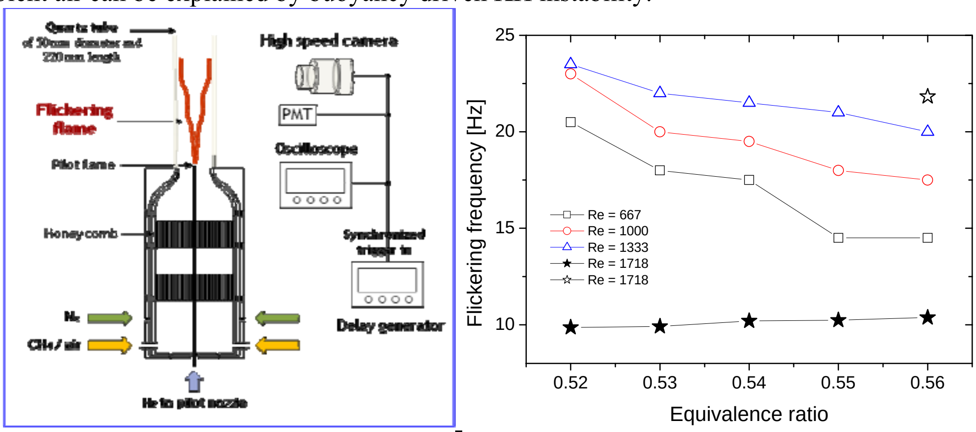

Figure 1 : Schematic diagram of experimental setup(a) and the flickering frequency of premixed flame in case B(solid symbols) with Reynolds number of 1718 and in case A(hollow symbols) with Reynolds number of 667, 1000, 1333, and 1718 as a function of equivalence ratio(b)

Figure 1(a) is a diagram of experimental setup used in the present research. Methane(99.999% pure research grade)/air mixture is fed into a burner and passes through honeycombs and a contraction nozzle for laminar flow and uniform axial velocity. In the burner exit, the flame is anchored at a pilot flame of hydrogen with 20 cc/min flow rate. Premixed flames with two different boundary conditions, i.e. without interaction with ambient air(case A) and with interaction with ambient air(case B), were observed. In case A, a quartz tube of 50 mm diameter and 220 mm length was used in order to prevent the interaction between the flame and the ambient air. Nitrogen gas was supplied into the outside nozzle with the same velocity to the reactants for preventing static pressure perturbation due to the on/off contact of flame front and tube inner surface. In case B, the quartz tube and the nitrogen gas were not used.

In case B, the flames and products interact with quiescent ambient air and the buoyancy driven KH instability is generated strongly in the shear layer between products and the ambient air. There also exists the buoyancy driven KH instability in oblique flame front but the instability in oblique flame front is weaker than that in the shear layer, thus the instability in the shear layer prevails in entire flow field, while in case A, the flames and products are protected from the interaction with ambient air. Therefore, the shear layer exists only around oblique flame front due to the baroclinic torque resulting from the different direction of density gradient and buoyancy force. Because of the above-mentioned difference, different characteristics of premixed flames in case A and B were found as followings.

I. In case B, the premixed flames flickered in every equivalence ratio conditions between flammability limit and flash-back limit, i.e. the critical equivalence ratio Φ_c did not exist.
II. In case A, the range of the flickering frequency with equivalence ratio was from 15 Hz to 25 Hz with equivalence ratio from 0.52 to 0.56 while the flickering frequency of case B changed very little around 10 Hz.

The dimensionless conservation equations show that the solution depends only on $g_x d_{flame}/u_L^2$, $g_y d_{flame}/u_L^2$, Pr, Le, and Λ_L F(T*, Φ*). The Prandtl and Lewis number are nearly constant at 0.8 and 0.958, respectively, for the air/methane mixture of equivalence ratio from 0.5 to 1.0. The terms of $g_x d_{flame}/u_L^2$ and Λ_L F(T*, Φ*) did not have influence on velocity distribution. Thus, with the assumption that the reaction rate does not depend flow characteristics or the flame plays a role of thermal energy source, the dominant parameter in flickering premixed flame without interaction with ambient air(case A) seems to be $g_y d_{flame}/u_L^2$. The dimensionless number $g_y d_{flame}/u_L^2$, a little different form of conventional Richardson number used in previous works, is now called as modified Richardson number and defined in equation.

$$\text{Conventional Richardson number } Ri = \frac{gd}{V^2}$$

$$\text{Modified Richardson number } Ri^* = \frac{g_y d_{flame}}{u_L^2}$$

Conventional Richardson number(Ri) is the ratio of buoyancy force acting on the products(g*d) and inertia force of the fuel jet(V^2) where d, g, and V represent burner diameter, acceleration constant of gravity, and fuel jet velocity, respectively. Modified Richardson number(Ri*) is the ratio of buoyancy force($g_y(\rho_u-\rho_f)d$) acting on products of the flame front volume in tangential direction and inertia force($\rho_u u_L^2$) of reactants in normal direction of the flame front. Larger Ri* means that the buoyancy force acting on products in tangential direction increases faster than the inertia force of reactants acting on the normal direction of flame front resulting in stronger buoyancy driven KH instability due to larger tangential velocity jump across the flame front. In other words, the magnitude of baroclinic torque and the residence time over which the torque acts affects the Richardson number or the tangential velocity jump across the flame front.

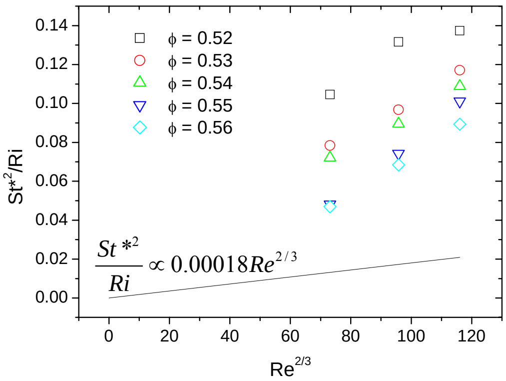

Figure 2 : Application of the present research into Kostiuk's empirical relation which used conventional Richardson number

From the experimental results of u_L and flame angle θ_f, and properties of mixture, modified Richardson number $g_y d/u_L^2$, where $g_y = g\sin\theta_f$, $d = \rho D_{th}/\rho_u u_L$, was calculated for each experimental condition. Here adiabatic temperatures for given equivalence ratios were calculated from the EQUIL Program of the CHEMKIN Collection and ρD_{th} were evaluated at the mean temperature of reactants and products and 1 atm.

Strouhal number was calculated from $St = fd_{flame}/u_L$ where u_L is the burning velocity and plotted against modified Richardson number. It was found that all data obtained under the equivalence ratio from 0.52 to 0.56 and the Reynolds number from 667 to 1333 could be plotted on one line and an empirical equation was obtained. As can be seen in Figure 2, the data of the present research showed large deviation from Kostiuk's empirical equation in flickering motion of Bunsen type premixed flame with interaction with ambient air(case B). This means that flickering motion in the premixed flame of inverted cone shape without interaction with ambient air(case A) is controlled by the same physical mechanism(buoyancy driven KH instability) as those of flickering premixed or diffusion flame with interaction with ambient air(case B) but with the modified Richardson number which has flame structure information of burning velocity and flame thickness.