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Effect of Air Ratio on Unsteady Partially Premixed Flames

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Abstract– The burning characteristics of unsteady partially premixed flames have been investigated in this paper. Two reaction zones namely rich inner premixed zone and outer diffusion wing were observed for all the equivalence ratios considered. This kind of structure is called double flame structure. Flickering of flames were observed due to the formation of toroidal vortices around the flame surface. These toroidal vortices are convected up as a result of buoyant acceleration. The flames are observed to oscillate in two different modes namely, bulk flickering and tip flickering. In the bulk flickering mode, the flame tip is chopped off from the flame surface and in the tip flickering mode, the flame surface is observed to oscillate up and down without any breakage of flame tip. Flames with higher equivalence ratio (greater than 6) exhibit bulk flickering and flames with lower equivalence ratio (less than 6) experience tip flickering. As the equivalence ratio is lowered by partial premixing of the fuel with more air, the flame height is reduced and the strength of inner premixed flame is increased. The amplitude of oscillation of the flame height also decreases with reduction in the equivalence ratio due to the formation of smaller toroidal vortices but the frequency of oscillation is found to increase slightly. A generalised Strouhal number – Froude number correlation has been obtained in the form $St \propto Fr^{-\beta}$, by varying the flow rates of air or fuel systematically, keeping the other parameters constant. The effect of increasing air flow rate is to increase the flickering frequency and increasing fuel flow rate is to decrease the flickering frequency.

Keywords**:** Unsteady flames, partial premixing, double flames, flame flickering.

1. Introduction

Partial premixed combustion is encountered in gas turbine engines, diesel engines, stratified charge IC engines, furnaces and composite solid propellants. Partially premixed flames are formed when a rich mixture of fuel/air mixes with a lean mixture of fuel/air or with quiescent air. The former results in a triple flame structure which consists of three reaction zones namely the rich premixed, diffusion and the lean premixed flames; the latter, on the other hand, results in a double flame structure which consists of an inner premixed flame and an outer diffusion flame. This type of combustion is practically observed in devices where a wide variation of equivalence ratio occurs and when there is insufficient time for fuel air mixing to result in premixed combustion.

Unsteady partially premixed flames have been studied by Shu et al. (1997) by injecting a fuel rich methane-air annular jet sandwiched between a central air jet on the inner side and co-flowing air on the outer side. They found that at high Froude numbers, the flame exhibited a steady state structure. At intermediate Froude numbers, the flame still exhibited a steady state structure even though a periodic rollup of toroidal vortices was observed in the plume region due to buoyant acceleration. At low Froude numbers, the rollup process occurred closer to the burner port which resulted in flame vortex interactions. Correlation between Strouhal number and Froude number for the oscillating flames was found to be of the form $St \propto Fr^{-0.38}$. Lock et al. (2005) reported that the flickering frequency is insensitive to variation in equivalence ratio but flickering amplitude increases with increasing equivalence ratio.

The effects of gravity on unsteady partially premixed flames have been investigated numerically by Qin et al. (2004). The flickering frequency was found to increase with an increase in g-value. They obtained a correlation between Strouhal number and Froude number as $St \propto Fr^{-0.57}$ which is similar to the one obtained for non-premixed normal gravity flames by Hamins et al. (1992). Hence they concluded that flickering at enhanced gravity is influenced by the same physical factors as under normal gravity conditions and the instability mechanism responsible for the buoyancy induced flame flickering is independent of the boundary conditions and flame configurations.

The structure and dynamics of unsteady laminar partially premixed methane-air flames were studied numerically and experimentally by Nogenmyr et al. (2010). They suggested that the outer diffusion flames might be governed by the Rayleigh-Taylor instability and the inner premixed flames by the Landau-Darrieus instability. The oscillation motion was characterized using the Strouhal number as a function of Froude number which is of the form $St \propto Fr^{-0.28}$. The effect of fuel type and equivalence ratio on the flickering of triple flames was investigated by Sahu et al. (2009). They found that the fuel type and associated chemistry have no effect on the flickering phenomenon and obtained a correlation of the form $St \propto Fr^{-0.50}$.Their work showed that flickering phenomenon purely depends on the dynamics of fluid flow. A detailed study on different mechanisms of flickering process was carried out by Sato et al. (2000) who reported two types of correlation, $St \propto Fr^{-0.50}$ for low fuel jet velocity and $St \propto Fr^{-0.41}$ for high fuel jet velocity. The former resulted in a bulk flickering mode where the flame tip is chopped off and the latter resulted in a tip flickering mode where the flame is found to oscillate without any breakup.

From the above mentioned studies, it is clear that various Strouhal number-Froude number correlations have been reported for partially premixed flames. It is unclear as to which of these correlations accurately characterize the flickering process of partially premixed flames and the effect of air ratio on the flickering has not been studied in detail. The objective of this paper is to report the structure, flickering frequency and Strouhal number-Froude number correlations of unsteady partially premixed flames at different equivalence ratios.

2. Experimental Procedure

2. 1. Experimental Setup

Fig. 1. Overall Geometry of Burner

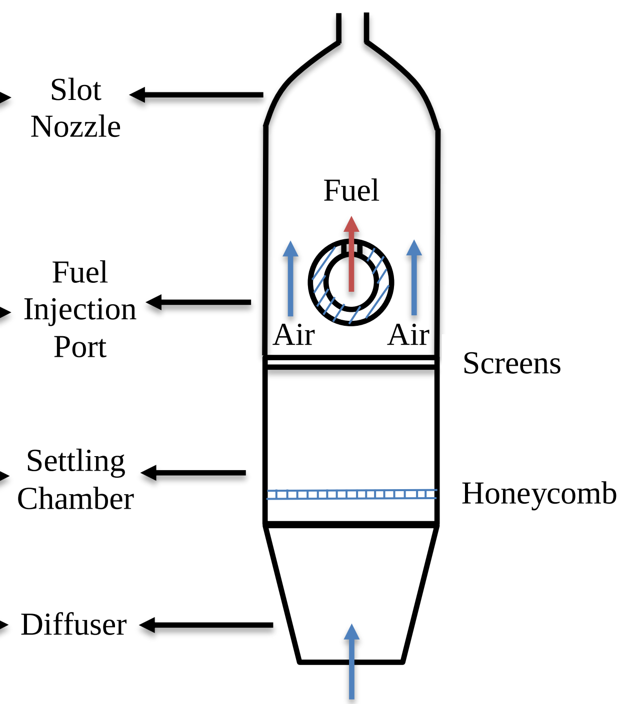


Fig. 2. Internal Geometry of Burner

The burner consists of a diffuser, a settling chamber, a fuel injection port and a nozzle. The settling chamber of dimensions 36 mm X 36 mm X 362 mm contains wire meshes and honeycomb to reduce the velocity fluctuations and to make the flow uniform at the nozzle exit. Air from compressor enters through the diffuser at the bottom of the burner. The overall geometry and internal geometry of the slot burner are shown in Fig. 1 and Fig. 2 respectively. The fuel used is methane which is sent laterally from both the sides of the fuel injection port. The fuel injection port is located at the middle of the settling chamber. Methane issues out of the five holes of diameter 0.8 mm in the fuel injection port while air enters as a coflow surrounding the methane jets. Methane is injected at an axial distance of 120 mm below the nozzle exit. Air and methane mix in the settling chamber and issue out of the contoured slot nozzle of exit dimensions 36 mm X 3 mm. The nozzle has a fifth order polynomial profile with a height of 36 mm and a lip thickness of 1.5 mm. The flow rates of air and methane are controlled using rotameters fitted in their individual lines. Typical experimental conditions considered in the study are listed in Table 1.

2. 2. Image Processing

A digital camera (Casio EX-F1) of pixel resolution 1280 X 720 is used to take high definition videos at 30 frames per second for a duration of 4 seconds. These videos are converted to frames which are then processed to obtain flame properties such as diffusion and premixed flame heights, flickering frequency and amplitude. An image processing code is developed using MATLAB to find the instantaneous diffusion flame height from each frame. This time series signal is processed using Fast Fourier Transform to find the flickering frequency and amplitude of the oscillating flame. From the frequency response curve, the highest peak frequency is identified as the flickering frequency. The resolution of 1 pixel of the camera corresponds to a distance of 0.2 mm. The error in fixing the position of the flame tip in the image is ± 3 pixels which corresponds to an error in measurement of ± 0.6 mm in flame height.

3. Results and Discussions

3. 1. Operating Conditions

In order to study the effect of partial premixing on flickering flames, four cases have been considered with equivalence ratio varying from 9.38 to 5.47 (Flame no. 1, 2, 3 & 4). By keeping the mass flow rate of methane constant, the air flow rate was varied accordingly to achieve these equivalence ratios. To obtain a generalised Strouhal number – Froude number correlation for the case of partial premixing, 3 fuel flow rates were considered and for each fuel flow rate, air flow rate was increased to achieve partial premixing. Similarly, to obtain a generalised Strouhal number – Froude number correlation for the cases with fuel velocity variation, 3 air flow rates were considered and for each air flow rate, fuel flow rate was increased (Flame no. 5, 6 & 7). Reynolds number defined based on the jet velocity at the nozzle exit and slot width of the nozzle (3 mm) was found to vary between 40 and 150, and Froude number defined as U_o^2/gw (U_o is the jet velocity at the nozzle exit and w is the slot width of the nozzle) is varied in the range of 3 to 30. Strouhal number is defined as fw/U_o where f is the flickering frequency.

Table. 1. Typical Experimental Conditions used in the study

Flame No.	Fuel mass flow rate ($x10^{-5}$ kg/s)	Air mass flow rate ($x10^{-5}$ kg/s)	Equivalence Ratio	Jet Exit Velocity (m/s)	Reynolds Number	Froude Number
1	2.22	4.1	9.38	0.619	91	13
2	2.22	5	7.58	0.715	106	17
3	2.22	6	6.35	0.776	120	20
4	2.22	7	5.47	0.868	135	26
5	1.70	4.1	7	0.565	83	11
6	2.22	4.1	9.38	0.619	91	13
7	2.77	4.1	11.71	0.704	98	17

3. 2. Effect of Partial Premixing on Flame Structure

In order to understand the partial premixing effects, fuel velocity is kept constant and the air velocity is gradually increased. The equivalence ratio varied from 9.38 to 5.47. For all the equivalence ratios considered, double flame structure was observed as shown in figure 3. The outer diffusion flame height is found to decrease with a decrease in equivalence ratio, since at higher level of premixing, less ambient air is required to complete combustion. The luminosity of inner premixed reaction zone increases as air flow rate increases. As the equivalence ratio approaches unity, the flame tends to become fully premixed in nature. It was reported by Bennett et al. (2000) that, though the inner premixed flame is always present, it is visible only from equivalence ratio of 4.107 for the axisymmetric burner flames. Unlike the axisymmetric burner flames, the double flame structure is visible in the slot burner flames for the entire equivalence ratio range of the present study.

From Tanoff et al. (1996), it is known that double flame structure could exist only at low flame strain rates. This implies that the slot burner flame adjusts itself to locations where the strain rates are low and exhibits a double flame structure for a wide range of equivalence ratios.

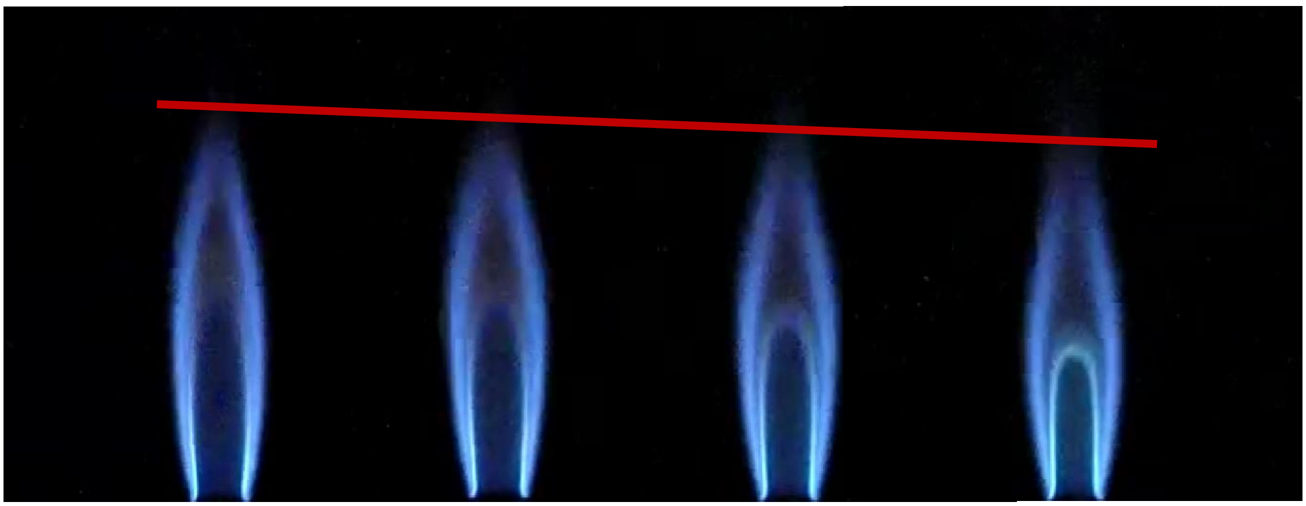


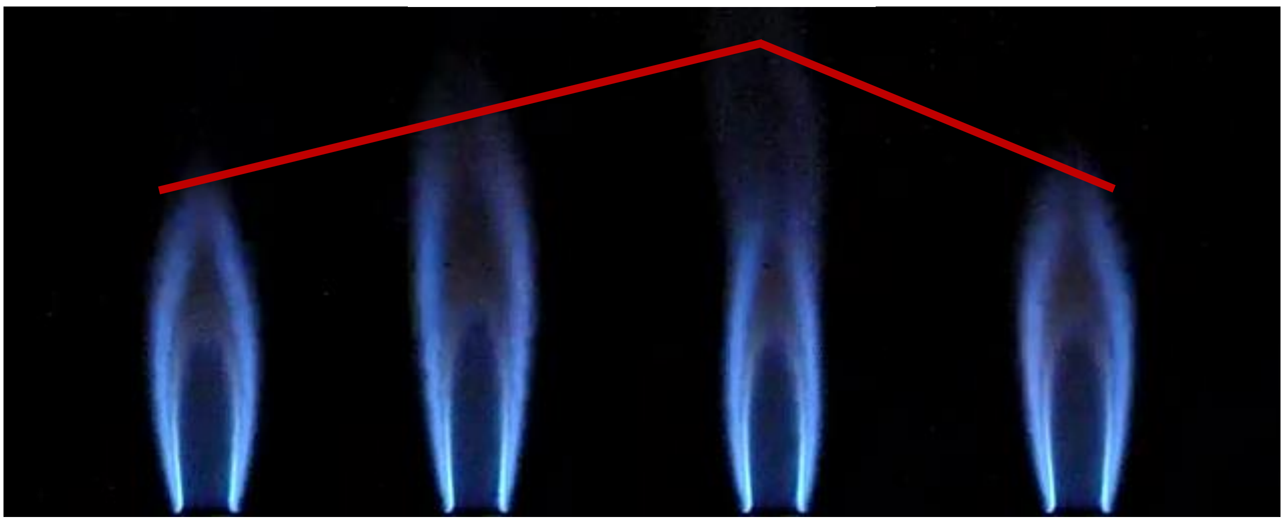
Fig. 3. Variation of flame height with partial premixing. Re varies from 91 to 135 and Fr varies from 13 to 26 as mentioned in the table 1.

Increasing the strength of inner premixed flame indicates that the reaction rates as well as the heat release have increased in the inner flame. Like the outer flame, the inner flame height also decreases gradually. This is because as more air is supplied, the excess fuel mixes with air and forms a burning mixture at a lower axial distance. Only for the flame with equivalence ratio of 5.47, a premixed reaction zone thickness is clearly observed.

3. 3. Bulk Flickering and Tip Flickering

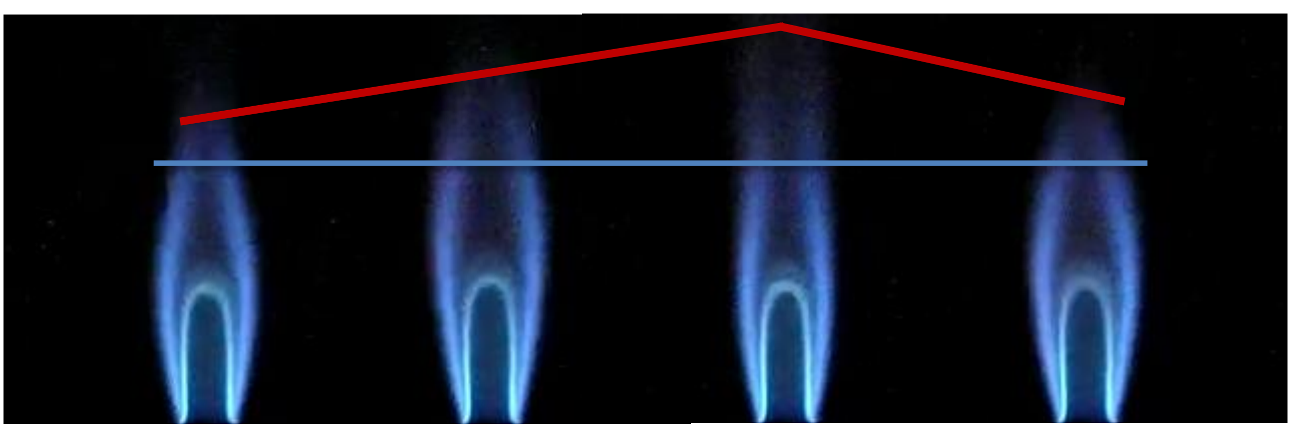
Boulanger (2010) reported that outer toroidal vortices are formed around the flame surface due to density difference between the hot gases and cold surrounding air. These toroidal vortices are convected up as a result of buoyant acceleration and counter rotating inner vortices are formed inside the flame surface due to density difference between the cold fuel jet and hot gases. For all the four equivalence ratios of the present study, the flames were found to oscillate due to the formation of toroidal vortices along the flame surface.

From figure 4, it is seen that the toroidal vortices interact with the flame surface resulting in periodic bulging and breakup of the flame. In the first snapshot, due to the formation of toroidal vortices, the flame base is wider. In the second snapshot, a bulge is seen exactly above the inner premixed flame which indicates that the inner vortices and outer vortices are merged along the centreline. When these two vortex structures merge, the inner flame is slightly stretched resulting in a small increase of its height (of the order of 1 - 3 mm). From the third snapshot, it is discernible that the merged inner and outer vortex structures are being convected up resulting in the breakup of the flame tip. The fourth snapshot and the first snapshot are similar indicating that this oscillation process is periodic, thus completing one cycle. The flickering frequency of this oscillating flame is 11 Hz. The frequency of oscillation is found to increase weakly as the partially premixing is increased, since the mixture velocity of methane and air is high. When the jet exit velocity increases, the convective velocity of the toroidal vortices also increase which results in the occurrence of more oscillation cycles per second and hence the rise in flickering frequency.



t = 0 | t = 33.33 ms | t = 66.66 ms | t = 99.99 ms

Fig. 4. Instantaneous Photographs of ER = 7.58 flame (Re = 106, Fr = 16) showing bulk flickering mode of oscillation



t = 0 | t = 33.33 ms | t = 66.66 ms | t = 99.99 ms

Fig. 5. Instantaneous Photographs of ER = 5.47 (Re = 135, Fr = 26) flame showing tip flickering mode of oscillation

As the equivalence ratio is reduced, the oscillation mode shifts to tip flickering mode; in this case, there is no breakup of flame tip as seen in figure 5. The toroidal vortices that merge in the centreline are not strong enough to create a breakup of flame tip. Instead they stretch the whole flame resulting in the increase of flame height. This might be attributed to the fact that as the air flow rate increases, the jet exit velocity increases causing an increase in shear forces. Due to higher shear, smaller vortices are formed which are not as strong as the vortices formed in the bulk flickering mode. The flickering frequency of this oscillating flame is about 11.95 Hz. A slight increase in the flickering frequency is observed as the mode shifts from bulk flickering to tip flickering. The inner premixed flame almost remains stationary throughout the cycle but the diffusion flame is affected to a significant extent as shown by the blue line in figure 5.

3. 4. Frequency Response Curve

The more the partial premixing, less is the amplitude of oscillation in the flame height. This difference is clearly visible in figure 6 where the FFT of diffusion flame height for various equivalence ratios is plotted. Higher amplitudes of oscillation for equivalence ratio values of 9.38, 7.58 and 6.35 are due to the bulk flickering mode giving rise to breakup of flame tip caused by larger vortical scales. On the other hand, for the equivalence ratio of 5.47, tip flickering mode is observed which is caused by small scale vortices. Slight increase in flickering frequency can be seen in figure 6 as the equivalence ratio is reduced.

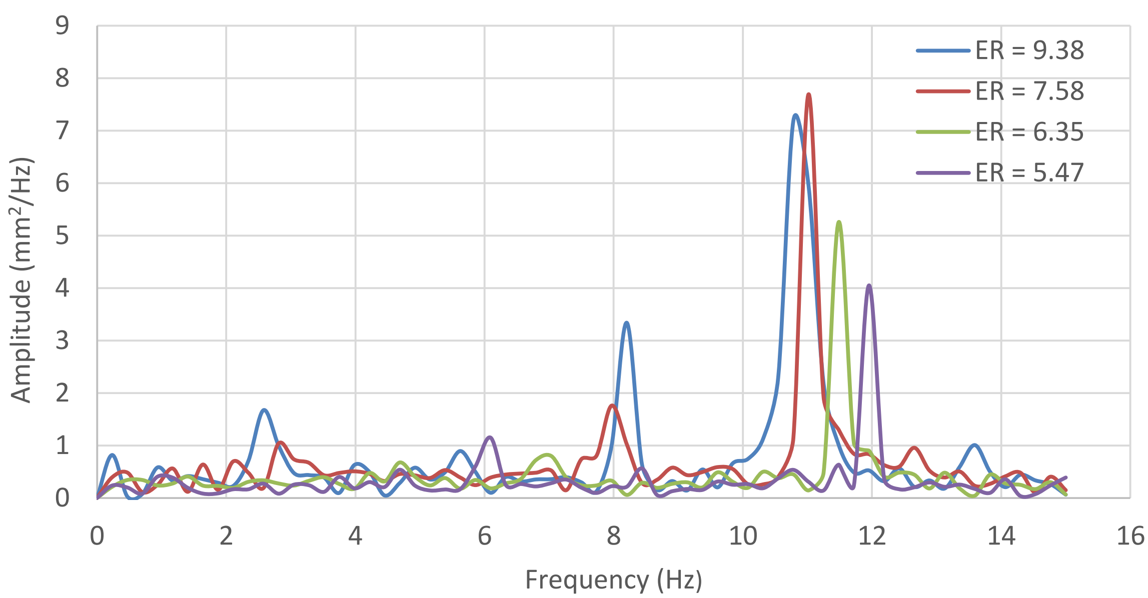


Fig. 6. Frequency response curve of diffusion flame height

The amplitude of oscillation of inner reaction zone (not shown here) also follows the same trend as the diffusion flame oscillation with the flame of equivalence ratio 9.38 having higher amplitude and the flame of equivalence ratio 5.47 having the lowest amplitude. This again indicates that the vortex structures are stronger and larger for higher equivalence ratios when compared to the case of lower equivalence ratios.

3. 5. Strouhal Number – Froude Number Correlations

In order to characterize the effect of air ratio on flickering frequency, the non dimensionalized frequency (Strouhal number) has been correlated with the Froude number which is a measure of inertial force to buoyancy force. For a given fuel flow rate, the air flow rate is increased gradually and the flickering frequency is estimated. Strouhal number is found using this flickering frequency and Froude number is also determined from its definition. A plot of St – Fr is shown in figure 7 for various fuel flow rates and air flow rates. Power law is used to obtain the St – Fr relation. Table 2 summarises the various St – Fr correlations and the dependence of flickering frequency on jet exit velocity for different fuel flow rates.

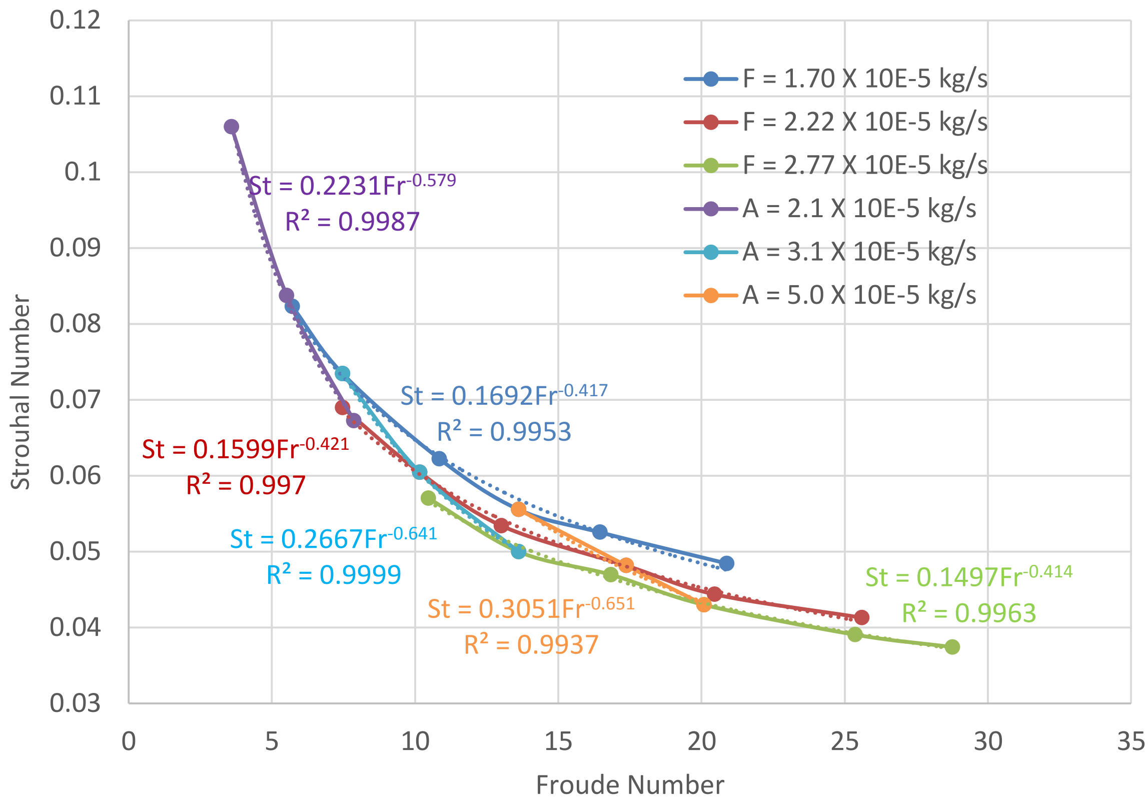


Fig. 7. Effect of air flow rate and fuel flow rate on St – Fr correlation for various fuel flow rates

It can be concluded that the effect of increasing air flow rate (i.e. increased degree of partial premixing) is to increase the flickering frequency. Sato et al. (2000) showed that if the exponent β in St – Fr relation is less than 0.5, then the inertial forces are more influential than the buoyancy forces. A generalised St – Fr correlation is defined for the effect of partial premixing on flickering flames by increasing air flow rate, which is given as

$$St \propto \left(\frac{1}{Fr}\right)^{\beta} \quad \text{Where } \beta < 0.5 \tag{1}$$

Table. 2. Effect of increasing air flow rate on St – Fr correlation

Fuel Flow Rate ($x10^{-5}$ kg/s)	St – Fr	f - U_o
1.70	$St \propto \left(\frac{1}{Fr}\right)^{0.417}$	$f \propto U_o^{0.166}$
2.22	$St \propto \left(\frac{1}{Fr}\right)^{0.421}$	$f \propto U_o^{0.158}$
2.77	$St \propto \left(\frac{1}{Fr}\right)^{0.414}$	$f \propto U_o^{0.172}$

Table. 3. Effect of increasing fuel flow rate on St – Fr correlations

Air Flow Rate ($x10^{-5}$ kg/s)	St – Fr	f - U_o
2.1	$St \propto \left(\frac{1}{Fr}\right)^{0.579}$	$f \propto U_o^{-0.158}$
3.1	$St \propto \left(\frac{1}{Fr}\right)^{0.641}$	$f \propto U_o^{-0.282}$
5.0	$St \propto \left(\frac{1}{Fr}\right)^{0.651}$	$f \propto U_o^{-0.302}$

Similarly, in order to understand the effect of increasing fuel flow rate on St – Fr correlation, the air flow rate is kept constant and the fuel flow rate is gradually increased. This was repeated for 3 different air flow rates and the results are summarised in Table 3. It can be seen that the effect of increasing fuel flow rate was to decrease the flickering frequency. The exponent β in the St – Fr relation is greater than 0.5 which indicates that the buoyancy forces are more influential than the inertial forces. At higher air flow rate, this exponent also increases, indicating the increase in dominance of buoyant forces. As a result, the flickering frequency is found to decrease with increase in jet exit velocity. A generalised St – Fr correlation for the effect of increasing fuel velocity on flickering flames is defined as

$$\mathrm{St} \propto \left(\frac{1}{\mathrm{Fr}}\right)^{\beta} \quad \text{Where } \beta > 0.5 \qquad (2)$$

4. Conclusions

Flickering characteristics of partial premixed flames have been investigated experimentally. Two modes of oscillation have been observed. Flames with equivalence ratio greater than 6 have bulk flickering mode of oscillation where breakup of flame tip is observed and flames with equivalence ratio less than 6 have tip flickering mode of oscillation where there is no break up of flame tip. Larger toroidal vortices are responsible for the breakup of flame tip in bulk flickering mode. A generalised St – Fr correlation in the form of $\mathrm{St} \propto \mathrm{Fr}^{-\beta}$ is obtained for the effect of increasing air flow rate and for increasing fuel flow rate. β is found to be less than 0.5 for the case of increasing air flow rate indicating an increase in flickering frequency and greater than 0.5 for the case of increasing fuel flow rate resulting in decrease of flickering frequency.

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