Impact of Acoustic Excitation Frequency on Laminar Premixed Flame

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1 Abstract

The response of an air/propane premixed conical flame in a one end closed tube at different excitation frequency (10-600 Hz) is investigated. The flame axial position in the tube can be adjusted, so that the flame response to the varying sound pressure level along the tube can be studied. The flame dynamic wrinkle structure and dilution behaviour under various excitation frequencies are measured simultaneously by a microphone and high speed colour camera. Through digital image processing, a range of flame properties such as the flame wrinkling displacement and the surface to volume ratio have been evaluated. It has been observed that the higher acoustic excitation frequency has a significant effect on flame oscillation characteristics. The variation of the displacement at a single point on flame boundary, the length of the boundary line and the flame surface to volume ratio are also sensitive to the local sound pressure level in the tube. As a result of the sound pressure perturbation and the change of boundary condition, the flame exhibited a varying degree of further air/fuel mixture dilution, which is indicated by the B/G ratio increase through Digital Flame Colour Discrimination techniques (DFCD).

2 Introduction

To achieve a better observation on the dynamic vortex structure [1], the gas expansion [2] and mixing behaviour [3] and other instantaneous and complex characteristics of an acoustically excited flame in a tube, a range of measurement techniques, including PIV [4], Schlieren [5], photomultipliers [6] have been applied. Many acoustic studies focus on soot suppression [7], thermoacoustic instabilities [8], dynamic structure [9] and etc. induced by sound frequency and sound pressure with the flame anchored at one specific position. Few papers have studied the flame response at the various positions in a tube/chamber, in which the acoustic properties are variable. It's desirable to investigate the flame dynamics in response to the complex acoustic system with controlled testing conditions.

The wrinkle flame front leads to the perturbation of flame propagation, chemical characteristics, heat release and other combustion primary properties. Many researchers have tried to find the theoretical

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principle of the curvature effect and then simulate it. However, due to the restricted factors and deviation in the formulation, only blurry concept has been provided on the flame fluctuating configuration. In this experimental study, a high-speed colour camera is applied to visualize the response of a laminar premixed flame to acoustic excitation at various positions and frequencies. The results are focused on the flame front oscillation, surface area to volume ratio and the chemiluminescence fluctuation, which have not been well explored to date.

3 Experiment Setup and Methodology

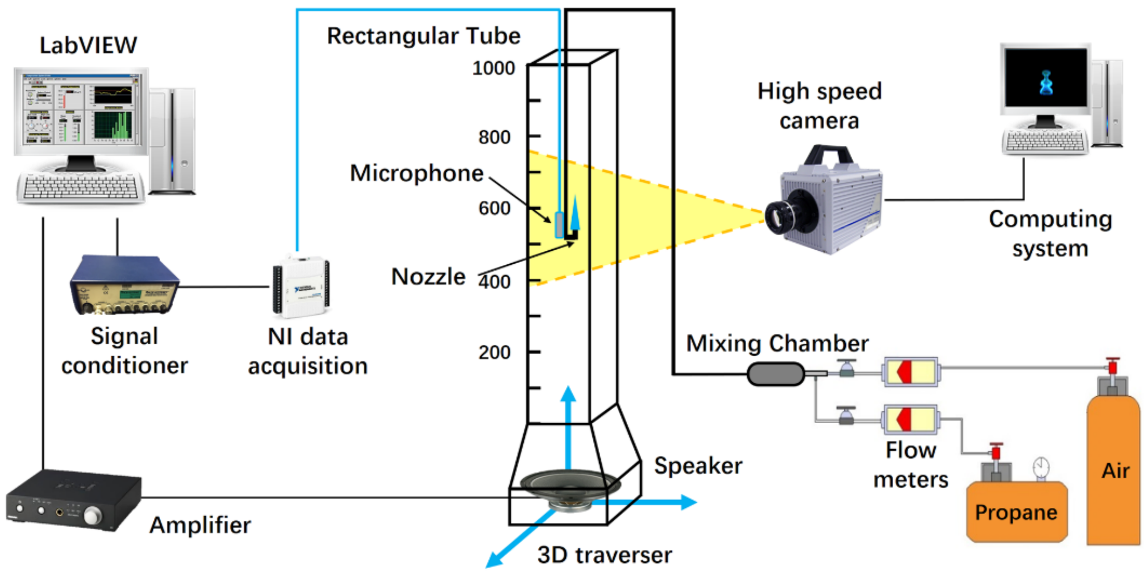


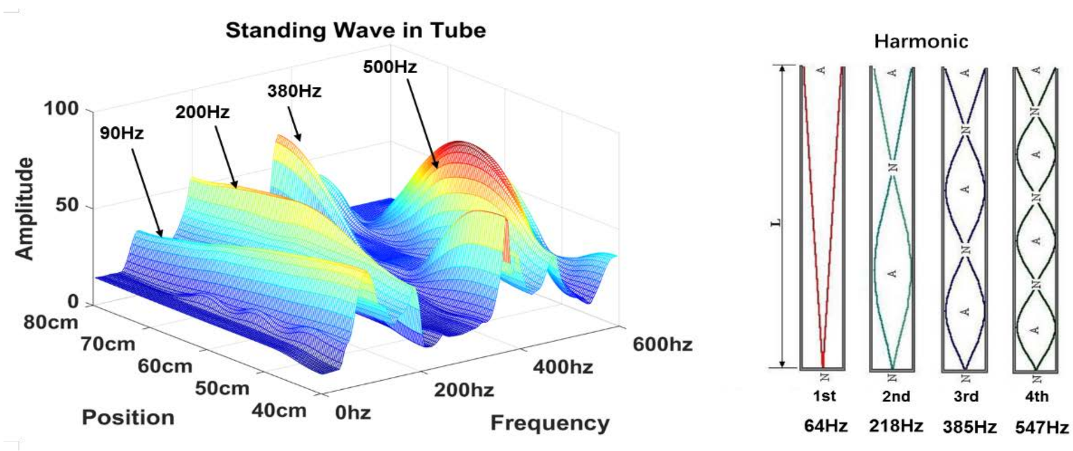
Figure 1. The schematic layout of the experimental apparatus setup

Figure 1 shows the experimental setup which includes a burner system, an image record system, a 3D position control 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 a rotameter. 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 nozzle position can be adjusted within the top end opened tube, which is made with four glass panels and braced by four steel brackets. The dimensions of the tube are 1000 mm in length and 120 mm in width of the square. Due to the non-constant cross section of steel holder at the bottom end, the flame pattern and the sound pressure have been recorded only at the positions from 40 cm to 80 cm. 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 was fixed at 3V. 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.

The flame has been recorded at different positions from 40mm to 80mm with 5mm intervals through the tube and excited at frequencies from 10 Hz to 600 Hz at each chosen position. To ensure the accuracy and generalization, 2000 images have been recorded per second at a shutter speed of 1/2000 second each condition. The data have been quantitatively analysed by MatLab image processing.

4 Results and analysis

Acoustic Sound Pressure Level in the Excited Tube

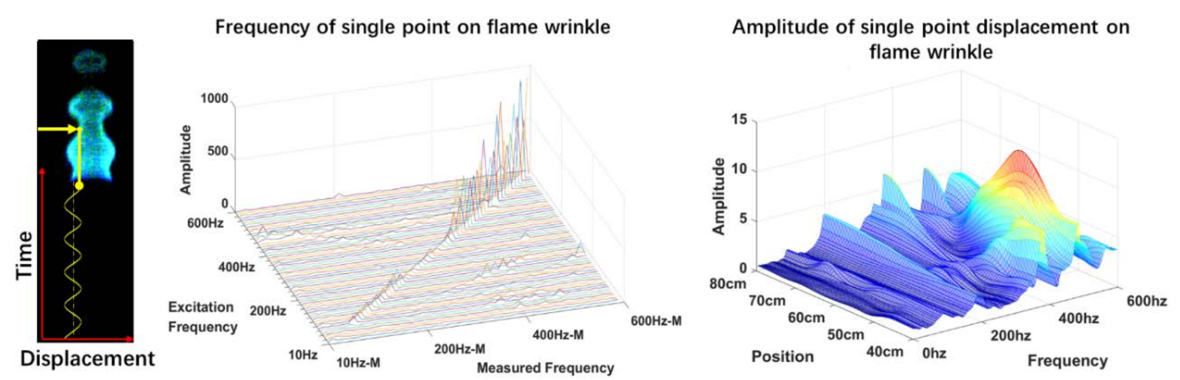


(a) (b)

Figure 2. (a) The experimental measurement of pressure responded to positions and frequency, (b) Theoretical prediction standing wave for one-end open and one-end closed tube

Figure 2 (a) shows the acoustic response sound pressure level generated at different acoustic excitation frequencies. The acoustic modes are found to be at frequency of 90 Hz, 200 Hz, 385 Hz and 500 Hz respectively. According to the results calculated by Chen [1] on the same equipment setting, the theoretical prediction of the response modes are at 64 Hz, 218 Hz, 385 Hz and 547 Hz, shown in Figure 2 (b), which assumes the tube positioned either in an open space or a very large room (high ceiling). Unfortunately, this experiment has to be carried out in a new lab space with low ceiling. Therefore, the ceiling and room effect cannot be ignored.

The Fluctuation of Single Point on Flame Wrinkle

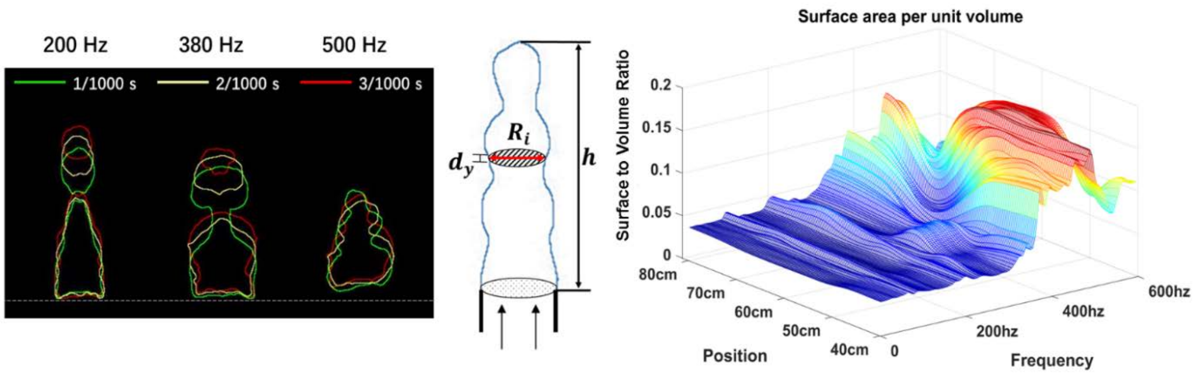


(a) (b) (c)

Figure 3. (a) Schematic of the single point displacement on the flame wrinkle; (b) the relation of the excitation frequency with the point measured displacement frequency; (c) the amplitude of the point displacement along the tube under various excitation frequencies

In Figure 3 (a), the displacement of the point shows a regular oscillation in the time scale. The principle of the oscillation has been investigated from two aspects, the frequency against the external excitation frequency, in Figure 3 (b), and the amplitude under various excitation frequencies along the tube, in Figure 3 (c). The measured frequencies match exactly with excitation frequencies, which indicates that the flame wrinkling correlates well with the acoustic disturbance. The amplitude of the flame wrinkling has a similar trend as the acoustic response in the tube. But the effect at lower frequency is less evident.

Flame surface area to volume ratio



(a) (b) (c)

Figure 4. (a) Samples of boundary lines of the instantaneous flame in 3/1000s; (b) Schematic of coordinates for flame front surface area and volume calculation; (c) Surface area per unit volume along the tube under various excited frequencies

The burning rate at a specific location increases through flame wrinkling is simply due to the increase in the surface area mentioned in Law's book [2]. However, the flame envelop is not continually enlarging with the increase of sound pressure in the high frequency range. It's mainly caused by the severe flame front volume shrink. Hence, the consequence indicated by Law can be described more reasonably by the surface area per unit volume.

$$a_{unit} = \frac{A}{V} \tag{2}$$

Where,

$$\mathrm{A} = \int_0^h d_L = \int_0^h 2\pi r d_y = \int_0^h \pi R_i d_y \tag{3}$$

$$\mathrm{V} = \int_0^h d_A = \int_0^h \pi r^2 d_y = \int_0^h \pi \left(\frac{R_i}{2}\right)^2 d_y \tag{4}$$

In Figure 4 (c), there is a basic similarity wave between the value of the surface area per unit volume and the acoustic sound pressure level inside the tube (Fig. 3 c). Even at the first harmonic frequency, the embossment can be easily distinguished. The anomalous wave profile occurs at the 4th harmonic. In these conditions, the flame was on the verge of the extinction due to the violent disturbance. The surface area per unit volume has been expanded to the maximum limitation. Additionally, it shows evidently that at the low frequency the flame surface area per unit volume doesn't have distinctive peaks even at the high sound pressure locations. On the other hand, the effect at high frequency is obvious even at the trough region.

Acoustically Induced Dilution Effect

In the previous studies of premixed hydrocarbon combustion, it is shown that the emission intensity ratio of CH^*/C_2^* can be correlated with the equivalence ratio [3]. According to the DFCD approach introduced by Huang and Zhang [4] and Yang et al [5], the higher B/G ratio indicates the flame burning at a leaner condition. It has been observed in this experiment that strong acoustic excitation would increase the B/G ratio, shown in Fig. 5, which means the excitation would further dilute the air/fuel mixture out of the nozzle.

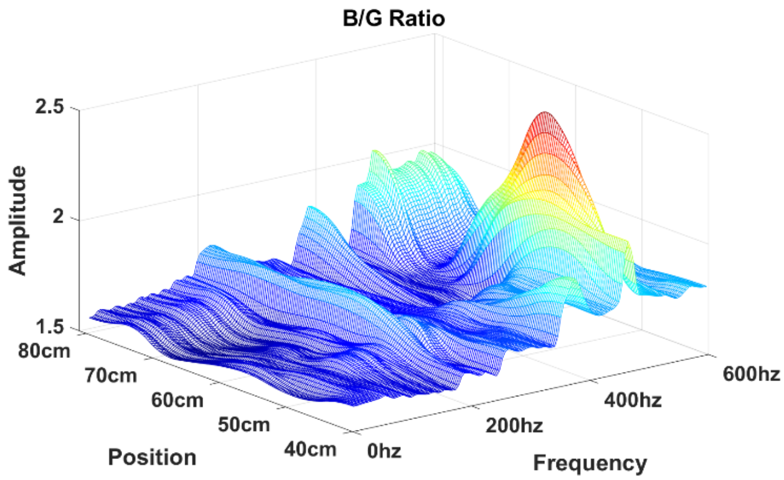


Figure 5. B/G ratio along the tube under various excited frequencies

The bottom of the tube is not sealed and fresh air can continually come into the tube although acoustically it is considered to be closed. Based on Chen's previous study [6], the evidence shows that the circulated fresh air is sufficient to keep the pure diffusion flame burning continuously. Hence, according to its similar feature as the Fig. 4(c), the dilution effect is mainly contributed by the enlarged surface area to fresh air. The wave profile of B/G ratio has a similar trend with the acoustic response in the tube, especially at the third and fourth harmonic frequency. In another word, under the 380 Hz and 500 Hz external acoustic excitation, the mixture of the flame has been diluted strongly in accordance with the local sound pressure. Whereas, at the low frequency range, the effect can be barely identified. This indicates that the mixture disturbance behaviour is not sensitive to the sound pressure fluctuation at low frequency.

5 Summary

This study has shown that the premixed combustion is sensitive to the frequency of acoustic perturbation. The investigated flame features include the flame wrinkle fluctuation frequency, amplitude, surface area to volume ratio and acoustically induced dilution behaviour. It has been observed that

- The flame wrinkle frequency and amplitude have a similar trend with the acoustic response in the tube.
- The lower excitation frequency has less impact on the all analysed aspects of flame features regardless of the sound pressure.

- The higher excited frequency will induce more severe disturbance and produce more evident changes, especially for the surface area to volume ratio and dilution behaviour.
- At higher excitation frequencies and local sound pressure level, the flame is prone to extinction.

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