Title : Jet diffusion flame properties in acoustic standing wave

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Abstract:
The acoustic excitation effect on flame characteristics of a diffusion flame jet inside a cylindrical tube has been presented and discussed. The flame under acoustic excitation has complex geometrical patterns, colours and dynamics. Three acoustic zones have been examined in detail. In the rarefaction zone, it has been observed that the yellowish diffusion jet flames change colours to blue either partly or completely, which imply the significant change in chemical reaction and the importance of burner nozzle position relative to the combustion chamber. In the high velocity fluctuation zone, mushroom like flame shape and flame necking are present and it seems that the high velocity fluctuation only affect the bulk movement of the flame. In the compression zone, no obvious flame change could be observed directly. Multiple signal measurement and analysis of jet flame dynamics in a loudspeaker induced standing wave have been presented. The sound pressure, velocity and the simultaneous measurement of two chemical species are carried out. The acoustic and velocity signals were measured at cold conditions along the central axis of the cylindrical tube in which the standing wave was created. Without acoustic excitation, the CH* and OH* signals are slightly out of phase. The flame oscillates around 13 Hz and sub harmonics are clearly visible. With acoustic excitation, the spectra have more chaotic frequency peaks. The space phase diagrams are less in phase in comparison with those without acoustic excitation.

INTRODUCTION

Acoustic coupling has strong effect on combustion process under confinement. Many related investigations could be found in literature (e.g. [1-6]). Acoustic forcing has been applied extensively to investigate the interaction of flame and acoustic wave [1, 2]. However there are limited publications on flame properties along the various phases of an acoustic standing wave. Recent experiments have shown that the acoustic properties along the standing wave are very different [7], especially when the acoustic forcing intensity is high. In a close and open acoustic chamber configuration, only part of the wave is reflected back from the open end. As a result the standing wave in a close and open acoustic chamber is different from the idea standing wave described in most of the published literature. Both positive and negative static pressure region has been observed in the acoustic chamber [7]. Basically the 'standing wave' could be divided into three distinctive regimes: compression, high velocity fluctuation and rarefaction. To investigate the flame behaviours in these three regimes, Farhat et al. 2005 [7] has carried out systematic of a diffusion flame traversing along standing waves at different acoustic mode. Three distinctive flame patterns have been identified [7], which corresponds to the compression, high velocity fluctuation and rarefaction regimes of the standing wave. The chemiluminescent emission measurement of a diffusion flame traversing along acoustic standing wave has been investigated by Farhat et al. 2005 [8]. These studies reveal the complex nature of flame and acoustics coupling. Further research is necessary. In this paper, multiple signal measurement has been carried out to further understand the complex interaction of flame and acoustic wave.

EXPERIMENTAL SETUP

The experimental apparatus could be found in references [7, 8]. It consists of a burner system, a signal generation and data collection system, a sound level meter, a fiber optic system for the collection of chemiluminescent emissions of the radicals, and a computer controlled 3D traverse system for easy data scanning and the change of flame position. The acoustic confinement is not a simple cylindrical tube due to the existence of a cowl connecting the loudspeaker to the cylinder. The origin of the vertical coordinate is set at the bottom end of the cylindrical section. The burner system has been described in detail if references [7, 8]. Propane fuel (C_3H_8) was supplied from a cylinder at initial flow rate of 100 ml/min, regulated by a control valve, and measured by a calibrated mass flow meter (rotameter).

The optical system used for the simultaneous measurement of two active chemical species (CH* and OH*) consists of a modified camera, two photomultipliers (PMs) and a randomly bifurcated fine fiber optic bundle. The camera body has been modified so that a bundle of fine optic fibers could be fixed at the back focal point to collect all the light through the front lens. The bundle of

fine fibers is bifurcated randomly into two equal subdivisions to produce two channels of light signals of the same intensity from the same imaged volume. Filters could then be added to each channel to measure two interested species. The properties of the two applied interference optic filters, CH and OH filters have a wavelength 430 ± 2.5 nm 307 ± 2.5 respectively. The subdivided fiber optic bundles are guided to two photomultipliers (ORIEL model 70704). Care has been taken to make sure that the PMs were working in the linear region of signal inputs versus the applied high voltage. The sampling rate is 5000 samples per second and the duration of each sampling is three seconds.

RESULTS AND DISCUSSIONS

For a close and open cylinder configuration, the acoustic displacement could be described as

$$y(x,t) = y_m \sin(kx - \omega t) + \alpha y_m \sin(kx + \omega t)$$

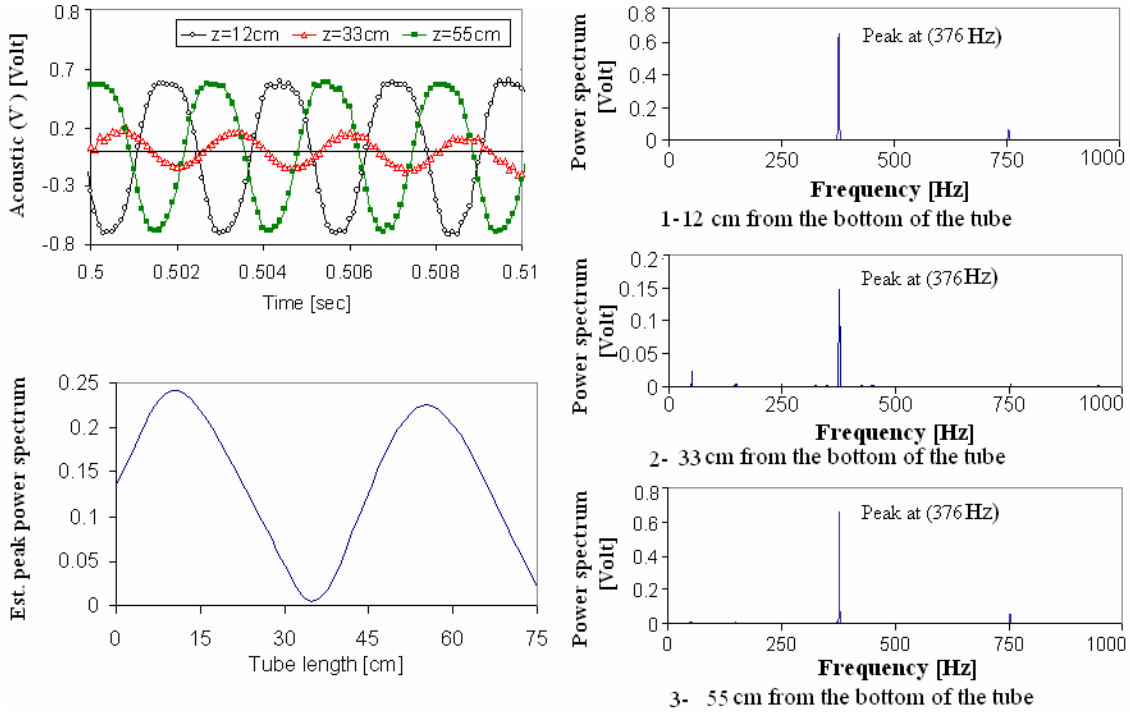


Figure 1 Acoustic signals (top left sub-figure) and spectra at different position along the tube. The voltage applied to the loudspeaker is 8 volts. The number in the brackets of the spectra represents the peak frequency. All the three measurements have the same data acquisition conditions. Shown in the bottom left sub-figure is the estimated peak power spectrum against the tube length.

where α is the percentage of wave reflected back into the cylindrical tube. Rearrange the above equation, we have

$$y(x,t) = 2y_m \sin kx \cos \omega t - (1-\alpha) y_m \sin(kx + \omega t)$$

The first term on the right hand side of the equation is the idea standing wave. Since the open end relies on diffraction for the acoustic wave to travel back to the cylinder, the real situation is much more complex than the above simple model. Experimentation is essential in understanding the acoustic behaviour.

The third mode of the rig (375 Hz) had been selected for detail investigations since this is the lowest mode which has all the three regimes of compression, high velocity fluctuating and rarefaction observable experimentally. Three burner positions had been selected along the tube, which are 12cm, 33cm, and 55cm above the bottom of the tube to represent the compression, high velocity fluctuating and rarefaction regimes respectively. The three flame patterns can be found in reference [7]. In the compression regime, the velocity fluctuation is at its minimum. The flame shape is almost the same as the case of without excitation. In the high velocity fluctuating regime, the pressure fluctuation is the minimum. The flame is yellowish in colour but the flame shape and dynamics are dramatically different. Mushroom like shape is dominant. Flame necking is also observed. The velocity fluctuation only induced the bulk movement of the flame but did not affect much on the mixing of the fuel and air. In the rarefaction regime, the velocity fluctuation is at its minimum. The pressure fluctuation p_{rms} is at its maximum but the pressure is lower than the atmospheric pressure. The flame colour has changed to blue which indicates that the mixing of fuel and air has changed significantly.

Figure 1 shows the acoustic signals at the three regimes and the power spectrum of each signal. It's clear from the figure that the measured signals are very close to the pure sine wave, high amplitudes are observed at the rarefaction and compression regimes, but the acoustic signal in the high velocity fluctuation zone is very low. The peak frequencies are the same for all the three positions and they are equal to the excitation. Sub-harmonics appeared in all regimes. In compression and rarefaction regimes high frequency (740Hz) harmonics is more visible. On the other hand low sub-harmonic frequency (75Hz) is observed at high velocity fluctuating regime. Figure 1 also shows the estimated peak power spectrum along the tube. High values are observed at both the compression and rarefaction regimes.

Figure 2 shows the rms velocity signal and its power spectrum at different regimes. It can be seen that the signals at compression and rarefaction regimes (velocity node) are very low compared with the signal at the high velocity fluctuating regime (velocity anti-node). As shown in the figure the peak frequency in the compression regime (520Hz) is lower than that in the rarefaction zone (1042Hz). The frequency at high velocity fluctuating regimes is 740Hz, which is double of the excitation frequency. The figure also shows that there are many of strong sub-harmonics at rarefaction and compression regimes, but in high velocity fluctuating regime the sub-harmonic is very weak. Here it should also be pointed out that the CTA signals could only be positive. Therefore the frequency will be the double of

those acoustic signals. Because of this the peak frequency of 740 Hz corresponds to the acoustic excitation frequency. From the figure it can be seen that high frequency fluctuation is observed in the rarefaction regime. Lower than the acoustic excitation frequencies are mainly observed in the compression regime. In both cases, the highest amplitudes do not correspond to the excitation frequency. In high velocity fluctuating regime, the amplitudes of sub-harmonics are much smaller than that of the excitation frequency. Whether the much higher sub-harmonic frequencies of the velocity observed in the rarefaction zone are an indication of good mixing is questionable. Higher frequencies do mean faster mixing time. However we should bear in mind that the rms velocities in both the compression and rarefaction regimes are very small compared with that in the high velocity fluctuating regime.

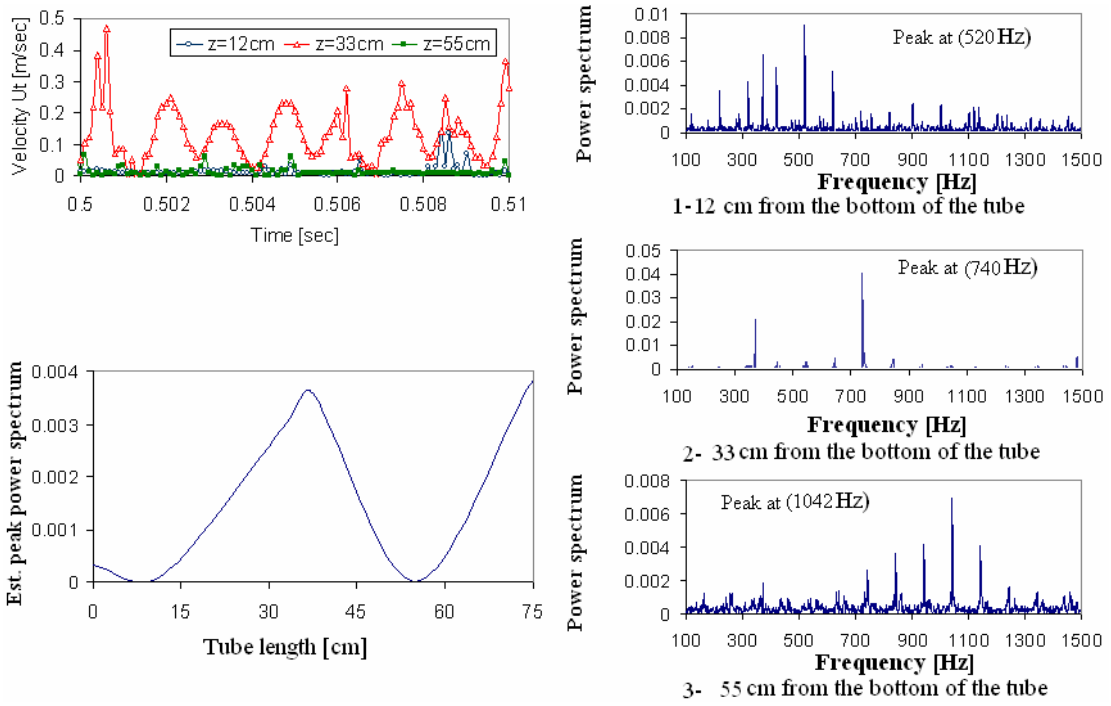
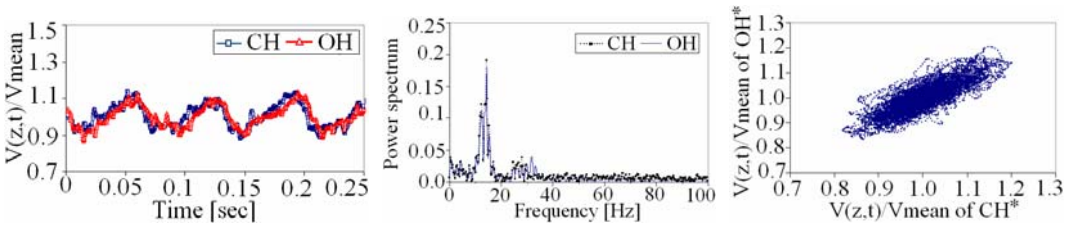
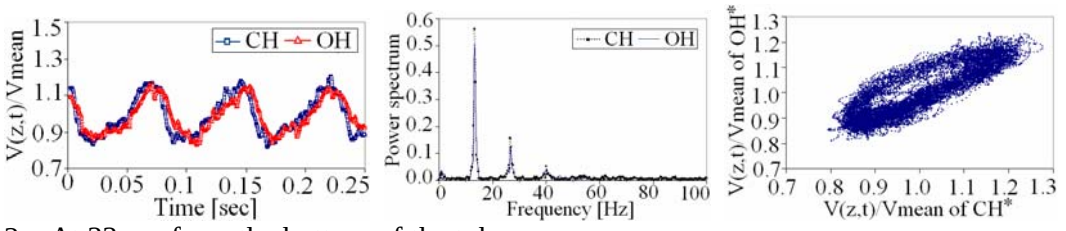


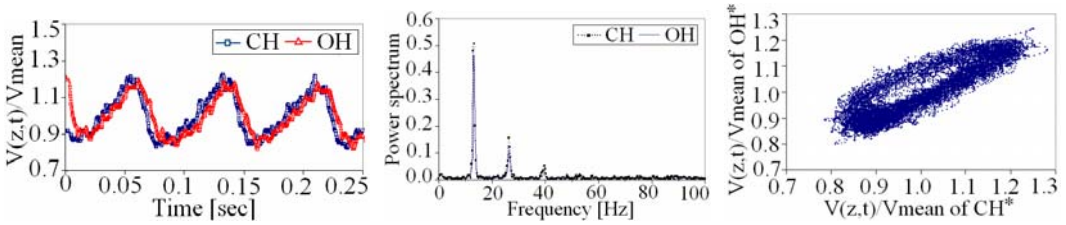
Figure 2 Velocity signals (top left sub-figure) and spectra at different position along the tube. The voltage applied to the loudspeaker is 8 volts. The number in the brackets of the spectra represents the peak frequency. All the three measurements have the same data acquisition conditions. Shown in the bottom left sub-figure is the estimated peak power spectrum against the tube length.



1 – At 12 cm from the bottom of the tube



2 – At 33 cm from the bottom of the tube



3 – At 55 cm from the bottom of the tube

Figure 3 CH and OH* radical signals, spectra, and phase space diagram at three different position along the tube (corresponding to compression, high velocity fluctuation and rarefaction) and without excitation. All the three measurements have the same data acquisition conditions. Fuel flow rate is 100ml/min.*

To understand more about the flame chemistry and dynamics, global chemiluminescent emissions of the CH* and OH* radicals have been measured simultaneously. To make the results more comparable, the fuel flow rate maintained at a constant value of 100 ml/min by readjusting the fuel control valve. At this fuel flow rate the Reynolds number based on the fuel nozzle diameter is 280. Figure 3 shows the normalised signals (by the mean), spectra and the phase-space diagram of the CH* and OH* radicals at the corresponding compression, high velocity fluctuation and rarefaction regimes. The measurement is carried out without acoustic excitation. It can be seen clearly that the there exits distinctive frequency peak for the unexcited diffusion flame. Because the flame is confined in the tube sub harmonic frequency also presents particularly when the fuel nozzle is further away from the loudspeaker. The phase-space diagrams indicate that the two signals are slightly out of the phase. Figure 4 presents the same measurement with acoustic excitation. As it can be seen from the figure, the results are dramatically different from those without acoustic excitation. First the signals of the two radicals are spiky and different in each acoustic regime. The spikiness of the two signals is reversed in the compression and rarefaction zone. On the other hand the two signals are similar in forms in the high

velocity fluctuation zone. Second the typical diffusion flame flickering frequency is not observable. The spectra are broadband and much higher frequency exists, especially in the rarefaction zone as observed. Third the phase-space diagrams indicate very different characteristics. The rarefaction zone has the widest spread in phase difference, which is followed by the high velocity fluctuation zone. From the above results it is clear that the frequency spectra of the flame chemistry do not correspond directly to either that of acoustic or velocity spectra.

CONCLUSIONS

In this paper, multiple signal measurements of jet diffusion flame dynamics in a loudspeaker induced standing wave have been carried out. The peak frequency of the acoustic signal is found to match the excitation frequency though small amplitude harmonic frequency is observable. The velocity spectra are more complex. The compression regime has lower frequency peaks. The rarefaction regime is observed to have higher frequency peaks than the excitation frequency while lower frequency spectra are found in the compression regime. The dominant frequency peak in the high velocity regime matches the acoustic excitation frequency. Two active chemical species have been tracked simultaneously. Without acoustic excitation, the spectra of each measured location are similar. Harmonic peaks are clearly observable. It is interesting to see that the two species are slightly out of phase. With acoustic excitation, each regime has very different characteristics. The results have demonstrated the complexity of acoustically induced hydrodynamic near fields and their coupling with combustion. Further research is required in understanding the observed phenomena.

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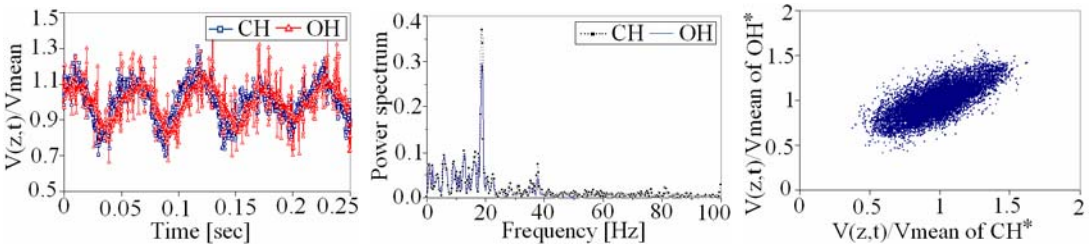
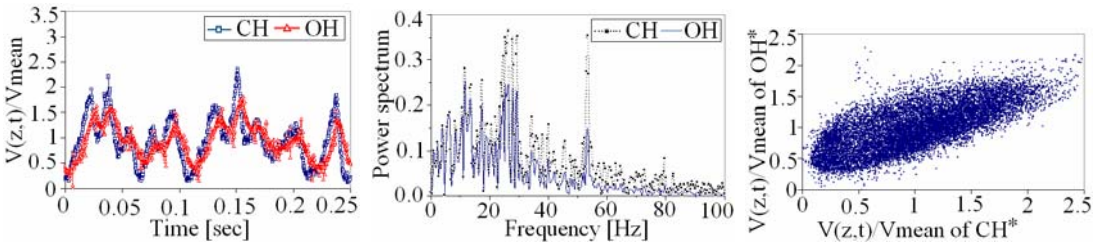
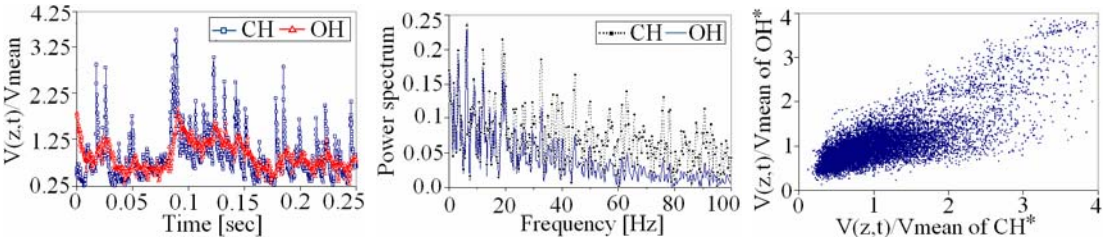


1 – High pressure fluctuating (compression), 12cm from the bottom of the tube.



2 – High velocity fluctuating, 33cm from the bottom of the tube.



3 – High pressure fluctuating (Rarefaction), 55cm from the bottom of the tube.

Figure 4 The CH and OH* radical signals, spectra, and phase space diagram at three different position along the tube, with excitation of 375Hz (second mode). The voltage applied to the loudspeaker is 8 volts. All the three measurements have the same data acquisition conditions. The signals are normalised by the mean value of each signal.*