Effect of low frequency burner vibrations on the characteristics of premixed flames

C. Kanthasamy, Vasudevan Raghavan* and K. Srinivasan

Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai, INDIA - 600036

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ABSTRACT

Mechanical vibrations in a burner are found to affect the characteristics of premixed flames. In the present experimental investigation, the effects of axial vibrations of a tubular burner on the characteristics of laminar premixed methane-air flames are investigated. The effect of the frequency and amplitude of the burner vibrations on the flame height oscillations are studied. At a low frequency of around 10 Hz, no effect of vibrations on flame characteristics is observed. At frequencies higher than 10 Hz, the amplitude of flame height oscillations is found to increase with increase in both frequency and amplitude of burner vibrations for the range of frequencies and amplitudes considered.

1. INTRODUCTION

Premixed flames are desired in several applications due to the reduced emissions. In a few applications such as in burners mounted in moving vehicles, such as pantry cars in trains, the burner system will be subjected to mechanical vibrations. Several researchers have studied acoustically perturbed jets [1, 2] and jet diffusion flames [3] to understand the unsteady reacting flows. Researchers also investigated the unsteady premixed flame dynamics in order to understand flow-combustion interactions and combustion instability problems observed in gas turbine combustors. In some cases the flow perturbations have been achieved by vibrating wire in the flow field [4–6], in other cases the perturbations are achieved by the acoustic excitations in the flow path [7–17]. These studies also investigated the heat release fluctuations, flame kinematics and flame deformation due to external perturbations. However, it is evident from the literature that flame oscillations in several of these studies are achieved primarily by acoustic excitations. The excitations are generally achieved by attaching a vibrating loudspeaker membrane in the flow path of the mixture. To the knowledge of the authors, the effect of mechanical burner (axial) vibrations on premixed flame characteristics is absent in the literature. This forms the motivation for this work. Some relevant studies on cold

*Corresponding author: E-mail: raghavan@iitm.ac.in;ksri@iitm.ac.in

jets, diffusion flames and premixed flames under acoustic/mechanical excitations are presented below.

Zaman *et al.* [1] studied the effect of acoustic excitations on the cold-flow jet characteristics using hotwire anemometry and concluded that the near-nozzle velocity field is significantly affected by the controlled acoustic excitations. Ni *et al.* [2] reported a review of possible usage of pulsations and oscillations (of baffled tubes or columns) in the flow-field as an effective tool for the enhancement of mixing and transport properties. Mohammad *et al.* [3] studied acoustically excited laminar diffusion flames both experimentally and numerically and reported that the oscillations induced in laminar jet flames modify the flame behavior such that the combustion process is in between laminar and turbulent. It was also showed that there exists a phase difference between the input oscillations and the corresponding response in the flame oscillations.

Markstein [4] qualitatively studied the effect of flow disturbances on the flame characteristics. The effects of both acoustic and structural disturbances on flame shapes were studied. A vibrating wire was kept in flame area and the changes in the flame front shapes were studied in detail using spark shadowgraph and schlieren images. Peterson and Emmons [5] systematically studied the stability of laminar premixed flames stabilized on a wire. The importance of Markstein curvature parameter on the stability of flames was emphasized. The velocity fluctuations observed in laminar flames were termed flame induced turbulence. Kornilov *et al.* [6] compared the premixed flame response to the acoustic oscillations and the flame response to the transverse flame holder vibration. They concluded that the cold flow field remains unchanged when the transverse vibration is introduced in the flame holder ring, and the flame responds to the vibrations akin to acoustic excitations. However, the vibration amplitudes considered were low (0.25 mm), and axial vibration of burner was not considered in their study.

Candel [7] provided a brief review of progress in combustion dynamics with emphasis on premixed flames. Baillot *et al.* [8] experimentally studied the kinematics and deformation characteristics of acoustically excited methane-air premixed flames. They reported that distortion and periodic oscillations are observed in the steady conical flame. They also showed that the flame looked like a thick front to the naked eye, termed as flame brush, in the cases where the acoustic input frequencies are less than a critical frequency of 200 Hz, above which the flame becomes insensitive to the input excitations. Furthermore, they showed that the flame oscillates with a frequency same as that of input excitations and the average of oscillating flame area is same as the steady flame area. According to this paper the flame tip portion was found to be more sensitive to the excitations when compared to other portions. In a similar study, Bourehla *et al.* [9] studied acoustically excited flames with excitation frequencies in the range of 20–1000 Hz and perturbation intensities in the range of 0–150%. In addition to the primary flame oscillations taking place at the burner input frequency, they also reported sub-harmonic flame oscillations in some ranges of input frequencies, which respond with half the input frequency. According to the authors, the flame behaved as a semi-autonomous system, where its responses were driven not only by input excitations but also by intrinsic nature of the system. They also confirmed the existence of the critical frequency as discussed in Baillot *et al.* [8].

Shreekrishna *et al*. [10] studied the heat release response of premixed flame subjected to equivalence ratio perturbations. They showed that the response of rich flames to equivalence ratio oscillations is fundamentally different from that of lean flames as the heat release rate depends on the equivalence ratio in the case of lean flames while the heat release rate is independent of equivalence ratio for rich flames. This was explained by the heat release curve plotted as a function of equivalence ratio. Lieuwen [11] investigated the kinematic response of a premixed flame under harmonic velocity oscillations and reported that the nonlinearity in response increases with an increase in Strouhal number.

Ducruix *et al.* [12] experimentally determined the transfer function of the response of a premixed flame to the incident acoustic perturbations. They concluded that the wrinkled flames are 180 degrees out of phase with the input disturbances. Karimi *et al.* [13] studied the dynamic response of acoustically exited premixed flames. From their experiments they concluded that the flame response is linear for low amplitudes (15% of mean velocity) however, the flame shows strong nonlinearity when the excitation amplitude reaches higher values. They also showed that the flame area perturbation does not progress up to the tip of the flame in the case of nonlinear response. Durox *et al.* [14] investigated the transfer function for the acoustically excited flames of different geometries such as 'V' and 'M' type flames and concluded about different stability regimes of flames of different geometries and also the effect of excitation amplitude on the response of the flames. Schuller *et al.* [15] proposed a unified model for the transfer function of conical and 'V' flames. They concluded that the flame response is explicitly dependent on the flame angle and they simplified the model for different angles of the flame. According to their model the conical flames act analogous to a low pass filter.

Rayleigh criterion and acoustic energy balance were investigated by Durox *et al.* [16] for acoustically excited open flames. Both 'V' and 'M' type flames were studied. The phase difference between pressure fluctuations and heat release fluctuations was studied in detail to conclude that in these two types of flames, pressure perturbations and the heat release rate perturbations are nearly in phase. Coats *et al*. [17] studied the experimental excitation of thermoacoustic oscillations of small premixed flames, which are typically found in multi-port domestic burners. The flame response and the heat release fluctuations were visualized and evaluated. They showed that the Strouhal number alone cannot characterize the fluctuations in small laminar flames but the equivalence ratio and flame angle also affects the characteristics of the flame fluctuations. The transfer function was measured and compared with the predictions of various analytical formulations and a new model of the flame oscillation was proposed. Weinberg [18] presented the relationship between the intensity of shadowgraph and the flame structure. He concluded that the maximum intensity lines in the shadowgraph are the locations where the temperature is 1.14 times the initial temperature.

Recently, Kanthasamy *et al*. [19] have studied the effects of axial mechanical vibrations of a tubular burner on the burning characteristic of a laminar jet diffusion flames. This present study is performed on the premixed flames almost in a similar manner to the diffusion flame study reported in [19]. The amplitudes of flame height oscillations of premixed flames are found to be smaller when compared to that of diffusion flames as the premixed flame is already fuel lean. In contrast to the diffusion flame oscillation spectra, the secondary harmonics were absent in the case of premixed flame height oscillation spectra even at higher frequencies (~30 Hz) of burner vibration. Also, there is no significant phase lag between burner vibration and flame height oscillations found in the premixed flames as the convection time scales ($\sim 5.5 \times 10^{-3}$s) are much lesser than the vibration time scales (1/input frequency) for all the frequencies considered in this study.

As evident in the literature review above, there is hardly any study on the effect of axial mechanical vibrations in premixed flame burners. With this motivation, experiments have been designed to impart harmonic mechanical oscillations to laminar premixed flame burners. Overall flow features such as jet entrainment, flame structure and shape are expected to be modified as a result of mechanical excitations to the burner. The flame angle variations and changes in pre-heat zones due to burner oscillations are studied using shadowgraph images.

2. EXPERIMENTAL SETUP AND PROCEDURE

2.1. Experimental setup

The schematic of the experimental setup is shown in Fig. 1(a). A tubular brass burner [Fig. 1(b)] of 4 mm internal diameter with 1 mm wall thickness is fitted to a settling chamber. The burner is mounted over a permanent magnetic vibration exciter (B&K 4808). A signal generator (Tektronix AFG 320) is used to generate the desired sinusoidal signals. The generated signals are passed through a power amplifier (B&K 2719) and then sent to the exciter. An IEPE accelerometer (B&K; Model 4513-001) of sensitivity 100 mV/g is used to calibrate the displacement amplitude of the burner-mount vibrations as a function of input voltage amplitude. Methane and air are supplied to the burner through pre-calibrated mass flow controllers (Aalborg; Model GFC17-07 & GFC37-11). The accuracy of mass flow rate measured is within ±1.5% and repeatability is ±0.5%.

To visualize the flame structure, a shadowgraph arrangement is set up. A projector lamp is used as light source, with a translucent paper as a cover to diffuse the light for required intensity. The light beam is then passed through a slit to produce a point source. A biconvex lens is used as collimator. The collimated light beam is captured after the light ray passes through the flame region, using a high speed camera from a suitable position. Hotwire anemometry is performed to investigate the cold flow entrainment spectra near the burner exit. A two-dimensional, constant temperature hotwire anemometer (DANTEC Mini CTA 54T30) is used with miniature type probe (wire diameter 5 µm).

2.2. Experimental procedure

Low frequency vibrations in the range of 10 Hz – 30 Hz, with amplitudes in the range of 0.25 mm - 1 mm are imparted to the burner in order to excite the flames. Due to the power restrictions of the exciter and the total weight of the burner and mounting, the displacement amplitude of burner vibration is limited to 1 mm. Typical burner oscillation spectra are shown in Fig. 2 for various frequencies with constant amplitude of 1 mm. These spectra are derived from the signals obtained from the accelerometer mounted on the burner base and show that the oscillations in acceleration

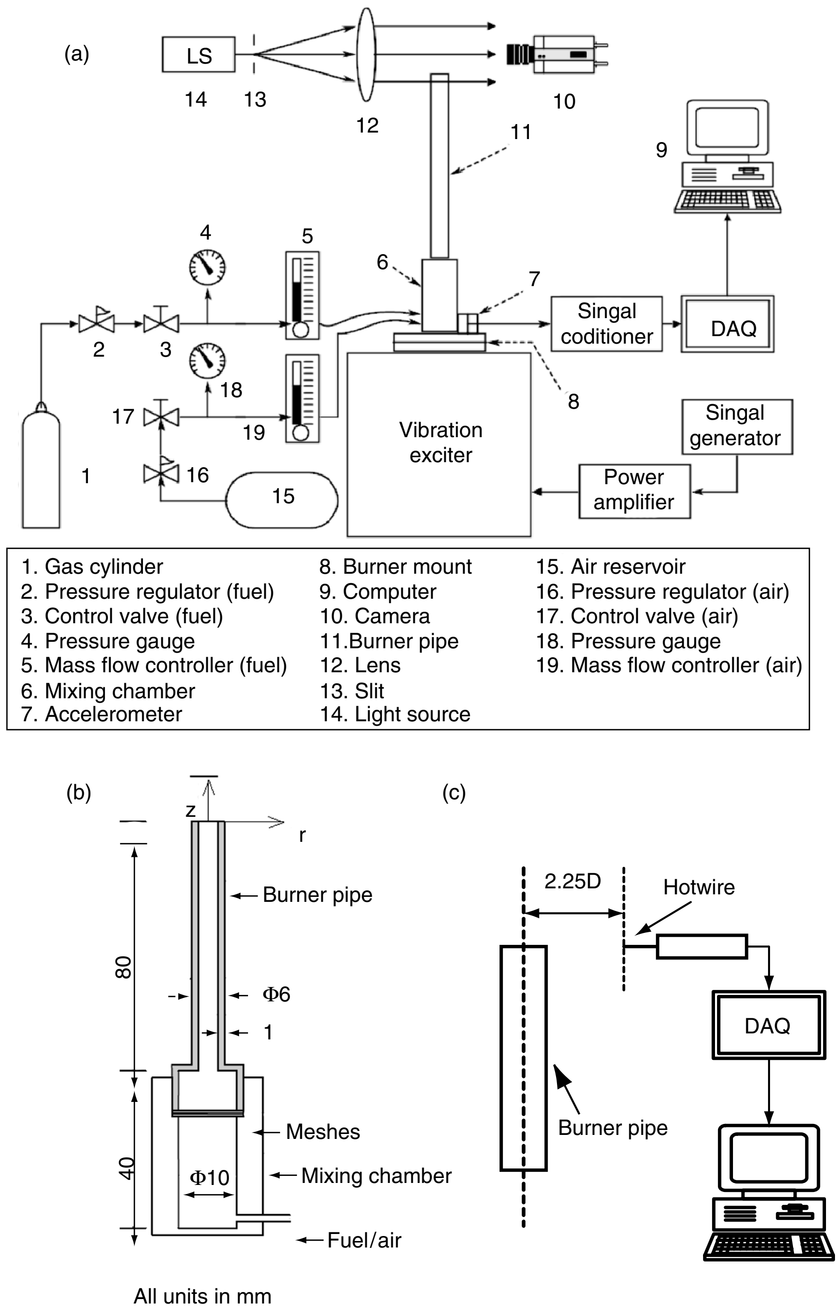

Figure 1: Schematic of (a) the experimental setup (b) the burner and (c) hotwire location.

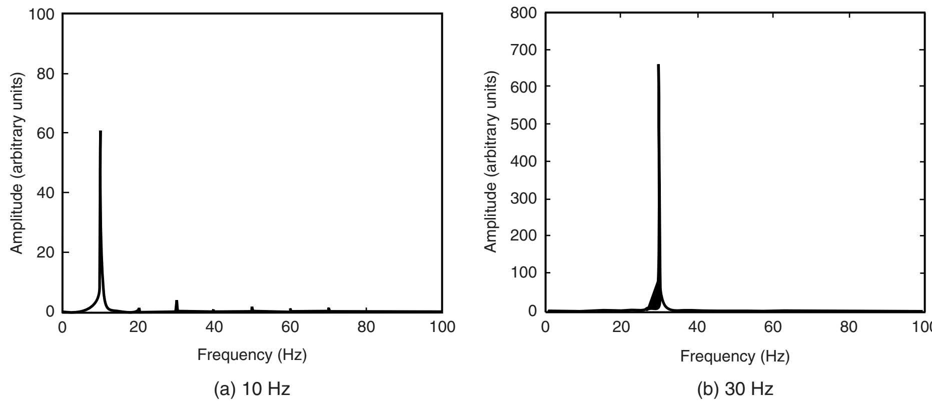

Figure 2: Acceleration spectra for exciter vibrations for 1 mm amplitude.

Table 1: Experimental conditions

Experimental conditions	
Gas mixture	Methane - air
Methane flow rate	0.89×10^{-6} kg/s
Air flow rate	11.13×10^{-6} kg/s
Equivalence ratio	0.76
Burner diameter	4 mm
Gage pressure	0.4 bar

predominantly follow the input frequency. The fuel is ignited near the burner exit after the required methane flow rate is set on the mass flow controller and required air flow rate is supplied to form the premixed flame. The flow Reynolds number is approximately 230. The required frequency and amplitude of vibration are set in the signal generator and the exciter is switched on to impart the vibrations to the burner.

After the burner is set to steady vibrations, direct flame videos are recorded using a high speed camera. The frame rate is set as 300 fps. Images are extracted from the high-speed video. The acquired images are processed using image processing software - ImageJ [22]. The images are processed in MATLAB to estimate the flame extent in the vertical direction. The images are acquired for 2 s (600 frames) and are processed for each case to encompass a minimum of 20 cycles. The time interval between the frames is 3.33 ms.

3. RESULTS AND DISCUSSION

3.1. Fluctuations in air entrainment

Hotwire anemometry is performed near the burner exit at the burner exit plane ($z = 0$) at a radial location of $r = 2.25D$ from the axis of the burner as shown in Fig. 1(c). In order to avoid placing the hotwire in the vicinity of the flame, these entrainment velocity measurements are performed only with cold air jet. In these measurements, the

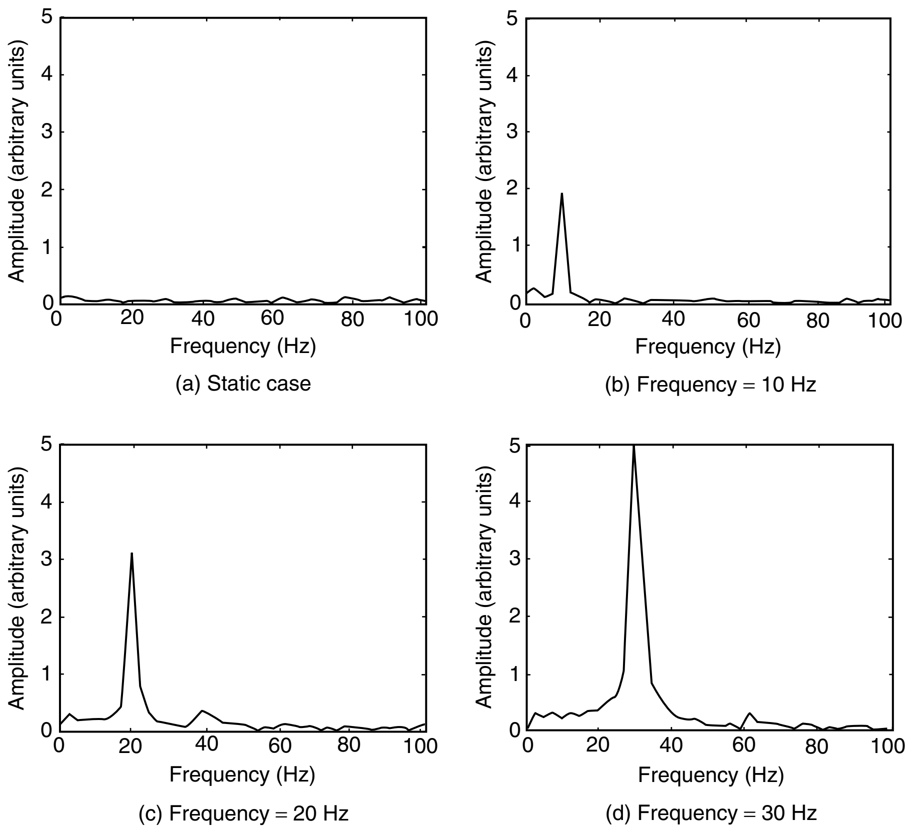

Figure 3: Spectra of velocity signals for (a) the static case and (b, c, d) for various frequencies of vibrations with 1 mm amplitude.

Reynolds number of the air jet is matched with that of the actual methane-air mixture jet. The data is acquired at a sampling frequency of 10 kHz, and the FFT analysis is performed using MATLAB. Figure 3 shows the spectra of the entrainment velocity signals for jets evolving from burner vibrated with 1 mm amplitude and various frequencies. The static (non-vibrating) case is also shown in Fig. 3(a). This confirms the fact that entrainment velocity closely follows the input vibration in the burner. Similar spectra are obtained for other amplitudes also, and it is observed in all the cases that the input vibration frequency dominates the velocity spectra.

3.2. Flame oscillations

A premixed flame with an equivalence ratio of 0.76 is considered. The flame oscillates as the vibration is imparted to the burner. As the burner is vibrated, a thick flame brush is visible to the naked eye, similar to those seen in turbulent premixed flames. Figure 4 shows the naked eye view of static and vibrated (with frequency 30 Hz and amplitude

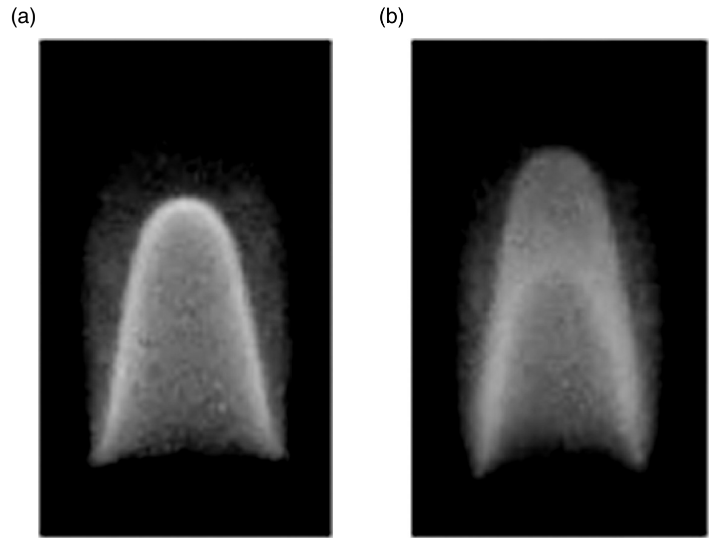

Figure 4: Naked eye view of typical (a) static and (b) vibrated flame.

1 mm) flames. The flame brush looks thicker than that is reported in Baillot *et al.* [8]. The thickness of the brush (at $r = 0$) shown in Fig. 4 includes the imposed oscillations of burner also, making the thickness of the flame brush approximately 2 mm (after removing the vibration amplitude (1 + 1 mm)). It is clear that the flame tip is affected more by vibrations than the other parts of the flame. The flame observed in the present study is not a classical conical flame. This is a strained button type flame as observed by Günther and Janisch [20]. The behavior of this type of flame from small burners is quite different from a conical flame. The laminar speed of this flame cannot be directly calculated from the flame geometry as it is done in the case of conical flames.

Figure 5 shows the instantaneous shadowgraphs of flames from vibrating burner for one typical vibration cycle, in comparison with that of flame on static burner for the vibrating amplitude of 1 mm and frequencies of 10 Hz. A lean mixture with equivalence ratio of 0.76 is considered. In the shadowgraph images, an inner cone region anchored to the burner lip is shown by high intensity white lines below which dark zone is present. This is the preheat zone. In the entraining atmospheric air side, there is a shadow line, which is represented by outer dark lines those start along the sides of the burner lip. The movement of the preheat zone is proportional to the movement of flame front. It is clear that the flame does not respond to the input vibrations when the frequency of vibration is as low as 10 Hz. The flame oscillates along with the burner lip as a rigid body. The preheat region height in these shadowgraphs at any point in time is almost comparable to the static case and there is no fluidic or independent flapping of flame front with respect to the burner exit. This is because the flame is very lean itself, and due to low frequency vibrations, the burner rim velocity is not sufficiently high to perturb the

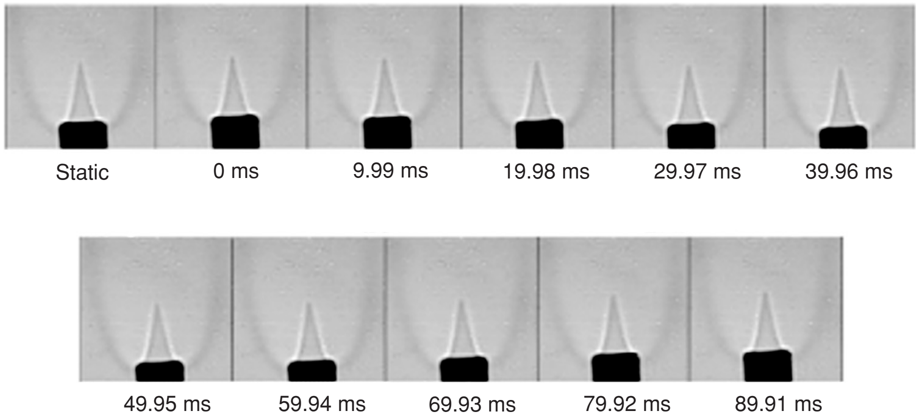

Figure 5: Instantaneous shadowgraphs of flames from static burner and burner vibrating with frequency 10 Hz and amplitude 1 mm ($\Phi = 0.76$).

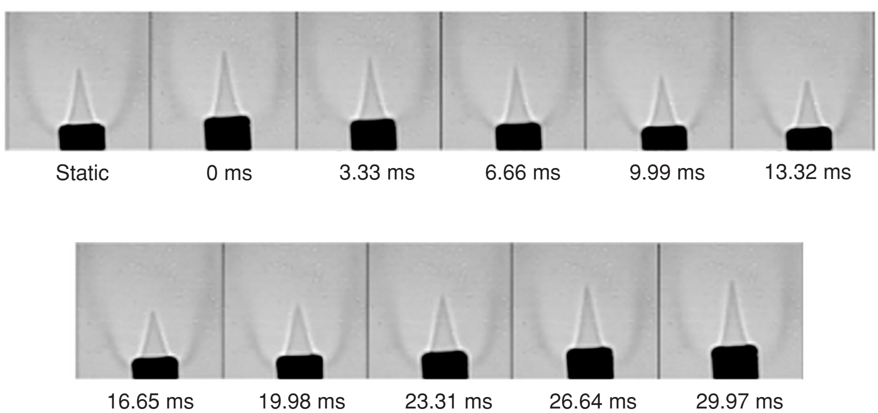

Figure 6: Instantaneous shadowgraphs of flames from static burner and burner vibrating with frequency 30 Hz and amplitude 1 mm ($\Phi = 0.76$).

entrainment and to achieve the significant equivalence ratio perturbations that form one of the main drivers in premixed flame dynamics.

Figure 6 shows the instantaneous shadowgraphs of the flame from the burner vibrating at a higher frequency of 30 Hz and with the same amplitude of 1 mm. At this higher frequency, the shadowgraphs show that there is significant flapping of the preheat zone with respect to the burner exit. As the burner moves downward [Fig. 6 (0-13.32 ms)], the burner movement and the entraining air are in opposite directions and this results in a higher relative entrainment velocity. As a result of this enhanced entrainment the reactant mixture becomes relatively leaner. This causes a reduction in the laminar flame velocity, since for the same unburned gas velocity, the preheat zone becomes shorter as clearly shown in Fig. 6 (0–13.32 ms). As the burner moves upward [Fig. 6 (16.65–29.97 ms)], the burner motion and the main component of the entraining air are in same direction. This causes a reduction in the entrainment velocity and the mixture becomes relatively rich. However, the overall equivalence ratio is less than unity. The preheat zone grows taller as seen in Fig. 6 (16.65–29.97 ms) because of increase in the laminar flame velocity.

The heat of reaction is very much sensitive to the changes in the equivalence ratios for lean mixtures. For near-stoichiometric or rich mixtures, the heat of reaction is almost insensitive to the changes in the equivalence ratio [10]. In Fig. 6, as the burner moves downward, the shadowgraph of the flame (preheat zone) becomes shorter. The heat of reaction decreases because of the possible condition that the reactant mixture becomes leaner. This is also shown from the movement of air-side shadow line, which moves closer to the flame as the burner moves downward; as the heat release rate decreases, the heat transfer rate towards the air-side also decreases, which eventually makes the shadow line to move closer to the flame/burner-rim. As the burner moves upward, this line moves away from the burner rim due to increase in the length of preheat zone (Fig. 6) and possible higher heat release. This is also because, in this part of the vibration cycle, the relative entrainment velocity decreases, and the mixture becomes relatively richer. Further experimental investigations, where measurements of velocity fields are to be carried out, are required to understand these phenomena. This movement of shadow line was quite opposite in the diffusion flame studies [19].

Figure 7 shows the instantaneous shadowgraphs for the same vibration frequency and amplitude (30 Hz, 1 mm), however for a slightly richer reactant mixture with an equivalence ratio of 0.91. From Fig. 7, it is clear that the amplitude of flame height oscillations is higher in this case when compared to the previous leaner case.

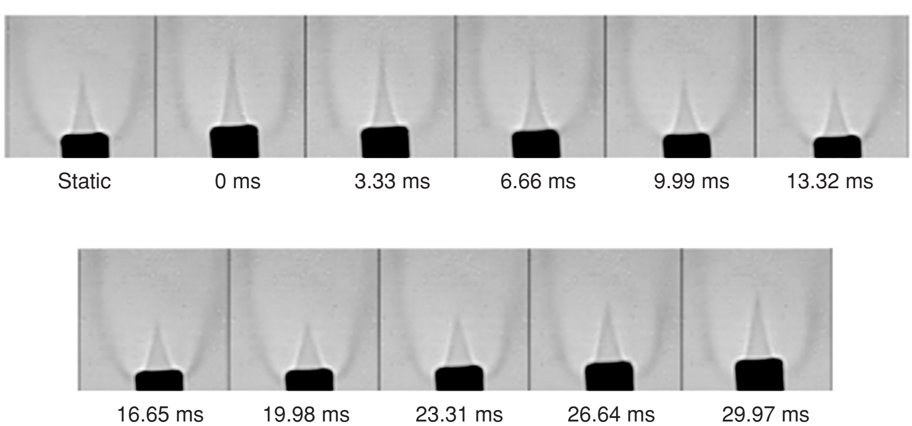

Figure 7: Instantaneous shadowgraphs of flames from static burner and burner vibrating with frequency 30 Hz and amplitude 1 mm ($\Phi = 0.91$).

The tip part of the inner flame zone is most affected due to the burner vibrations (Fig. 4). The oscillation of the instantaneous location of flame tip is an important parameter in the study of flame deformations due to vibrations. The instantaneous axial locations of the flame tip are measured from instantaneous shadowgraph images of the flame. Figure 8 shows the amplitude of flame height oscillations (A_f) for various frequencies and amplitudes of the burner vibrations. The amplitude of the flame-tip oscillations is almost zero for the vibration frequency of 10 Hz, irrespective of the vibration amplitude as discussed earlier with respect to Fig. 5, and hence is not shown here. At higher burner vibration frequencies, as the vibration amplitude increases, the flame oscillation amplitude also increases. This is because the amplitude of entrainment perturbations mainly depends on the burner rim velocity. The burner rim velocity increases with increase in frequency or amplitude of vibration. However, it is seen that the amplitude of flame-tip oscillations is less than the burner vibration amplitude in almost all the cases. At the vibration frequency of 30 Hz, until the amplitude is less than approximately 0.75 mm, the flame-tip oscillation amplitude is seen to be higher than the vibration amplitude. Baillot *et al.* [8] reported the importance of detailed study of flame height oscillations in deriving the tip speed of the flame front.

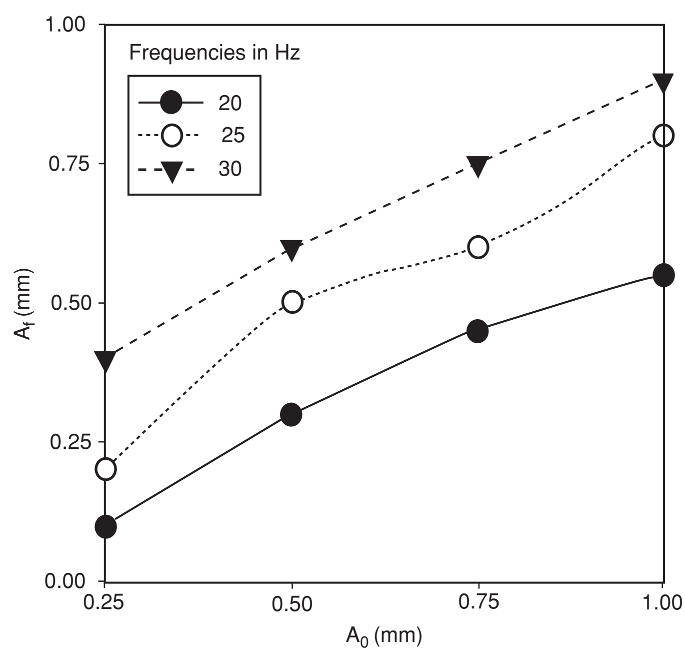

Figure 8: Amplitude of flame height oscillations and mean tip speed of the flame front for various frequencies and amplitudes.

Figure 9 shows the amplitude of flame height oscillations with respect to burner exit for two different equivalence ratios. The input frequency of 30 Hz and amplitude of 1 mm case are considered. As the mixture become richer the flame becomes more responsive to the burner vibrations. For the equivalence ratio of 0.91, it is clear that the value of A_f is always higher than the value of A_0 for all the cases because the richer flames are more sensitive to the fluctuations in the flow field near the burner exit. This is because the entrainment rate depends on the density ratio of the gases. The entrainment is high in lighter jets than in the heavier jets [21]. The amplitudes of flame height oscillations are however very low compared to those of diffusion flames reported in [19].

Figure 10 shows the spectra of flame height oscillations for the highest burner vibration frequency and amplitude. It is clear that the flame height oscillations follow the input frequency predominantly. There are no harmonics found in these oscillations for the frequencies considered in this study.

Figure 11 shows the time history of flame height oscillation with burner vibration for a vibration frequency of 30 Hz and amplitude 1 mm. It is clear from Fig. 11 that the flame height oscillations are almost in phase with burner vibrations even for the highest frequency and amplitude considered in this study. This is exactly an opposite trend to the characteristics of jet diffusion flames at the same vibration condition [19], where it is seen that the flame height oscillations were out of phase to the burner vibrations. This is due to the dependence on the entraining air in the case of a jet diffusion flame.

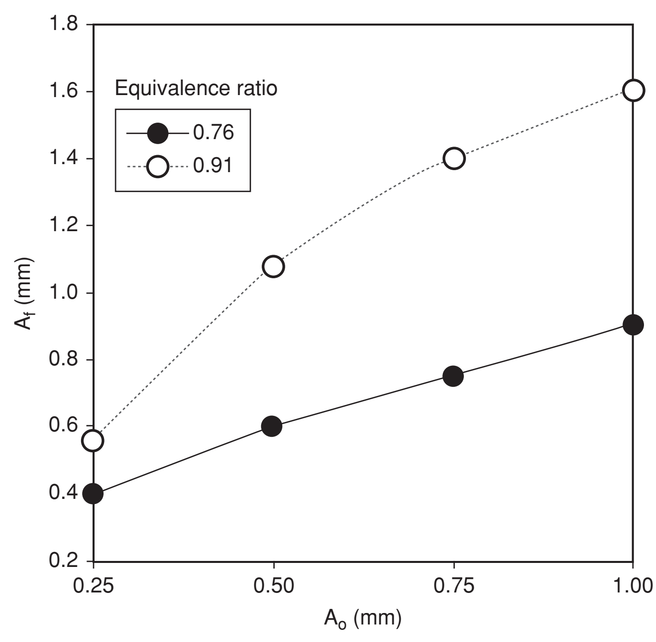

Figure 9: Amplitude of flame height oscillations for various equivalence ratios, at a frequency of 30 Hz.

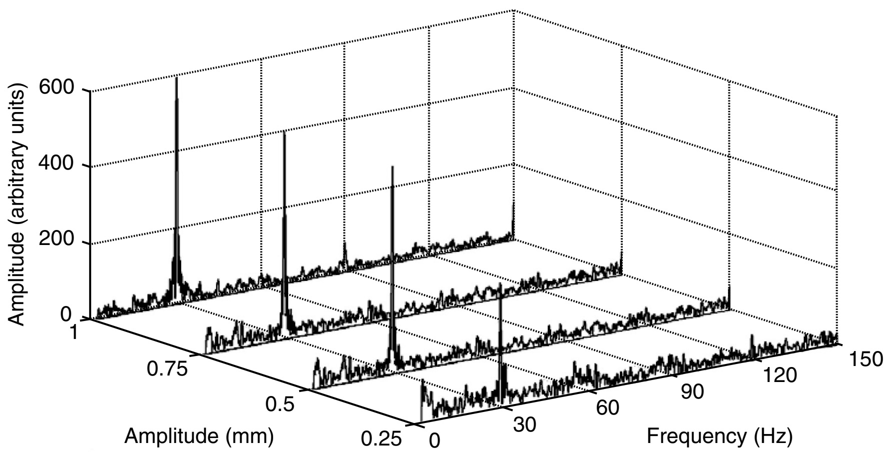

Figure 10: Spectra of flame height oscillations for 1 mm amplitude.

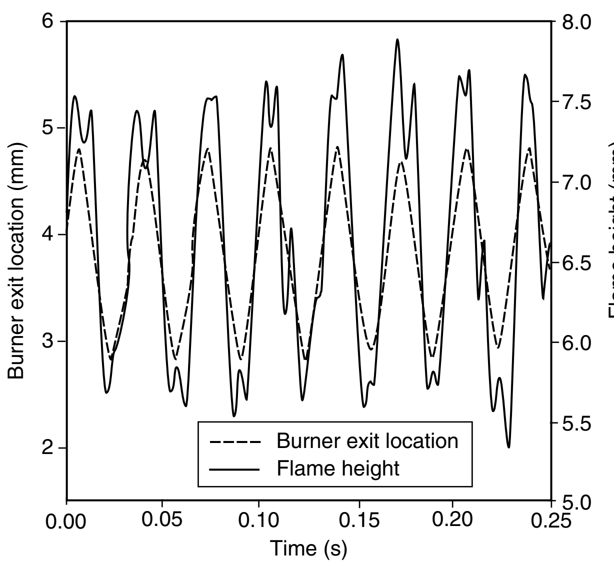

Figure 11: Time history of flame height oscillation and burner vibration for 30 Hz frequency and 1 mm amplitude.

4. CONCLUSIONS

Burner vibrations are found to significantly affect the characteristics of the premixed flames. High speed instantaneous shadowgraph images of premixed flames anchored to vibrating burners are examined in detail. It is observed that the tip of the flame responds more to the input burner vibrations than the other portions of the premixed flame front.

The oscillations of the flame height are found to follow the input frequencies predominantly. The amplitude of flame height oscillation is found to increase with increase in both the frequency and the amplitude of burner vibrations. At lower frequencies (as low as 10 Hz), the flame moves along with the burner as though it is a rigid body with no change in flame shape and structure with respect to the burner exit. However, as the input frequency increases, the flame oscillates with respect to the burner exit also, in addition to the input oscillation. This is because of the changes in entrainment due to the burner vibrations. These changes in entrainment due to burner vibrations are confirmed by hotwire anemometry near the lip of the burner.

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