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Lifted and reattached behaviour of laminar premixed flame under external acoustic excitation

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ABSTRACT

The flame chemiluminescent emission fluctuations and the vortex structure of the lifted jet flame under acoustic excitation were studied in this investigation. By employing high-speed visualization and DFCD (Digital Flame Colour Discrimination) image processing method, the fluctuation of the instantaneous mixture fraction has been found highly correlated with the lifted height variations. It has been observed that during the flame drifting to downstream, there is no obvious shifting on the mixture fraction. However, when the flame travels back to upstream, the fuel mixture has been evidently diluted. In addition, the stabilisation mechanism can be further explained by analysing the velocity fluctuation of the vortices in the shear layer via PIV. Measurements show that, the turbulent stretching at the shear layer generated by the excitation leading to the flame lift-off. On the other hand, the Kelvin-Helmholtz vortices in the unburn part play a key role in preventing flame lift-off. But, the excessive external acoustic excitation leads to blow-off due to over dilution and increased lifted height.

1. Introduction

In most industrial applications, jet flame lifted off is always been regarded as the most undesirable instability problem, as it's unstable and easy to blow-off abruptly. Hence, the stabilization and extinction mechanism have been widely investigated numerically and experimentally.

A non-premixed jet flame has a tendency to lift off from the burner nozzle position when the jet velocity of the flame is over a critical value of U_c [1]. With the increasing of the jet velocity, the lifted height will increase and when it's beyond certain critical height and the flame will be blown off [2]. Therefore, the stability of the lifted flame is an important parameter for basic combustor design. Scholefield and Garside's theory [3] claimed that the transition to turbulence is a prerequisite for the lifted diffusion flame stabilization and the flame anchors at a point where the flow is turbulent. Gollahalli [4] argued that the flame will tend to stable at the position where the local flow velocity balance the normal flame propagation velocity. Navarro-Martinez and Kronenburg [5] have demonstrated that the excessive turbulent stretching at the nozzle leads to the lift-off and they also claimed that auto-ignition can be used to promote the flame stabilization mechanism. Recently the observation from Kiran and Mishra's [2] visual experiment proved the flame lift-off height varies linearly with jet exit velocity. They presented a semi-empirical correlation between the normalized lift-off height to the nozzle exit diameter.

$$\frac{H_L}{D_f} = 1.8 \times 10^{-3} \frac{U_f}{D_f}$$

H_L: lift-off height
D_f: diameter of the fuel tube
U_f: fuel jet velocity

In addition to the velocity effect, The stoichiometric burning on the physical mechanism blowout has been investigated by Broadwell et al. [6] and Pitts [7]. According to their study on diffusion flame, the fresh air entrained by the vortices structure cools down and over dilutes the flame jet, which leads to the flame extinction.

For a lifted flame, it has been shown by many researchers that, the rolling-up processes of vortices structure generated by the bluff body or acoustic perturbation will prevent the lifted flame from propagating downstream [8–12]. Flame response to specific external excitation in the terms of frequency and amplitude was studied theoretically and experimentally by Demare and Baillot [13]. They concluded that secondary vortices are sufficiently powerful to make the flame propagate oppositely. The flame lifting and reattaching characteristics and hysteresis zone where the flame anchoring may occur has been noticed by Gollahall in 1986. [4] The study of diffusion flame stability mechanisms

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in the hysteresis region by acoustically exciting the unburned components has been investigated by Lin et al. [14] and [9], The most significant effect was found when the acoustic frequency matched the fundamental frequency of the vortex. Chao et al. have demonstrated that, the acoustic excitation at certain frequencies could extend the blowout limit by more than 25% [9]. Moreover, the stability method of acoustic excitation on lifted flame also has been proved to be feasible for soot suppression and emission control [15–17].

On the other hand, Kim et al. [18] and Kartheekeyan et al. [19] have observed that, for premixed flame, the flow oscillation affects the local strain rate at the shear layers, which contributes to the fluctuation of heat release rate and mixing rate. Additionally, the unsteady vorticial structure pass by can stretch and quench the flame [20]. However, the variation of the local fuel to air ration by these vortices cannot be ignored as it will be demonstrated in this study. Chen and Zhang has experimentally investigated the nonlinear coupling characteristics on different equivalence ratios of propane/air flame [21]. It has showed the existence of complex nonlinear frequency components created by the coupling of buoyance driven instability and the acoustic excitation.

While the acoustic excitation has been widely investigated from two aspects: the acoustic stabilization mechanism for diffusion flame and the flame shear layer dynamic experimentally [19,22–26] or numerically [27] for premixed flame. There is lack of the knowledge on the transient dynamics of the lifted and reattached phenomenon for the premixed flame. The present work investigates a conical laminar premixed flame in a rectangular tube excited by acoustic wave. A comprehensive analysis on the premixed flame periodically lifted and reattached phenomenon induced by external acoustic excitation with the combination of diagnostic methods, colour imaging [28], schlieren and PIV methods. The periodical mechanism has been addressed from two aspects: the velocity field of the vorticity at the shear layers and premixed flame stoichiometry burning propagation preference. The Digital Flame Colour Discrimination (DFCD) technique is a unique method to analysis equivalence ratio fluctuation and the transient flame shear layer dynamics. It provides a more intuitive evaluation on the fuel concentration distribution. Combined with the Kelvin-Helmholtz vortex structure observed from the schlieren method, the results provide a good explanation for the flame reattachment progress. The oscillatory behaviour of laminar flame dynamic structure and lifted height are experimentally investigated with time resolved contour line detection method.

2. Experiment setup

The schematic of the experimental apparatus is shown in Fig. 1 and the actual picture of the setup is shown Fig. 2. The experimental setup mainly contains two systems: a burner system and an acoustic generating and sound acquisition system. 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 fuel nozzle is customized built, and the main dimensions are listed in the in Fig. 2 the unit of mm. The shell of the nozzle can be separated into two parts, named top holder and bottom holder. These two parts are sealed properly when flame on. Inside of the shell, it mainly contains a swirler to stabilize the flame and a honeycomb to smooth the fuel flow.

The dimensions of the tube are 1100 mm in length and 114 mm in width of the square. A large chamber is deliberately chosen so that the feedback mechanism from the flame itself can be minimised. The details geometry of the square tube is shown in Fig. 1(b). It consists the transparent top tube and steel pyramidal tube at the bottom. As the top end of the tube is open, to avoid the disturbance of the ventilation system in the lab, the nozzle position should keep a certain distance away from the top end. Considering the field of observation and the repeatability, the flame pattern and the sound pressure have been recorded within the range of the tube from 400 mm to 800 mm. The acoustic generator was 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 3 V. 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. The measurement uncertainty is presented in Table 1.

According the Previous research done by Chen [29], the four resonant frequencies in this duct are 63.61 Hz, 218.01 Hz, 385.11 Hz and 547.71 Hz. These results are measured at the room temperature condition without the flame on. The standing wave in the duct can be affected by the temperature and the flame. Therefore, the experimental measurements of the acoustic responses were made along the length of the tube using a microphone with the flame on. The pressure value has been recorded at different position from 400 mm to 800 mm with 2 mm intervals through the whole tube and the measurement point was in the centre of the tube. The range of excitation frequency was from 20 Hz to 600 Hz in increments of 5 Hz, with a voltage amplitude of 5 V. The experimental observation in Fig. 3 indicates that the first four modes of the present rig are 90 Hz, 200 Hz, 380 Hz, and 500 Hz.

The acoustic induced lifted-off behaviour is more evident under the high excitation frequency and high-pressure condition. Hence, the acoustic excitation frequencies of 380 Hz and 500 Hz were set as main frequencies for further investigation.

The optical record setup consists of a Photron-SA4 high speed colour camera with Sigma zoom 24–70 mm lens and the computer control and recording system. Both of the colour and schlieren images were recorded by the high-speed camera at the full frame of 1024 × 1024 pixels. The colour image recording method is shown in Fig. 4(a). To avoid the background noise signals affecting the weak flame signal detection, the experiments were carried out in a dark room in addition to using black background behind the flame. To ensure the accuracy and generalization, 2000 images were recorded at a shutter speed of 2000 images per second at each condition. The images were analysed by MatLab.

A single mirror schlieren imaging system was applied to visualise the flow dynamics and vortex structure. With this configuration, vortices in the hysteresis region and the self-illuminated flame were both clearly shown in the schlieren images. The setup for schlieren system is shown in Fig. 4(b). It consists of a point light source and one $\lambda/10$ parabolic mirror with 75 mm diameter and 75 cm focal length. A knife edge is placed at the focal point, just in front of camera, to adjust the brightness and contrast.

The flow field is measured by a PIV system which consists of a laser sheet generator, a laser pulse synchroniser, a seeding generator, a data acquisition system and data analysis software, shown in Fig. 4(c). A double-pulse ND: YAG laser, operating at a wavelength of 532 nm, a pulse rate of 15 Hz and an energy per pulse of 190 mJ is used in this experiment and it is synchronized with a TSI Powerview™ Plus 4MP Camera used to capture particle images. The Laserpulse Synchroniser model 610,035 from TSI is a timing control unit for the PIV applications. It automates control of the timing between laser pulses, camera, camera interfaces and image acquisition. For PIV measurements, these signals are controlled by the synchronizer via Insight 3G data acquisition, analysis and display software. A solid particle generator and average 3 μm titanium dioxide TiO_2 seeding particles are used in this experiment. These seeding particles are injected into the tube with the fuel and air together.