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Nonlinear response of buoyant diffusion flame under acoustic excitation

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HIGHLIGHTS

- ▸ The methane diffusion flame is investigated under different acoustic excitations.
- ▸ Four types of nonlinear modes are identified in the frequency spectra.
- ▸ The nonlinear physical mechanisms are analyzed using flow visualisation methods.

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ABSTRACT

Using nonlinear theory as guidance, the expected (both reported and unreported) nonlinear response modes of a laminar diffusion flame to external acoustic excitation are investigated at different frequencies (6–100 Hz). The flame oscillating frequency is analyzed using digital signal and image processing techniques, while the hot gas dynamics are visualized by a high speed schlieren imaging system. The natural flame flickering frequency of the burner is 7.8 Hz. It has been observed that both the excitation frequency and amplitude play a role in the resultant dominant flame oscillation frequency. In this study, four nonlinear modes are identified, including frequency division, frequency doubling, sum/subtraction of the excitation and natural buoyancy frequency, and frequency amplitude increasing with enhanced excitation signal. From the schlieren images, it is found that all the nonlinear phenomena observed are due to the coupling between buoyancy and acoustic excitation near the nozzle exit field. The resultant change in hot gas flow structure and evolution affects the flame frequency behaviour subsequently.

1. Introduction

Buoyant diffusion flames have been intensively studied in combustion science. It is found that laminar diffusion flames have a typical flickering/oscillating behaviour at a low frequency range of 10–20 Hz [1]. The flame flickering frequency is relatively independent of fuel type, nozzle dimension and jet exit velocity [2–5]. In a flickering flame, the flame and flow interactions show periodic and reproducible characteristics. The flame oscillation frequency is dominated by buoyancy-driven instability and correlated with large toroidal structures outside the visible flame zone [4,6,7]. Buckmaster and Peters [8] employed a linear instability theory and showed that the flame buoyancy could result in a modified Kelvin–Helmholtz type instability.

In addition to natural buoyancy-induced oscillation, flame behaviours can also be significantly altered by applying external acoustic excitation. Acoustically excited flames have been studied intensively because acoustic perturbation is advantageous as a means to control the flame oscillating at specific frequencies; and therefore it is convenient to be synchronised with other measurement devices. Depending on the frequency and magnitude, the addition of forced acoustic field can produce considerable modifications to the dynamic flame structures and movements [9]. The use of external acoustic perturbation also has an effect on combustion at chemical-level, resulting in the change of emissions [10], molecular concentrations and consequently the perceptual flame colouration [11]. Furthermore, for a practical burner or combustor with high noise levels, the acoustic perturbation sources may cause serious combustion instability phenomena [12]. Therefore, exploring the detail physical insight of the acoustic excited combustion process is of great importance.

In acoustic excited diffusion flames, both natural buoyancy effect and excitation perturbation shows sinusoidal wave fluctuations. In the case of a linear system, the response to a sinusoid is always a sinusoid at the same frequency and does not depend on the amplitude of excitation. In the case of a nonlinear system, it can be shown that sinusoidal forcing results in response components at frequencies other than the excitation frequency. In particular, the distribution of energy amongst these frequencies depends on the level of excitation [13]. The buoyant diffusion flame is found

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to show nonlinear response to acoustic excitation in specific conditions. Sub-harmonic flame response in pulsed buoyant diffusion flames have been previously reported in a laminar slot burner flame with air-side forcing [14] and in transitional jet flames with fuel pulsing [15]. The sub-harmonic phenomenon has also been found in acoustic excited premixed air/methane flames [16]. Furthermore, the sub-harmonic flame structures were interrogated through the use of 2D laser diagnostics [17]. In their work, the flame oscillations at $f/2$, $f/3$, $2f/3$, $f/4$ and even $f/5$ of the excitation frequency have been observed. In another experimental investigation, the diffusion flame shows half the peak frequency of that of the pure fuel when different fuels (methane and propane) are mixed [18]. The main objective of this investigation is to apply nonlinear theory to explain the observed nonlinear response modes of an acoustically excited diffusion flame. In the meantime, original digital flame colour image processing techniques have been applied to find new nonlinear response modes, which can be explained by nonlinear theory but have not been reported in combustion community.

2. Experimental setup

The schematic layout of the experimental apparatus is illustrated in Fig. 1a, which is similar to the design in the reference of [19]. The burner utilised in this study is designed to establish a wide range of diffusion and premixed bluff-body stabilised flames. Gaseous fuel is supplied from a fuel bottle and controlled by a dedicated flow-meter. The range of flow rate for fuel is 0–50 slpm (standard litre per minute). The gaseous fuel enters the mixing chamber from the lower-end of the combustor. A honeycomb section is located above the mixing chamber, which straightens the flow along the burner length towards the nozzle exit. The flame is established and stabilised by a conical bluff-body structure (shown in Fig. 1b) at the combustor exit. The outer diameter of the nozzle exit is 42 mm with the conical bluff-body diameter of 29.6 mm, thus giving a blockage ratio of 0.5. In this investigation, methane diffusion flame at volumetric fuel flow rate of 5 slpm is considered. External acoustic excitation is provided by two loudspeakers which are forced by a power amplifier whose amplitudes and frequencies could be controlled as desired. These speakers generate periodic pressure oscillation which modulates the fuel flow conducted to the burner. In the current experiment, the flame characteristics under an acoustic excitation frequency range of 6–100 Hz are investigated. Two microphones are placed at different points of the vertical burner pipe to detect the pressure oscillation caused by acoustic excitation. A photomultiplier (PMT) tube device is applied to record the flame flickering frequency based on the flame light emissions. The time-resolved flame images are captured by a Phantom V210 high speed camera. A Z-type schlieren setup, with a pair of parabolic mirrors (150 mm in diameter), is used to observe the hot gas structure development. The high speed direct/schlieren imaging, the acoustic pressure measurement and PMT signals are synchronized for tractable analysis.

3. Experimental results

3.1. Frequency analysis of acoustic and PMT signals

For consistency throughout this paper, symbol f_m is designated as the dominant flame flickering frequency, f_e the acoustic excitation frequency and A_e the acoustic excitation amplitude respectively. During the experiments, the fuel flow rate is kept at 5 slpm, which corresponds to a mean exit flow velocity of 0.82 m/s and a low Reynolds number at 215. Since the current burner has a relatively large outer diameter and a central bluff body, very weak annulus fuel jets are generated in current flow conditions. Thus the effects of forcing are manifested only in the nearfield region of the nozzle exit. In order to understand the effect of acoustic excitation on flame dynamics, six cases are selected to illustrate different phenomena, with the case conditions listed in Table 1: Case 1 is the natural flickering flame without acoustic excitation; and Cases 2–6 are the typical flames modulated at excitation frequencies of 8 Hz, 8 Hz, 50 Hz, 30 Hz and 30 Hz respectively. In the experiments, the PMT signals

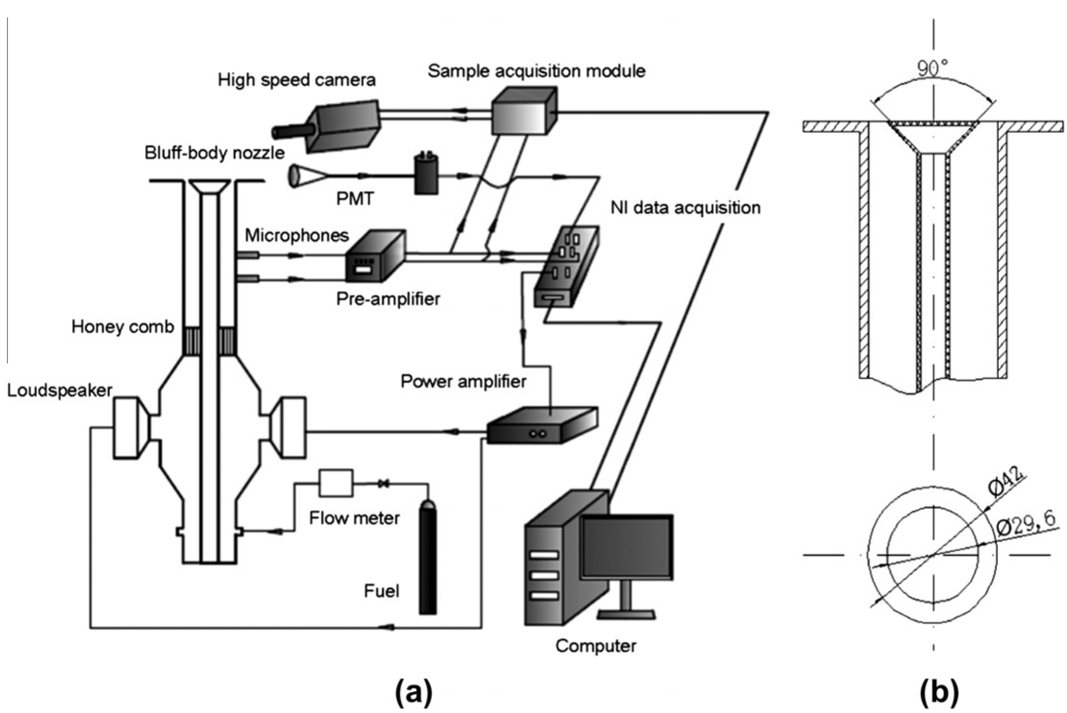

Fig. 1. (a) Schematic of the experimental setup. (b) Dimension of the bluff body.