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Experimental observation of the nonlinear coupling of flame flow and acoustic wave

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ABSTRACT

This is an experimental investigation to study the nonlinear coupling characteristics of a propane/air flame with acoustic standing waves, using chemiluminescence emission and phase-locked PIV measurements. A variety of coupling modes are observed for the excitation source with combustion instability oscillations and its harmonics and sub-harmonics. The frequency analysis shows that flame/acoustic coupling behaviour results in complex nonlinear coupling. The coupling behaviour is weak at lower excitation intensities (0.3 V). At a voltage amplitude of 2 V, the results show that the excitation frequency (f_e) is only coupled with the sub-harmonic frequency ($f_e/5$) for the premixed flame. However, for the diffusion flame, more complex frequency components are observed, which exhibit relationships of $f_e \pm f_f$ and $f_e \pm f_e/5$. At a voltage amplitude of 13.7 V, the sub-harmonic frequencies ($2f_e/5$ and $3f_e/5$) and the premixed flame buoyancy oscillations (f_f) are increased. PIV measurements provide detailed flow velocity vector fields in an acoustically excited tube for different phase angles and the effect on the flames at different equivalence ratios, which increases the understanding of flame oscillation behaviour. It is found that all of the nonlinear phenomena that are observed occur because of the coupling between buoyant and acoustic excitation and create complex nonlinear frequency couplings.

1. Introduction

Combustion instability is commonly observed in practical combustion systems, such as furnaces and gas turbines. Flame–acoustic interaction is one of the major reasons for these undesirable phenomena in an enclosed combustion system. It is known that the range of acoustic frequencies, amplitudes and phase angles can affect the flame dynamics. Due to the thermoacoustic mechanism, the amplitude of acoustic oscillations can grow and therefore their effect on the flame dynamics also grows [1,2]. These effects are enhanced in a combustion chamber, because there is coupling between an unsteady heat-release rate and acoustic pressure. Under certain conditions, this coupling can result in increased thermoacoustic instability oscillations and consequently lead to failure of the system [3,4]. Practically, these unstable processes occur in the nonlinear regime, where the system oscillates at a limit cycle [5]. Determining the mechanism of thermoacoustic instability is complex because it involves a number of different phenomena.

It is seen that flame dynamics are significantly altered by acoustic excitation. Acoustically excited flames are useful for research involving flame–acoustic interactions because acoustic perturbation is an advantageous means of control for a flame that oscillates at specific frequencies [6]. The acoustic signal can also be synchronised with other measurement devices. Depending on the frequency and magnitude, the addition of a forced acoustic field can considerably modify the dynamic flame structures and movements. The use of external acoustic perturbation also has an effect on combustion at the chemical level, which results in a change in the emissions and the molecular concentrations [7,8]. There have been many studies of nonlinear flame oscillations using acoustically excited flames. Kim et al. [8] and Kartheekeyan et al. [9] demonstrated that external forcing an induced flame periodic oscillation can further create undesirable nonlinear oscillations that affect the initial flow velocity and the mixing rate for a premixed flame. Experimental work has shown that flames exhibit nonlinear responses under various acoustic and combustion conditions. In nonlinear systems, the flame oscillation wave and the acoustic excitation wave can induce other frequency components, besides the excitation frequency. For instance, a sub-harmonic flame response was found in pulsed premixed methane/air flames in the studies by Bourehla and Baillot [10]; and Williams et al. [11] showed the existence of sub-harmonic flame oscillation components of $f/2$, $f/3$, $2f/3$, $f/4$ and $f/5$ in a laser-based investigation of the structures of a acoustically excited flame. Huang et al.

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[12] identified nonlinear couplings between the buoyancy driven flame instability and acoustic excitation using high speed colour imaging and an innovative colour digital image processing technique for an acoustically excited and baffle-stabilised diffusion flame burner.

Most of these studies concentrate on external excitation in a fuel pipe in an open space. Not many studies involve the observation of nonlinear flame dynamics in an acoustically forced tube and their coupling behaviour. Recently, the authors have used a phase-locked PIV system to study the flow characteristics for a propane diffusion flame at different nozzle position along an acoustically excited tube [13]. The results show that the diffusion flame dynamics are significantly affected by the standing wave in a tube because of the large velocity oscillation in the acoustic flow in the anti-node area. The main objective of this study is to use nonlinear theory to explain the observed nonlinear response modes for an acoustically excited premixed flame in a tube. A chemiluminescence emission measurement system (PMT) is used to systematically examine the oscillating frequency of propane–air flames at different intensities of acoustic excitation, especially the nonlinear coupling of the flame dynamics and acoustic excitation. Detailed flame flow velocity fields and vorticity are measured and calculated using a PIV (Particle Image Velocimetry) system, to make use of more useful physical flame parameters from the two-dimensional spatial information and to further understand the flame/acoustic coupling behaviour.

2. Experimental setup

The schematic layout of the experimental apparatus is illustrated in Fig. 1. The design is similar to the design in reference [13]. It consists of a burner system, a computer controlled 3D traverse, a signal generation and a synchronisation system, a PIV system and a chemiluminescence emission measurement system (PMT). The square tube was used to simulate the enclosed environment of a practical combustion chamber. The burner utilised in this study was designed to produce a wide range of premixed stabilised flames. Gaseous fuel (Propane) and air were respectively supplied from the fuel bottle and the compressed air bottle and were controlled by dedicated flow-metres. The flow rate for the propane was set at 55 ml/min. Using this fuel flow rate, three equivalence ratios of premixed flames were set as the main parameters. The experimental conditions are listed in Table 1.

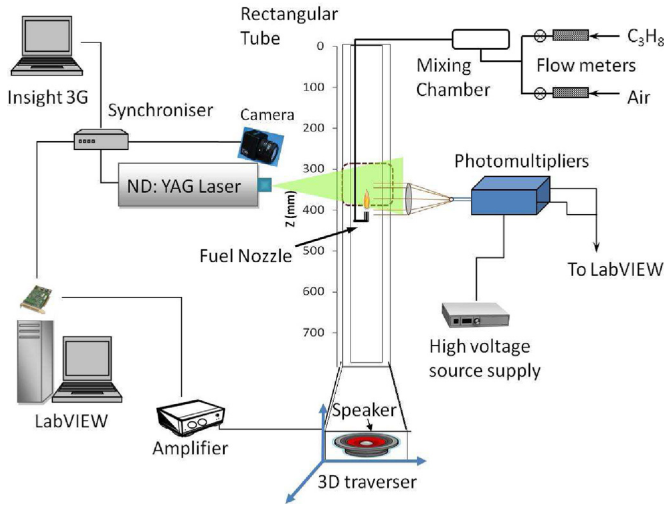

Fig. 1. The schematic layout of the experimental apparatus.

Table 1
Propane/air flow parameters in the experiment.

Equivalence ratio (Ø)	Air mass flow rate (kg/s)	Fuel mass flow rate (kg/s)	Air flow rate (ml/min)	Fuel flow rate (ml/min)	Velocity (m/s)
1.5	1.82×10^{-5}	1.75×10^{-6}	910	55	1.28
3	9.10×10^{-6}	1.75×10^{-6}	455	55	0.67
5	5.46×10^{-6}	1.75×10^{-6}	273	55	0.43

External acoustic excitation was provided by a loudspeaker, which was driven by a power amplifier whose amplitude and frequency signals were controlled by a PC base LabView system. The driving amplitude was defined using the peak-to-peak of the output voltage (*V*) of the amplifier and was set at 0.3 V, 2 V and 13.7 V for the study. The details for the burner system, the PIV system and the signal generation and synchronisation system are the same as those for [13]. The chemiluminescence emission measurement apparatus consisted of two photomultipliers (ORIEL, Model: 70704), a high voltage source supply, a converging lens arrangement, optical filters and a randomly bifurcated fine fibre optic bundle. This optical system measured the flame chemiluminescence intensity using a photomultiplier-tube (PMT). The filtered light collected from the flame was used a set of monochromatic filters. Transmission of the light signal was accomplished using a fibre optic cable. The CH^* chemiluminescence was collected using a lens system, which was designed to image the flame onto the end of a fibre optic cable. The data outputs from the multipliers were displayed and stored in a PC based system. A National Instruments DAQ card and LabVIEW software were then used for data acquisition, monitoring and analysis. The acoustic excitation signal, the PIV trigger timing and the PMT signals were synchronized to allow a logical analysis.

3. Results and discussion

Previous research [14] proved that the first four resonance frequencies of the present rig were 65 Hz, 220 Hz, 385 Hz and 550 Hz, respectively. The acoustical node and anti-node regions also fit the observable area for the current test rig at an external excitation frequency of 385 Hz. Therefore, an acoustic excitation frequency of 385 Hz was set as the main frequency for further analysis. The burner nozzle was positioned in the acoustic anti-node region (see Fig. 1) to determine how the flame wave responded nonlinearly to acoustic excitation. Fig. 2 shows the visible flame images at different equivalence ratios at an excitation frequency of 385 Hz and a voltage amplitude of 13.7 V (2 V in the case of Ø = 1.5). The strongly oscillating diffusion flame case is also shown in Fig. 2a. It is seen that under the same acoustic excitation, the premixed flame is more stable than a diffusion flame. The flame pattern is also more stable when the air–fuel mixing ratio is increased. At an equivalence ratio of 5, a reddish flame colour is only visible at the flame tip. The flame oscillation behaviour is similar to that for the diffusion flame, but it is much weaker. At Ø = 1.5, which is the flammability limit for the current nozzle, the flame oscillation is the weakest of all the test cases. The flame cone angle remains almost constant under acoustic forcing. However, the flame can be extinguished suddenly by a slight increase in amplitude. These observations demonstrate that the behaviour of the premixed flame is quite different to that for a diffusion flame under acoustic perturbation. A diffusion flame can become a lifted flame, a partially premixed flame or a partially extinct flame type, during each flame oscillation cycle.