Stabilisation Mechanism of a Flickering Methane Diffusion Flame with Co-flow of Air

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Abstract— **The effects of co-flow air velocity on the flickering behaviour and stabilisation mechanism of a laminar flickering methane diffusion flame are investigated. Photomultipliers, high speed photography accompanied with digital image processing techniques have been used to study the change in global flame shape, the instability initiation point, the frequency and magnitude of the flame oscillation. It has been observed that the flame dynamics and combustion characteristics of co-flow diffusion flame are strongly affected by the co-flow air velocity. The oscillation frequency was observed to increase linearly with the co-flow velocity, whilst, the frequency amplitude was observed to continuously decrease. When the co-flow velocity has reached a certain value the buoyancy driven flame oscillation was completely suppressed. The high speed imaging has revealed that the co-flow of air is able to push the location of instability initiation point beyond the visible flame to create a very steady laminar flow region in the reaction zone. It is observed that the oscillation magnitude and wavelength decrease continuously as the co-flow air increases. The average oscillating flame height behaviour, however, was observed to be bimodal. It was initially enhanced by the co-flow air then starts to decrease towards the stabilised level. This height was observed to remain almost constant after stabilisation, despite further increase at air flow rate. It has been confirmed that, the flickering frequency is not a function of fuel flow rate but more co-flow rates are needed in order to suppress the flickering of the flames at higher fuel flow rates.**

Index Terms—**Diffusion flames; Co-flow air; Flame dynamics; Outer vortices; Flickering Suppression.**

I. INTRODUCTION

Laminar oscillating flames provide an opportunity to take advantage of the repeatability of the oscillations from cycle to cycle in investigating the phenomena of unsteady combustion. It is well known that the mechanism behind oscillation of laminar diffusion flames is attributed to the interactions between flame and vortices both inside and surrounding the luminance flame. The generation of the outer toroidal vortices has been attributed to a Kelvin–Helmholtz instability driven by a buoyancy induced shear layer surrounding the flame surface [1-3]. Therefore buoyancy affects on the shape and flickering frequency of diffusion flames. It is speculated that the frequency of the outer vortices correlated with the flame oscillation frequency [4]. Buoyancy is directly related to the Froude number (*Fr*), which is a dimensionless number comparing inertia and gravitational forces. In fluid dynamics *Fr* can be viewed as the ratio between the stream velocity and the velocity of the fastest surface wave ($Fr = U/(gd)^{1/2}$), where U is the fluid mean velocity and '*g*' the gravitational acceleration and '*d'* is the characteristic length (for example fuel nozzle or air exit diameter). An alternate definition used in combustion studies is ($Fr = U^2/(gd)$) where each of the terms on the right have been squared. This form is the reciprocal of the Richardson number that expresses the ratio of potential to kinetic energy. Consequently it can be conducted that the Froude number of the fuel jet is controlled by gravity level, diameter of the nozzle, fuel properties, and fuel flow rate [5].

Buoyant laminar jet diffusion flames are known to oscillate at low frequencies, typically within the 10–20 Hz range, depending upon the operating conditions [1, 2, 4, 6-8]. The axisymmetric, low frequency oscillation of flow and flame structures depends only weakly on the type of fuel, the fuel nozzle size, and the exit velocities of the fuel jet [1-3, 8-10]. However, the coherent flow structures in the air co-flow strongly interact with the reaction zone, which ultimately may lead to local flame extinction [8]. These structures, could be observed in the co-flow region, whereas vortical structures inside the flame surface were detected only when contoured fuel nozzles and large jet velocities were employed [2, 3, 8]. In spite of the extensive amount of research work related to the evolution of structures in buoyant jet diffusion flames, a definite and rigorous interpretation of the mechanisms leading to the formation of coherent flow structures is still lacking [2]. Indeed it seems that the closer understanding of diffusion flame instabilities due to formation of outer vortices might be gained by studying the influence of co-flow air on the flame dynamics.

Much work has been reported in the literature relating to the combustion of fuel jets in still air or in parallel co-flowing streams [2, 3, 11-14]. The blow-out limit [13, 15, 16] and the stabilisation mechanism of turbulent [14-16] or laminar [7, 17-20] lifted jet diffusion flame in co-flow of air have been studied extensively. However, the co-flow air effect on the dynamics of laminar un-lifted diffusion flames is left almost unattended in literatures.

The lift-off height in co-flow jets was found to increase highly nonlinearly with fuel jet velocity and was sensitive to the co-flow velocity. The blow-out and reattachment velocities however decreases linearly with the increase in co-flow velocity [21]. The numerical simulations of methane-air diffusion flames by Montgomery et al. [14] indicate that the momentum of the co-flowing stream acts in

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combination with the jet momentum to push the base of the flame farther away. For steady, turbulent diffusion flames, the strength of an air co-flow can potentially have a noticeable effect on the flame length as well [14, 22]. According to the results of Hermanson et al. [23] the addition of co-flow generally caused an increase in the mean flame length of turbulent ethylene jet diffusion flame puff. Results obtained by Gu et al. [24] indicate that, although generally flame stability shows an increase by air velocity, the addition of steam into air flow brings about a reduction in the flame stability. The results of Lingens et al. [2, 3], indicate that generally a diffusion flame with the co-flow of oxygen oscillate with a lower frequency in comparison with a flame in the co-flow of air at the same flow rates.

Change in combustion flow field by varying fuel or air flow rates result in the change of different aspects of flame properties, i.e., flame geometry, combustion stability, soot emission and temperature field. Impact of pressure and fuel type and flow rate on the flickering behaviour of laminar diffusion flames has been studied in our previous papers [10, 25]. Interestingly, during the experiments on the effects of fuel and air flow rates on diffusion flame dynamics the effects of change in co-flow air on oscillation behaviour of methane diffusion flame was found to be very pronounced. It is however, the increase in fuel flow rate was observed not to change the flickering frequency despite having a strong effect on the magnitude of oscillation [25]. Co-flow air was observed to modify dynamics of a flickering methane diffusion flame to such an extent that the flame oscillations were totally suppressed (stabilised). The results tend to be more interesting when it was noticed that the co-flow air increases the flame flickering frequencies while decreasing the oscillation magnitude until the flame instability suppression mode. The objective of this study is to investigate in details, the co-flow air flow rate (velocity) effects on laminar non-lifted diffusion flame dynamics using experimental approach.

II. EXPERIMENTAL SETUP

The co-flow air burner used in this study is able to produce a classic Burke–Schumann [26] laminar diffusion flame is shown in **Fig. 1**. The flame is stabilised on a tapered fuel nozzle with an exit diameter of 4.57 mm. Gaseous methane (CH_4) fuel was supplied from a compressed gas cylinder regulated by a needle valve and measured by a calibrated mass flow meter with 1% full scale accuracy. During each set of the experiments, the methane mass flow rate of 0.3 slpm (standard litres per minute) were kept constant at all air flow rates. Co-flow air is supplied from a compressed air bottle into the burner and is diffused using a layer of glass beads, after which a honeycomb structure with 1.5 mm diameter holes is used to straighten the flow. Co-flow air was controlled by a needle valve to produce a range of mass flow rates from 1 to 20 slpm through a coaxial air exit nozzle with a shroud diameter of 37.8 mm. The mean fuel jet exit velocity was approximately 0.34 m/s with the Reynolds numbers (*Re*) of 91.5 in all set of experiments. The air exit velocities are in the range of 0.05 to 0.31 m/s with the *Re* from 102 to 685. One may then conclude that all flows were in laminar mode during all sets of experiments. The maximum *Fr* of the fuel stream is calculated to be 2.8 and the maximum *Fr* of the co-flow air is 0.3 at 20 slpm of air flow rate based on the air exit hydraulic diameter.

The optical system used for the real-time measurement of flame light emissions is shown schematically in **Fig. 2**. The chemiluminescence (photomultipliers) setup has been explained in details in our previous papers [10, 25]. The summation of the soot light and chemiluminescence of OH* and CH* at the two chosen wavelengths (at 308±2.5 nm and 430±5 nm respectively) are measured. The intensity of the filtered light is converted into voltage signal which is captured by an analogue to digital data acquisition card (National Instruments PCI-MIO-16E-1) at 5000 samples per second with a sampling duration of 4 s. Real-time signal processing was performed by using a LabVIEW 8.5 virtual instrument (VI) to obtain the flame flickering frequency.

To capture the evolution of the flame structure, a digital monochrome high speed camera (Photron FASTCAM SA-3) has been used. The camera uses a mega pixel resolution CMOS sensor and provides full resolution images (1024 x 1024) at frame rates up to 2,000 fps (frames per second). This framing rate with a camera shutter speed of 1/5,000 s was found to be optimum to capture the full details of the flame flickering and to avoid image saturation.

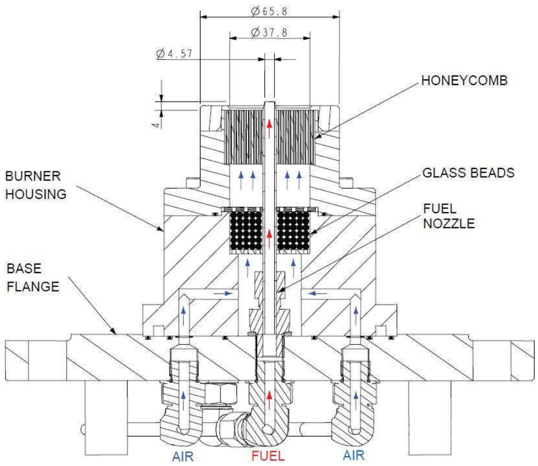

Fig. 1: Cross-section of the co-flow diffusion flame burner.

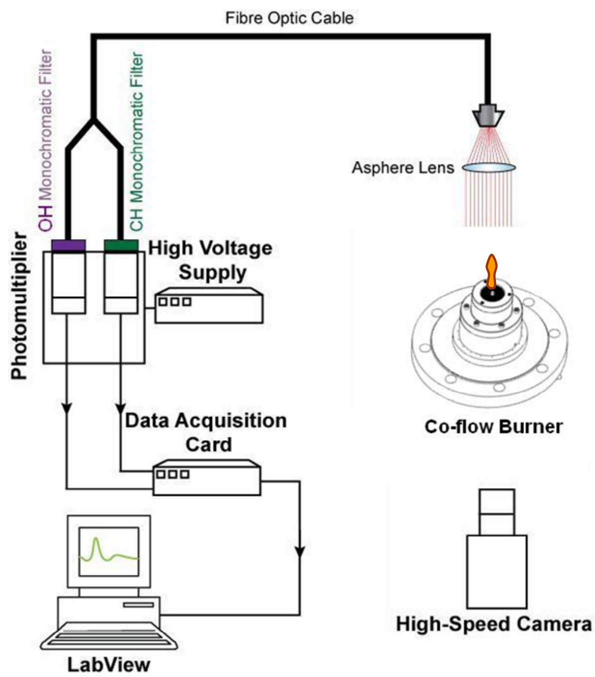

Fig. 2: Schematic of the experimental setup.

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III. RESULTS AND DISCUSSION

It is observed that in a methane flame with no co-flow, a regular self-exited flame oscillation (flicker) appears when the fuel flow rate is increased above a critical value (0.1 slpm). In this study methane flame at 0.3 slpm fuel flow rate at different co-flow air velocities are examined. A full cyclic sequence of high speed images of methane-air diffusion flames at 0.3 slpm (at nozzle mean velocity of 34 cm/s) fuel flow rate and without co-flow air is shown in **Fig. 3**-a. The time interval between two consecutive images is 5 ms. A regular and reproducible oscillation was observed in this flame due to the acceleration of hot gases and periodic interaction of flame/vortices in flame and surrounding air. The flame bulge is formed since the toroidal vortex below the flame bulge moves the flame surface radially outward while the one above the bulge drags the flame surface inward [8]. The outer vortices enhance the fuel-air mixing at some instant and consequently the local burning rate increases leading to necking and quenching of a portion of the flame tip. At zero co-flow the separated part of the flame presents almost a rounded bubble shape. However by start of blowing the co-flow air at 3 slpm (4.6 cm/s), it was observed that the regular flame necking and separation is happening faster and the flame shows a small stretch in the direction of blowing co-flow. The size of the separated tongue of flame decreased and the geometry of this part was changed to almost a lozenge shape (see **Fig. 3**-b). For higher flow rates of co-flow air at 5 slpm (7.7 cm/s), obvious flame bulge and necking starts to occur at higher position of the flame. As a result, a smaller chunk of flame is detaching from the main body (see **Fig. 3**-c). The flame tip of the methane flame at 7 slpm (10.7 cm/s) air was observed to flickering with about 1.5 mm rms (root mean square) without any separation from the flame tip (see **Fig. 3**-d). The most striking result to emerge from the data is that, when the co-flow air flow rate (velocity) is increased to 10 slpm (15.3 cm/s), the flame oscillation is totally suppressed (stabilised). The decrease in Kelvin-Helmholtz and buoyancy driven instabilities and also change in the initiation point of the toroidal vortices (instability initiation point) by the increase of co-flow air can be the main physical explanation behind this interesting phenomenon. It means the co-flow of air is able to push the outer toroidal vortices beyond the visible flame, then the buoyancy driven instability is only effective in the plume of hot gases above the visible flame. It has to be noted that a flame with a flame tip root mean square (rms) flicker less than 1% in the flame height has been considered as a stable flame [27].

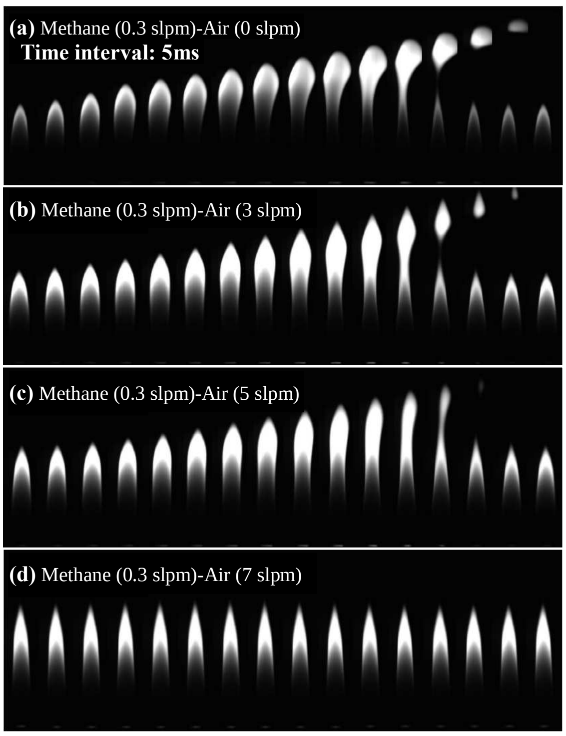

Fig. 3: Full cyclic sequences of high speed images of methane (0.3 slpm)-air diffusion flames at increasing co-flow air rates; (a) 0 slpm, (b) 3 slpm (c) 5 slpm and, (d) 7 slpm. The time interval between two consecutive images is 5 ms.

The co-flow air is found to strongly modify the oscillation magnitude and the oscillation wavelength of the flame. The magnitude of oscillation (L_f) in a flickering flame is defined by the distance between the flame lowest (H_f-*min*) and highest (H_f-*max*) heights. The oscillation wavelength (λ) is defined by the length of the separated part of the flame at the moment of separation (tip cutting). Also in a stabilised flame, the flame height and the maximum flame width are characterised by 'H_f' and 'b' respectively. The flame height is defined as a distance from the exit nozzle to the tip of visible flame. The definitions of flame scale parameters and the outer vortices locations are presented in **Fig. 4**.

The maximum oscillating flame height (H_f-*max*) of methane (0.3 slpm) flame at different fuel and air flow rates was found to increase with co-flow until the air flow rates of 5 slpm. In contrast the minimum oscillation flame height (H_f-*min*) was observed to increase continuously from its minimum (in the flame without co-flow) to its maximum (in the flame at stabilisation flow rate). In other word, the co-flow air is able to decrease the oscillation magnitude of flame. The average flame height (H_f-*ave*), however, shows an initial stretch in the flame height by increasing co-flow rate from zero after which at a certain flow rate the average flame height starts to be decreasing to its stabilised level (H_f). The initial stretch of flame by co-flow air can be attributed to the increase in shear layer momentum between co-flow flux and the visible flame outer boundaries. The height of stabilised flame, after suppression, was observed to remain almost constant despite further increase at air flow rate (see **Fig. 5**).

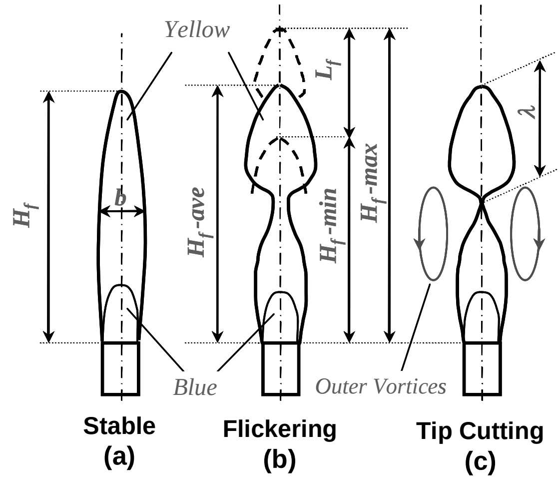

Fig. 4: Definitions of flame scale parameters in (a) Stable (Stabilised), (b) Tip flickering and (c) Tip cutting flames as well as the location of the outer vortices.

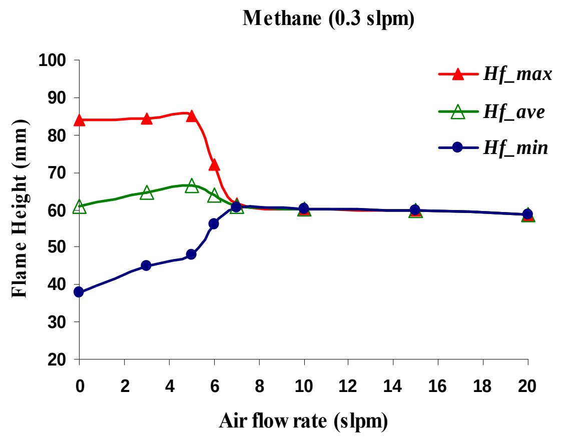

Fig. 5: Maximum (H_f-max), minimum (H_f-min) and average (H_f-ave) of the oscillating flame heights for a methane (0.3 slpm) flame at different air flow rates.

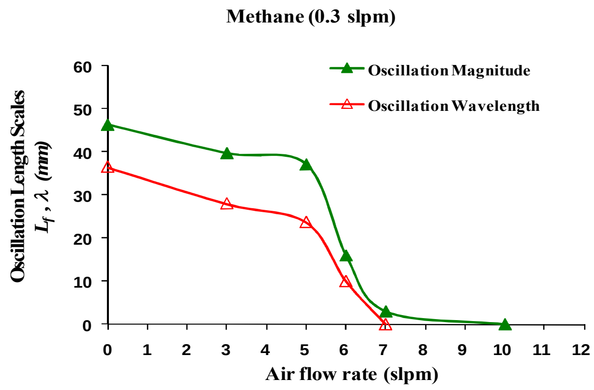

Fig. 6: Flame oscillating magnitude (L_f) and wavelength (λ) generally decrease towards zero by increase in co-flow air.

It is clear that, the outer vortices tend to move along the flame centreline symmetrically. At low air flow rates (exit velocities), the Froude number is decreased, the buoyant acceleration becomes increasingly significant, and toroidal vortices roll up periodically due to the Kelvin-Helmholtz instability. Subsequently, a larger chunk of the flame tip is periodically detached and burned out (bulk flickering flame [5]). It is apparent from the previous discussion on the change of oscillation flame heights by co-flow air that the oscillation magnitude (L_f) tends to decrease by increase at co-flow air up to the suppression flow rate. As noted earlier "L_f" in a flickering flame is defined by the distance between the flame lowest (H_f-*min*) and highest (H_f-*max*) heights. As shown in **Fig. 6**, the flame oscillation magnitude (L_f) at all fuel flow rates are gradually decreasing towards zero by increasing the co-flow air. The rates of decrease show a steeper gradient at co-flow rates close to the suppression flow rate. The results obtained from the analysis of flame high speed images also show that co-flow air is able to push the inception points of instabilities farther downstream and as a result the necking part of the flame, towards the flame tip. The oscillation wavelength (λ) also demonstrates a quick decrease from its maximum at no co-flow to zero at 7 slpm of air for methane flames at 0.3 slpm fuel flow rates respectively (see **Fig. 6**). The decrease in the length of the separated part of the flame at the moment of separation (λ) is also obvious from the high speed images of methane flame at increasing co-flow rate (see **Fig. 3**). The observation to emerge from the comparison between the trends of L_f and λ is that after a certain flow rate increase of air the tip cutting of flame stops but still flame tip flickering is exists (see **Fig. 6**). Some more co-flow of air is needed to bring the flame tip flickering to a suppressed (stabilised) flame mode.

This may be explained by the scaling of buoyancy with Froude number as the rollup vortices occur closer to the burner port. This increases the convective velocity at the base of the flame surface. The vortices then convect downstream and interact with hot plume downstream of the flame as well. By increase at the air flow rate the vortices convect downstream, they interact at higher heights of visible flame and also with hot plume downstream of the flame. As a result a smaller chunk of flame are detaching by vortices. Nevertheless, the rollup process is highly periodic and the flickering frequency obtained from the Fast Fourier Transform (FFT) of chemiluminescence history and also from the instantaneous flame high speed images shows a noticeable increase in peak flickering frequencies. By further increase at flow rate of air the outer vortices pushed farther downstream by co-flow resulting in lower interaction of flame vortices. It was observed from a certain air flow rate, no more flame tip cutting occurs and only a tip flickering flame is exist. The flickering was periodic and the flickering frequency is increased as well. Beyond certain co-flow air flow rate it was observed that there is no significant flame-vortex interaction, and the flame flickering is suppressed, the flame exhibits a totally steady (stabilised) behaviour. This is attributed to the fact that the rollup occurs far downstream of the flame region, and the vortex structures are relatively weak and interact only with the hot plume. The stabilised methane diffusion flame is convex in shape (has a bulbous in appearance) and its maximum width is wider than the burner nozzle exit diameter. Whilst adding more co-flow air to the stabilised flame, it was observed that the maximum width of the flame (*b*) at all fuel flow rates show a gradually decrease with linear trends. This is attributed to the effects of shear layer forces due to higher air velocity at the flame boundary. This brings more fresh air to the flame surface, resulting in more air diffusion to the reaction zone which increases the burning velocity as well.

The mean pixel intensity (MPI) and the corresponding Fast Fourier Transform (FFT) of the data for frequency measurement are obtained from the flame high speed images. **Fig. 7** shows the graphs of MPI and the frequency spectra of methane (0.3 slpm) flame at no co-flow air (a and b respectively), and 7 slpm of co-flow rate (c and d respectively). The MPI as an arbitrary unit (a.u.) was measured by image processing using MATLAB®. The maximum of this value corresponds to the maximum light emission of flame; similarly, a minimum refers to the minimum flame emission after burning out of the detached part. Decrease in the flame flicker and increase at the flickering frequency by co-flow air can be observed from these set of data. The Maximum of MPI (MPI_max) shows a decreasing trend by co-flow air, the minimum of MPI (MPI_min), however, shows a rapid increase. The differences between these two parameters (dI) are decreasing by co-flow air from its maximum at zero co-flow to its minimum at air suppression air flow rate (10 slpm) and onwards (see **Fig. 8**).

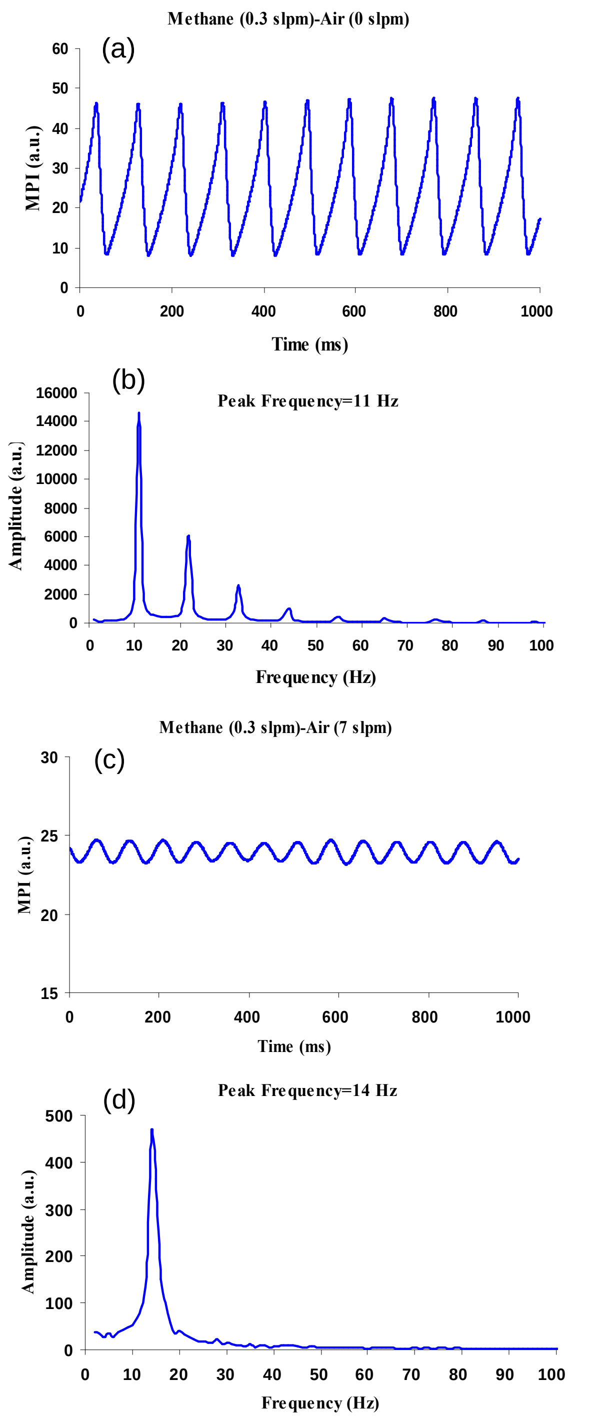

Fig. 7: Mean Pixel Intensity (MPI) and the corresponding flicker frequencies of methane (0.3 slpm) diffusion flame without co-flow air (a and b respectively) and at 7 slpm of air flow rate (c and d respectively).

The average of MPI values in a full data-range of high speed images coupling with the standard deviation (σ) of MPI are shown in **Fig. 9**. The standard deviation (σ) of MPI, measured from the intensity variation in the flame high speed images, tends to be another indicator of the flame fluctuations. The average of MPI, which is an indicator of the average flame luminosity, increases first by increasing the air flow rate, then decreases with the further increase in co-flow air. The standard deviation (σ) of MPI, however, in a whole cycle of the flame oscillation, decreases continuously with the increase of co-flow air towards zero. This may be considered as another indicator of flame flickering suppression by the co-flow air. It has to be noted that in our previous study [10]

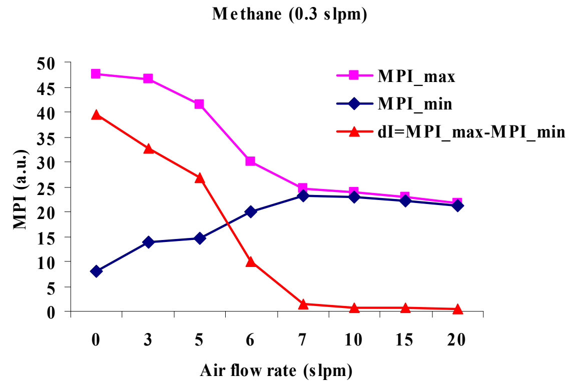

Fig 8: Maximum and minimum values of mean pixel intensity (MPI) from the flame high speed images in a whole cycle of the flame oscillation (methane (0.3 slpm) at different air flow rates). The subtraction of these two parameters (dI) decreases towards zero at the suppression air flow rate (10 slpm) and onwards.

the standard deviation (σ) of MPI was also found to be a general indicator of the trends of flame oscillation wavelength (λ) and magnitude (L_f), in the study of diffusion flames dynamics at elevated pressures.

Interestingly, it was observed that the co-flow air is able to increase linearly the peak flickering frequency of methane diffusion flame. In other word, when the air velocity and Froude number is increased, the flame flickering frequency increases accordingly. However, the qualitative nature of flame-vortex dynamics remains essentially the same. The frequency spectra obtained from FFT analysis of high speed imaging data and chemiluminescence setup are in a good agreement. **Fig. 10** presents the linear trend of the peak (dominant) flickering frequency of the methane flame with increase at air flow rate. The frequency amplitude, however, was observed to decrease fast with co-flow particularly near the air suppression flow rate (see **Fig. 10**).

The experimental results clearly demonstrate that the co-flow air has a strong effect on diffusion flame dynamics and stabilities. Since the evolution of a large scale structure is governed by Kelvin–Helmholtz instabilities and buoyant acceleration, the frequency, flame and vortex mutual interaction and energy distribution are controlled by the conditions of the air flow [28].

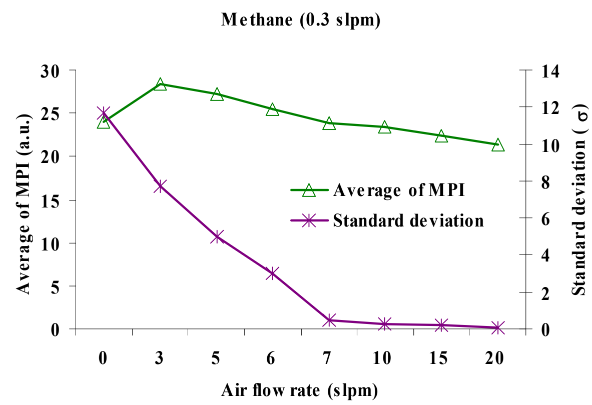

Fig. 9: Average of mean pixel intensity (MPI) of the flame high speed images in a whole cycle of flame oscillation and the standard deviation (σ) of MPI at different co-flow rates.

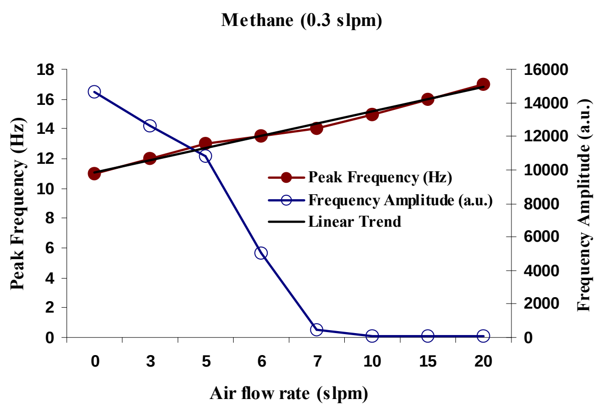

Fig. 10: Peak oscillation frequency increases linearly by co-flow air.

The frequency spectra of the flame from FFT analysis of mean pixel intensity (MPI) of the flame high-speed photographs and chemiluminescence results are greatly in agreement, however, the photomultipliers failed to measure the very low amplitude frequencies of the flames after suppression. The power spectra of the flame emissions, by collecting the radiation spectrum at OH* and CH* emission bands using interference filters, are shown in **Fig. 11**. The frequency spectra of methane (0.3 slpm) flame at zero co-flow (see **Fig. 11**-a) shows that the methane flame flicker with one dominant frequency and as many as six harmonic modes. The flame has a dominant (peak) frequency of 10.75 Hz and six noticeable harmonics peak frequencies at 21.5, 32, 42.75, 53.5, 64, 74.75 Hz, each with lower amplitude than the previous frequency. This methane flame at 3 slpm of co-flow (see **Fig. 11**-b) clearly exhibits an enhanced flickering with the higher peak frequency spectra of 12 Hz. By adding more co-flow (at 5 slpm) the peak frequency increased to 12.75 Hz (see **Fig. 11**-c). The co-flow rate of 7 slpm (see **Fig. 11**-d) was found to be almost a transient mode between flickering flames and stabilised one. Although the peak flickering frequency still is increasing at this flame but lower numbers of harmonics were noticeable. This is however, at some instances flame tend to show a decrease in flickering magnitude (L_f), maintaining the same flickering frequency.

In order to study the suppression co-flow rates at different fuel flow rates, four cases of methane flow rates (0.2, 0.25, 0.3 and 0.35 slpm) were examined. It is found that the higher flow rates of co-flow air are needed to suppress flickering of the flames at higher fuel flow rates. Therefore the ratio of the air velocity to the fuel velocity, γ, is a stability controlling parameter. From the frequency spectra, obtained by the chemiluminescence setup, the suppression flow rates of co-flow air for methane flames at fuel flow rates of 0.2, 0.25, 0.3 and 0.35 slpm were measured to be 5, 7, 10 and 13 slpm respectively. It has also been confirmed that, the flickering frequency is not a function of fuel flow rate but it is improving with co-flow air with a linear trend (see **Fig. 12**). It has to be noted that a flame with a flame tip rms (root mean square) flicker less than 1% in the flame height has been considered as a stable (stabilised) flame.

It has been observed that the flame dynamics and stability of co-flow diffusion flame are strongly affected by the co-flow air velocity. When the co-flow velocity has reached at certain value the buoyancy driven flame oscillation was completely suppressed. In four cases of methane flow rates at different co-flow air velocities the global flame shape, the instability initiation point and the frequency and magnitude of the flame oscillation have been characterised. In this study a comprehensive experimental data of methane diffusion flame at different flow conditions are compared. Since the evolution of a large scale structure is governed by Kelvin–Helmholtz instabilities and buoyant acceleration, the frequency, mutual interaction and energy distribution are controlled by the conditions of the flow.

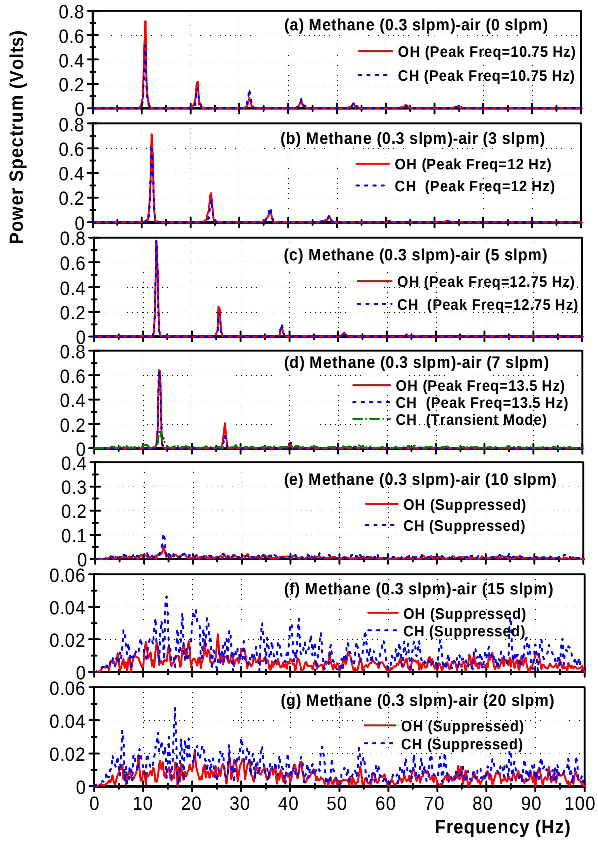

Fig. 11: Frequency spectra, obtained from chemiluminescence setup, for methane (0.3 slpm) diffusion flames with co-flow air at 0, 3, 5, 7, 10, 15 and 20 slpm flow rates (from (a) to (g) respectively). The increase at peak frequency by co-flow and suppression of oscillation at higher flow rates of air are evident from graphs.

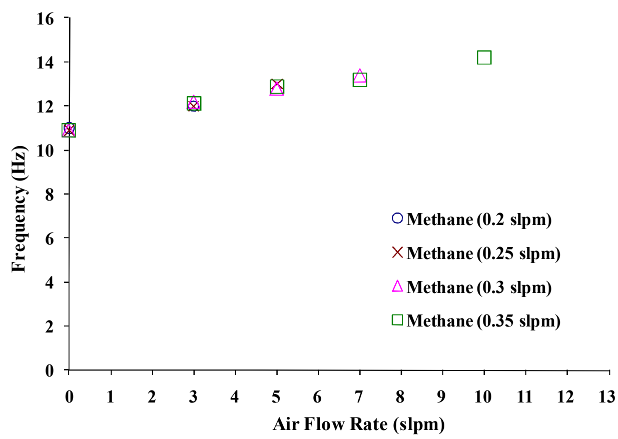

Fig. 12: The peak flickering frequencies of the methane flames at four fuel flow rates (0.2, 0.25, 0.3, 0.35 slpm), and at different air flow rates, obtained by photomultipliers setup. The graph confirms that the flame flickering frequency is not a function of fuel flow rate by improves linearly by the co-flow rate. Photomultipliers failed to measure the very low amplitude frequencies of the flames after the flickering suppression.

IV. CONCLUSION

Experiments were conducted on a co-flow diffusion flame burner to investigate the effects of co-flow air flow rate (velocity) on the flickering behaviour of methane-air diffusion flames. The buoyant acceleration of hot gases outside the diffusion flame surface can cause shear-layer rollup, leading to the formation of toroidal vortex rings, which then interact with the flame surface or the hot plume downstream of the flame, depending upon the value of the Froude and Reynolds number. The instability behaviour of the flame was observed to be strongly sensitive to the co-flow air velocity. The most striking observation is that, when the co-flow air flow rate (velocity) is increased to a certain level, the flame oscillation is totally suppressed (stabilised). It is found that the higher flow rates of co-flow air are needed to suppress flickering of the flames at higher fuel flow rates.

From the high speed images it can be seen that Kevin Helmholtz instability was initiated at the very beginning of the fuel nozzle when there is no co-flow air. With the increase of air co-flow flow rate, the instability initiation point was found to move downstream gradually as outer toroidal vortices interact only with hot plume of gases father downstream of visible flame. Obviously, the visible flame will become stable if the outer instability initiation point is well downstream of the visible flame position.

The average oscillating flame height behaviour was bimodal with an initial stretch by increasing co-flow then starts to be decreasing by adding more co-flow, up to its completely stabilised (suppressed) level. The average of mean pixel intensity (MPI), which is an indicator of the average flame luminosity, increases first with the co-flow air flow rate then decreases with the further increase of co-flow air flow rate. However, the standard deviation (σ) of MPI in a whole flame oscillation cycle decreases all the way towards zero with the increase of co-flow air as an indicator of the suppression of the flame oscillation.

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