Dynamic flashback induced by sound wave in a premixed bluff-body stabilized flame

Liuyong Chang¹, Zhang Cao¹ and Lijun Xu¹*

¹ School of Instrumentation and Opto-Electronic Engineering, Beihang University, Beijing 100191, China
*Corresponding author’s e-mail: lijunxu@buaa.edu.cn

Abstract. Flashback is a critical issue for premixed flame, because it can result in increased pollutant emissions and serious mechanical damage. In this study, the sound wave is used to induce velocity fluctuation which further induces the flashback. The structure of the dynamic flashback induced by sound wave in a premixed bluff-body flame is studied using a high-speed camera. The sound pressure level is fixed at 94 dB and the sound frequency is set at 10 Hz, 30 Hz and 60 Hz, respectively. The flame images show that the transient structure of flashback can be obtained clearly by the high speed camera and the structure of flashback at different sound frequency is different. This indicates that the oscillation frequency of the instable flame affects the structure of flashback seriously.

1. Introduction
Bluff-body flame holder has been widely used in practical applications, e.g., gas turbine combustor, scramjet combustor and industrial furnaces [1]. In recent years, lean premixed combustion is adopted widely to reduce the NOx emissions [2-3]. Lean premixed combustion requires the air and fuel to be mixed upstream of the combustion chamber. Generally, the velocity of mixtures in premixing tube is much larger than the flame propagation speed to avoid the occurrence of flashback [4]. However, flashback will occur in two conditions below:

(1) The velocity of mixtures adjacent to the wall is so low as that the flow velocity is close to the laminar flame propagation speed.

(2) The flame instability reaches a certain amplitude resulting in the sudden propagation of flame against the flow direction.

Flashback is a series problem for premixed combustion, because it can result in increased pollutant emissions, serious mechanical damage and even security accidents [5]. Therefore, studying on the flashback mechanism is meaningful and necessary. In reality, a lot studies have been done to investigate the phenomenon of flashback. For example, Konle and Kiesewetter used the particle image velocity (PIV) and planar laser induced fluorescence (PLIF) simultaneously to investigate the flashback mechanism of a swirl burner [6]. Nauert et al. used a high speed camera to analyse the flashback in lean premixed swirling flames experimentally [7]. Sayad et al. used OH-PLIF to investigate the flashback mechanism and flashback limit at two moderate swirl numbers [8].

However, these works mainly investigate the flashback induced by the flame instabilities and mainly focus on the swirling flame. The flashback of bluff-body stabilized flame also needs investigation in-depth. Besides, sound wave can cause oscillation of flow velocity [9], and further induce flashback. The frequency and sound pressure level (SPL) of sound wave can be detected and
controlled easily. Therefore, investigation flashback induced by sound wave can help to understand the mechanism of flashback induced by flame instabilities.

The major object of this paper is to investigate the structure of flashback induced by sound wave. A high-speed camera is used to capture the transient flame image of premixed bluff-body stabilized flame. A loudspeaker is used to modulate the flow velocity. The flame images at the sound frequency ($f_s$) of 10 Hz, 30 Hz and 60 Hz under the SPL of 94 dB are presented and compared to study effect of the sound frequency on the flashback structure. This can be used to analyze the effects of oscillation frequency of instable flame on the flashback in premixed bluff-body stabilized flame. This paper is organized as follows: In section 2, the experimental setup used in this study is described. The experimental results and discussions are given in section 3. Sections 4 concludes the research results.

2. Experimental setup

An acoustically excited bluff-body burner was used in the present study. Fig.1 shows the schematic the experimental setup, which mainly includes a conical bluff body, a circular tube, a loudspeaker, a sound pressure level, a high speed camera and a computer. Same with our previous work [10], the larger diameter ($D_1$) and the half-angle of the conical bluff-body is 8 mm and 40°, respectively. The bluff-body is fixed on a rod with diameter of 1 mm concentrically mounted within the tube and the inner diameter of tube ($D_2$) is 10 mm. Hence the blockage ratio $\beta$ [11] is 0.64, which is calculated by:

$$\beta = \frac{D_2^2}{D_1^2}$$

The fuel and air are supplied into the tube from the holes near the bottom of tube. The mixing between the air and fuel starts when the air enters the tube and continues downstream through the mixing length ($L=100$ mm). The compressed fuel with a composition of 80% butane and 20% propane is used as the fuel in this study. The flow rates of air and fuel are controlled accurately using the mass flow controller (MFC, Sevenstar-CS200A). The loudspeaker was mounted at the bottom of the tube to introduce oscillations on the flow like the work of Wang et al. [12]. The loudspeaker is controlled by a Matlab procedure according to:

$$y = A \cdot \sin (2\pi \cdot f \cdot t)$$

where $y$ is the sound wave, $A$ is the amplitude, $f$ is the frequency and $t$ is the time series. The sound pressure level (SPL) meter is set at the upper end of tube, just as the work of Chen et al. [13], to measure the forcing amplitude before ignition. After the SPL is obtained, the SPL meter was taken away and the flame was ignited. The high speed camera (FASTCAM SA-Z) is used to capture the transient flame images at a data acquisition (DAQ) of 1000 frames per second (fps) and the flame images are transferred into the computer through a USB cable. During experiments, the equivalence ratio and the sound pressure level are fixed at 1.0 and 94 dB. The sound frequency is set at 10 Hz, 30 Hz and 60 Hz.

Fig. 1. Schematic of the experimental setup.
3. Results and discussions
In this study, a loudspeaker is used to introduce oscillations on flow velocity at the outlet of the bluff-body burner, just as the work of Lawn et al. [14]. Under a certain equivalence ratio and a certain sound frequency, flashback occurs when the SPL exceeds a certain value. In this study, the sound pressure level is fixed at 94 dB at the sound frequency of 10 Hz, 30 Hz and 60 Hz, respectively. Fig. 2 shows the flame images captured by high-speed camera at sound frequency of 10 Hz and SPL of 94 dB. The dotted lines in the flame images indicate the inner boundary of the premixing tube. It can be seen from the images that the flame outside the premixing tube presents a fungoid structure. The internal flame outside the premixing tube presents a structure of “π”, which is caused by the compression effect of sound wave. With the increase of time, the length of the flame outside the premixing tube increases. There is no flame in the premixing tube at t=0s, and appears flame in the premixing tube at t=0.002s. At t=0.002s, the area of flashback is very small as shown in Fig. 2. The area and the length of the flame inner the premixing tube increase to the maximum value at t=0.004s. At this time, the margin of the flame inner the premixing tube presents a shape of “S”. The narrowest position of the flame inner the premixing tube approaches to the bottom of the bluff body. After t=0.004s, the area of flashback decreases as shown in the flame images at t=0.006s and t=0.008s. At t=0.006s, the upper flame inner the premixing tube blows out, and the intensity of bottom flame inner the premixing tube is decreased. At t=0.008s, the flame inside the premixing tube disappears.

Fig. 2. Flame images captured by high-speed camera at \( f_s = 10 \) Hz and SPL=94 dB.

Fig. 3 shows the flame images captured by high-speed camera at \( f_s = 30 \) Hz and SPL=94dB. The overall structure of the flame at this condition is quite different with that at \( f_s = 10 \) Hz. There is no fungoid structure and no structure of “π” at this condition. The flashback appears at t=0.002s and the intensity of flashback increases to the maximum value at t=0.004s. At t=0.004s, the flame inner the premixing tube do not presents the shape of “S”. The maximum area of the flashback is smaller than that at \( f_s = 10 \) Hz and SPL=94dB. However, the reactions of the inner flame are more intensity compared with that at \( f_s = 10 \) Hz. At t=0.006s, the flashback almost disappears as shown in Fig. 3. The flashback disappears completely at t=0.008s.

Fig. 3. Flame images captured by high-speed camera at \( f_s = 30 \) Hz and SPL=94 dB.

Fig. 4 shows the flame images captured by high-speed camera at \( f_s = 60 \) Hz and SPL=94dB. It can be seen that the flashback also occurs at t=0.002s, disappears at 0.008s. The maximum area at this
condition is smaller than that at $fs=30$ Hz. Besides, the reactions of the inner flame are weaker than that at $fs=30$ Hz. The flame inner the premixing tube presents no regular structure as shown in the flame images at 0.004s and 0.006s in Fig. 4.

In total, the maximum area and maximum length of the flashback decreases as the sound frequency increases from 10 Hz to 60 Hz at SPL=94 dB. The reactions of flame inner the premixing tube at $fs=30$ Hz are more intense than that at $fs=10$ Hz and $fs=60$ Hz.

![Flame images captured by high-speed camera at $f_s=60$ Hz and SPL=94 dB.](image)

### 4. Conclusions

In this paper, the structure of dynamic flashback induced by sound wave in a premixed bluff-body stabilized flame is captured by a high speed camera. The images show that the flame inner the premixing tube presents a shape of “S” for the sound frequency of 10 Hz, and presents no regular structure at the sound frequency of 30 Hz and 60 Hz. The maximum area and the maximum length of the flame inner the premixing tube decreases as the sound frequency increases from 10 Hz to 60 Hz. The reactions of the flame inner the premixing tube at the sound frequency of 10 Hz are more intense than that at 30 Hz and 60 Hz. This indicates that for the actual instable flame, the high oscillation frequency decreases the length of flashback and enhances the intense of the reactions in the flame inner the premixing tube.

### Acknowledgments

The authors gratefully acknowledge the financial support from the National Natural Science Foundation of China (Grant No. 61620106004 and 61827802).

### References

[1] Chaudhuri, S., Kostka, S., Renfro, M.W., Cetegen, B.M. (2010) Blowoff dynamics of bluff-body stabilized turbulent premixed flames, Combust. Flame, 157, 4: 790-802.

[2] Jones, W.P., Marquis, A.J., Wang, F. (2015) Large eddy simulation of a premixed propane turbulent bluff body flame using the Eulerian stochastic field method, Fuel, 140: 514-25.

[3] Chang, L., Lin, Y., Cao Z., Xu, L., (2020) Effects of water vapor addition on NO reduction of n-decane/air flames, Energ. Source Part A, 42, 12.

[4] Kurdyumov, V., Fernandez-Tarrazo, E., Truffaut, J.M., Quinard, J, Wangher, A., Seargy, G. (2007) Experimental and numerical study of premixed flame flashback, Pro. Combust. Inst., 31, 1: 1275-82.

[5] Dam, B., Love, N., Choudhuri, A. (2011) Flashback propensity of syngas fuels, Fuel, 90, 2: 618-625.

[6] Konle, M., Kiseswetter, F., Sattelmayer, T. (2008) Simultaneous high repetition rate PIV-LIF-measurements of CIVB driven flashback, Exp. Fluids, 44, 4: 529-538.

[7] Nauert, A., Petersson, P., Linne, M., Dreizler, A. (2007) Experimental analysis of flashback in lean premixed swirling flames: conditions close to flashback, Exp. Fluids, 43, 1: 89-100.
[8] Sayad, P., Schonborn, A., Klingmann, J. (2016) Experimental investigation of the stability limits of premixed syngas-air flames at two moderate swirl numbers, Combust. Flame, 164: 270-282.

[9] Jing, W., Cao, Z., Zhang, H.Y., Qu, Q.W., Xu, L.J. (2017) A reconfigurable parallel data acquisition system for tunable diode laser absorption spectroscopy tomography, IEEE Sensors J., 18, 2: 528-539.

[10] Chang, L., Cao, Z., Fu, B., Lin, Y., Xu, L. (2020) Lean blowout detection for bluff-body stabilized flame, Fuel, 266, 15.

[11] Balachandran, R., Ayoola, B., Kaminski, C., Dowling A. Mastorakos, E. (2005) Experimental investigation of the nonlinear response of turbulent premixed flames to imposed inlet velocity oscillations, Combust. Flame, 143, 1-2: 37-55.

[12] Wang, G., Liu, X., Wang, S., Li, L., Qi, F. (2019) Experimental investigation of entropy waves generated from acoustically excited premixed swirling flame, Combust. Flame, 204: 85-102.

[13] Chen, L, Wang, Q., Zhang, Y. (2012) Flow characterization of diffusion flame in a standing wave, Exp. Therm. Fluid, 41: 84-93.

[14] Lawn, C.J., Williams, T.C., Schefer, R.W. (2005) The response of turbulent premixed flames to normal acoustic excitation, Pro. Combust. Inst., 30, 2: 1749-56.