Experimental Investigation on the Flame Wrinkle Fluctuation under External Acoustic Excitation

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1 Abstract

The flame front wrinkle response of laminar premixed conical flames to acoustic excitation is investigated experimentally with a focus on the fluctuation amplitude along the downstream and the response frequency under various harmonically forced frequencies and sound pressure. By using a high-speed colour camera and a microphone, the acoustic data and the induced flame dynamic characteristics are measured simultaneously. It has been observed that the higher sound pressure induces more severe flame oscillation which is more evident at higher harmonic frequency. The fluctuation amplitude grows linearly along the flame length and both the frequency and sound pressure has a positive effect on the growth rate. The frequency of the flame boundary displacement at any chosen height of the flame correlates well with the excitation frequency. The domain frequency peak becomes more apparent with the increase of sound pressure in four frequency groups and under the high sound pressure the sub-harmonic frequencies also can be noticed. Under the strongly perturbed condition, the flame wrinkle is observed to have nonlinear coupling with flame lift-off oscillation

2 Introduction

Flame instability is a fundamental topic of interests in combustion study and it has been investigated for many years. Most of the random perturbation are undesirable, such as flame lift-off [1] and thermoacoustic instabilities [2]. However, well-controlled acoustic excitation can be applied to control the soot level, that may help to achieve the target of emission control [3]. Unfortunately, the physics behind the instability response is still not clear due to the complexity of the instantaneous interaction between the self-induced flame dynamics and acoustic excitation [4]. The complexity further increases when the vortex interaction [5] and various excitation mechanisms involved in the phenomenon.

The flame front wrinkle is one of the most significant feature under acoustic excitation, which is associated with heat release [6]. Advanced visualization approaches, like the schlieren and PIV, and numerical simulation have been applied to analyse the fluctuation characteristics. The flame instability

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induced by fuel flow oscillation has been studied theoretically and numerically by many researchers [7–9]. However, few of them discussed the flame dynamics in response to external excitation. The objective of this research is to understand the wrinkle characteristics of laminar premixed conical flame in response to the various sound intensities under harmonically forced frequencies in a one end open tube.

3 Experiment Setup and Methodology

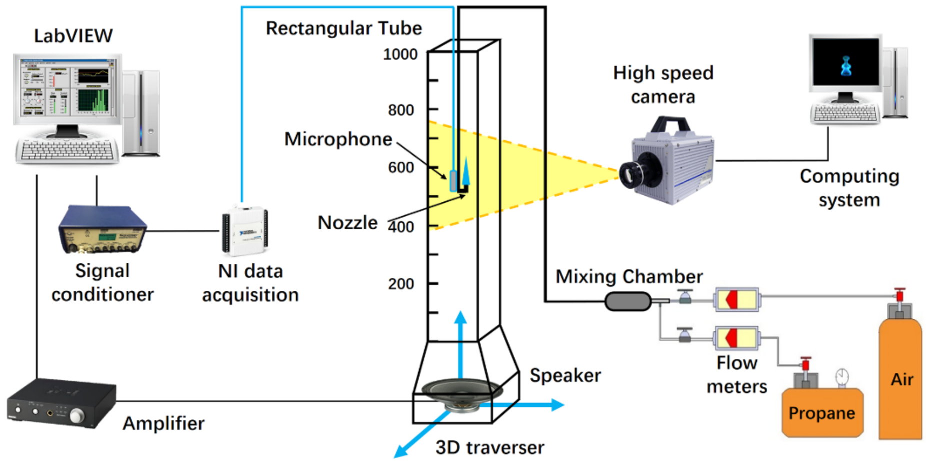


Figure 1. The schematic layout of the experimental apparatus setup

Fig. 1 shows the experimental setup which includes a burner system, an image record system, a sound acquisition system and an acoustic generator. In the burner system, the gaseous fuel and air are supplied from a propane cylinder and air compressor. The flow rate is controlled by the rotameters. The fuel and air are connected with a mixing chamber to produce a premixed flame at the equivalence ratio of 1.4 (C_3H_8, 0.12 L/min; Air 2.046 L/min). The acoustic generator is placed at the bottom end of the tube and fixed on a computer controlled 3-D traverse system. The frequency of the acoustic generating system was controlled by LabVIEW and the output voltage (V) of the amplifier can be adjusted. The reading of the sound pressure was collected by a microphone which is mounted at the nozzle and recorded by the National Instruments DAQ card. An optical setup consists of a Photron-SA4 high speed colour camera with Sigma zoom 24-70 mm lens and the computer control and recording system. According to the experimental measurement with excitation frequency from 10 Hz to 600 Hz and the sound pressure standing wave recorded in Figure 2. The actual harmonic excitation frequency is 90 Hz, 200 Hz, 380 Hz and 500 Hz, those four frequencies will be considered in the following study.

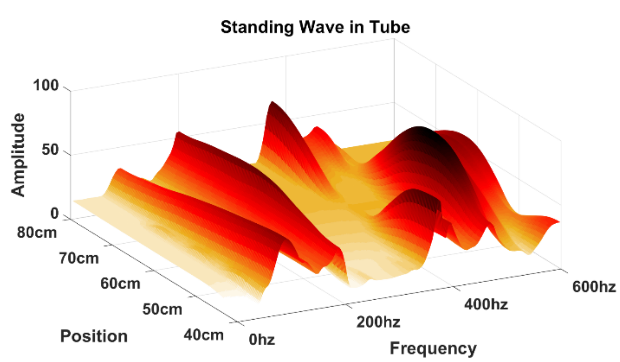
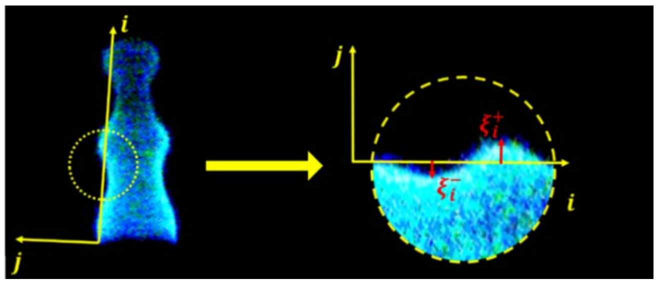


Figure 2. the experimental measurement of pressure respond to position and frequency

The flame has been imaged under these four forcing frequencies under the measured sound pressure of 10 Pa, 25 Pa and 40 Pa at the flame nozzle position. To ensure the accuracy and generalization, 2000 images have been recorded per second at a shutter speed of 1/2000s for each condition. The data have been quantitatively analysed by MatLab image processing.

4 Results and analysis



(a) (b)

Figure 3. Schematic of the flame front configuration (a) and the wrinkle coordinates (b)

Axisymmetric premixed laminar conical flames submitted to harmonically external acoustic excitation are investigated in this study. The geometry is a 2D flame captured by high-speed camera with the selected enhancement technique by image processing shown in Figure 3 (a). The coordinate system in Figure 3 (b) is chose to be in the alignment with the laminar flame at stable condition as the method introduced by Shim and Lieuwen [8]. The i-axis is tangential to the stable flame edge and the j-axis is perpendicular to it. The ξ_i^+ and ξ_i^- represent the displacement of perturbation of the flame front to the steady position at the location of i-axis and the $\pm$ symbol indicates the direction. As the vertical axial symmetry structure of the flame, only one side will be calculated in the following analysis.

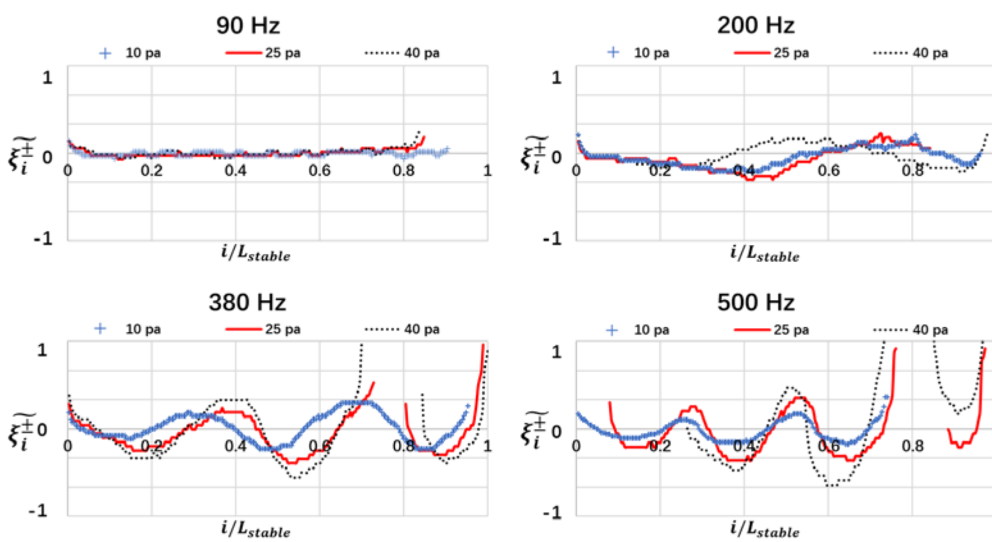


Figure 4. The instantaneous fluctuation magnitude of the sample flame front from each excitation group along the normalized i-axis

Figure 4 plots the Instantaneous flame wrinkle spatial variation along the i/L_{stable} axis at four forcing condition with sound pressure 10 Pa, 25 Pa and 40 Pa, where the L_{stable} is the unperturbed flame length.

A clear expression for $\boldsymbol{\xi_i^{\pm}}$ is obtained in normalization form by Eq. (1). The plot clearly shows the displacement is growing with the sound pressure in each frequency excitation and more evident fluctuation is observed in the high forcing frequency group. Moreover, the fluctuation growing with the downstream distance.

$$\widetilde{\xi_i^{\pm}} = \frac{\xi_i^{\pm}}{|\xi_{max} - \xi_{min}|} \tag{1}$$

In order to achieve a clear view on the wrinkle perturbation and the propagation character, the results will be analysed from two aspects, the amplitude of the oscillation along the downstream and the frequency of wrinkle displacement at point 0.5 of the i/L_{stable}axial position under the four forcing frequencies.

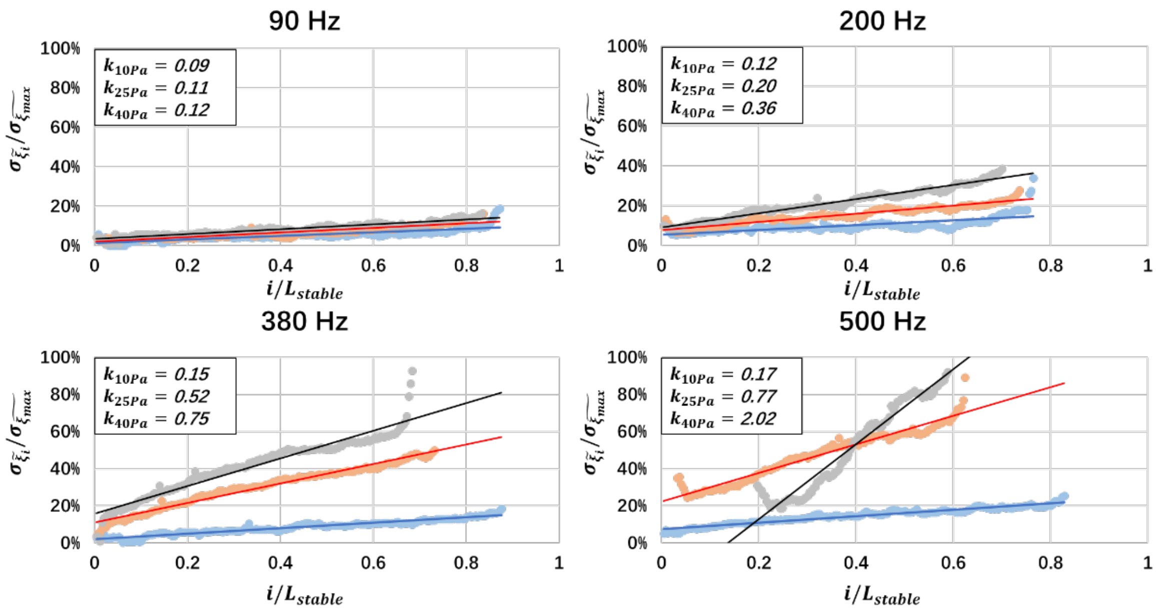


Figure 5. The fluctuation magnitude on downstream direction at different excitation cases

Figure 5 presents the fluctuation amplitudes of the flame wrinkle under each excitation condition, where the average amplitude of 2000 images in 1 second for each position on the downstream direction is calculated in the form of the standard deviation by Eq.2.

$$\sigma_{\tilde{\xi}_i} = \sqrt{\frac{\sum_{n=1}^{N}(\tilde{\xi}_{ni} - \bar{\tilde{\xi}}_i)}{N-1}} \quad , \text{(N=2000)} \tag{2}$$

The wrinkle amplitude on the vertical coordinate is given in normalization form $\sigma_{\tilde{\xi}_i}/\widetilde{\sigma_{max}}$ shows the perturbance effect grows with the axial position. The solid lines calculated by linear curve-fitting for these points present a direct view on the amplitude growing trend. The result from the external excitation is opposite to wrinkle destruction behaviour when the flame wrinkle induced by the flame base oscillation, studied by Shin & Lieuwen [8]. The wrinkle growing in size mechanism can be explained by the nature of coherent structures aroused by Brown & Roshko in 1974 [10]. The value of slope character k is the indication of the wrinkle expansion rate. As can be obviously noticed from the graph, the increase rate of the wrinkle is not only promoted by the external induced sound pressure at the action point, but also the harmonic frequency value. In addition, under the higher forcing frequency, the growing rate of k with the sound pressure is more remarkable than those under the lower frequency.

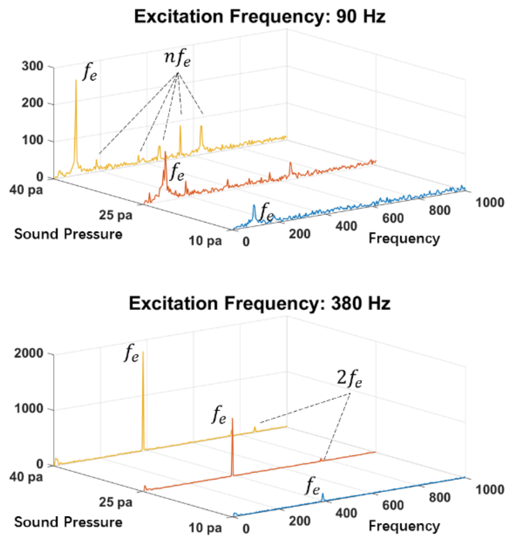
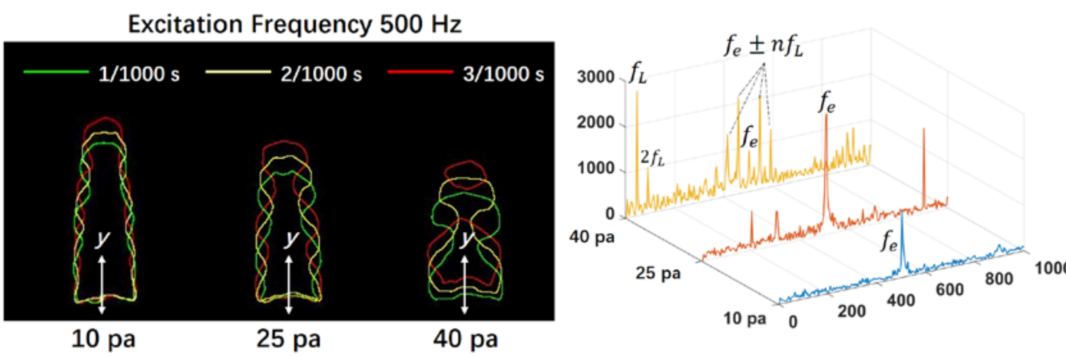


Figure 6. The relation of excitation frequency with wrinkle perturbance frequency the under various sound pressure condition

As shown in the Figure 6, beside of the displacement amplitude of the wrinkle changed with the excitation, wrinkle also shows a different oscillation frequency peaks under the different excitation. The measured frequencies match exactly with excitation frequencies f_e, which indicates that the flame wrinkling correlates well with the acoustic disturbance. Additionally, the frequency peaks become more prominent and its sub-harmonic frequencies nf_e show more apparently when the sound pressure going high. The buoyancy driven flame flicking effect shows no evidence on the premixed flame front wrinkle fluctuation. This result matches with the result of the nonlinear coupling flame intensity frequencies studied by Chen and Zhang [4]. What also needs to be mentioned is that, in the 500 Hz excitation case under the highest pressure, the sub-frequency f_L and its sub-harmonics frequencies $f_e \pm nf_L$ exhibited in the result. It's most likely caused by the lift-off phenomena, therefore the flame oscillated in both i-axis and j-axis direction and the result illustrates the coupling frequency of the both directions.



(a) (b)

Figure 7. (a)Samples of boundary lines of the instantaneous flame in 3/2000s from 500Hz frequency groups; (b) FFT for the lift-off fluctuation in y-axis

To obtain a better view on the lift-off behaviour, the boundary line of the flame front has been extracted and shown in Figure 7 (a). The three sequential samples of the flame front contour lines at 1/2000 second interval from the 500 Hz frequency excitation case are drawn in each of the forcing pressure condition. The root segment of the front exhibits a noticeable lift-off fluctuation in the vertical y-axis direction and the amplitude is increased with the increase of the perturbed pressure. Figure 7 (b) shows the lifting oscillation frequency peaks. For the lower sound pressure cases, the frequency peaks match with excitation frequency f_e. Under the highest pressure, the lift-off frequency f_L and its sub-harmonic frequencies become dominant frequency and nonlinearly couples with f_e, which presents a similar trend as wrinkle fluctuation frequency peaks.

5 Summary

- The wrinkle amplitude shows an increasing trend along the downstream direction under external excitation condition.
- Both of the external forcing frequency and the sound pressure on the action point have a positive effect on the flame wrinkle amplitude growing rate.
- The growing rate presents a linear trend against the axial distance.
- The flame wrinkle frequencies match exactly with excitation frequency.
- Under high acoustic excitation condition, the non-linear wrinkle oscillation frequency mode can be explained by the involvement of the lift-off behavior.

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