Mode Transition of Interacting Flickering Flames

Anek BUNKWANG, Tsuneyoshi MATSUOKA, and Yuji NAKAMURA*
Toyohashi University of Technology
1-1 Hibarigaoka, Tempaku, Toyohashi 441-8580 Japan

1 Background and Objective of This Study

Flame flickering is one of typical buoyancy-induced instability phenomena and rich literatures are available on this regard [e.g., 1-2]. Nevertheless most of the existing works have been devoted to the dynamic behavior of the single fire and effect of their interaction is quite limited. The present work is motivated on this regard through investigation of the effect of interaction of multiple separated fires systematically. To model on the target phenomena, jet-diffusion flames are used for the present purpose. Thermocouple mounted at the flame base of the burner exit can tell the periodic motion of the flame behavior. Better understanding of the buoyancy-driven instability in a precise manner is the main target on this work. Although the presence of in-phase and anti-phase flickering behavior depending on the burner separation distance has been observed in past works [3-5], all of them were phenomenological, and less quantitative discussions have been provided. To clarify this issue, we have developed the well-controllable experimental system previously [6-7]. In this study, in order to examine the transition mechanism in scientific way, key parameters, namely, fuel flowrate, burner diameter, and burner separation distance, are systematically modified and key modeling strategy is then obtained.

2 Experiment

Since the details of adopted experimental and numerical models have been found elsewhere [6, 7], only brief description is made here. Experimental setup applied in this study is shown in Fig. 1. All experiments were performed at open atmosphere but inside the mesh screen to avoid an undesirable disturbance. Two identical circular burners, whose diameter, d, was employed in this study. Research-grade methane was issued at identical flowrate, Q, which was finely controlled by flow-control system consisted with the calibrated manometer at more than 99% of accuracy. The distance between two burners, L, can finely set in the range of 0.0-100.0 mm by using the optical stage. The condition at L = 0 mm means that two burners are perfectly aside, therefore, the burner axes are at distance of d, burner diameter. Dynamic flame behaviors were recorded by high-speed camera (CASIO EX-F1: 300 fps with 512 x 384 pixels). Fine thermocouples (TCs: K-type, junction dia.: 0.25 mm) were equipped near the burner tips to record the time-variation of signal via data logger. Harmonized frequencies, *f* [Hz], were obtained by analyzing the TCs' signal by operating the Fast Fourier transformation (FFT).

For optical image visualization, Schlieren imaging is employed in order to visualize the hot plume via shadow caused by the varying density. The system introduced in this study was shown schematically in Fig. 1. The experiment apparatus was positioned between the two collimating mirrors and spacing distance was set at 5 m. Stroboscope (Types: MSX-1A, Metered variac: 0-240V, Flashing range: 100-26000 rpm, Flashlamps: xenon) was used as a light-source. The focal length and diameter of the mirrors are 3.5 m and 0.28 m, respectively. The knife-edge and light source were placed at the focusing point of parabolic mirror and high speed camera was positioned with tripod closely to while a 300 mm zoom lens to fill the image plane was active. The spatial resolution is 0.58 mm/pixel in the imaging plate. Unrefracted light ray is blocked by cut-off implement that results in the gray pixel-intensity level of the background.

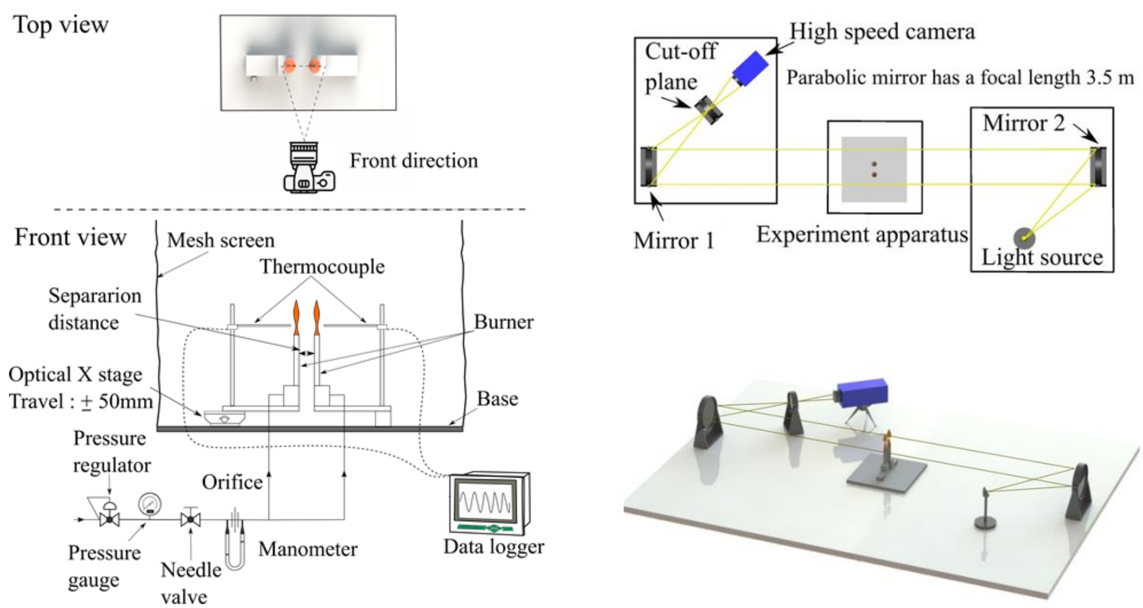

Fig.1 Schematics of experimental apparatus.

3 Results and Discussion

3.1 In-phase and Anti-phase Modes of Pulsating Motion

Figure 2 shows the typical sequential pictures of the pulsating methane-air jet flames obtained with various fuel flowrate (*Q*) and burner diameter (*d*) and the burner separation distances (*L*), together with the correspinding Schlieren images. As found by the previous work [6-7], it has been identified two kinds of dynamic modes exhibited by the interacting flames, such as in-phase and anti-phase modes, depending on the adopted condition. In the left, typical images of in-phase mode is shown, whereas the one of anti-phase mode is shown in the right. As seen in the figure, two buoyant flames successfully synchronized and the solid periodic motion can be attained. FFT of TC signals shows an apparent peak at the certain frequency, ensuring the dynamic motion shall be characterized by that frequency. Although not shown here, from the top view image, such synchronized motion occurs on the 2-D plane so that flame dynamics in depth direction from front-view images is neglected. In this regard, Schlieren imaging from front view would deliver beneficial yet sufficeint information of flame dynamics.

Based on the Schlieren imaging, it is understood that the hot plume over the flame are fully developed and merged when in-phase mode is presented, then the large hot plume can drive the whole dynamics of the flame. On the contrary, when the anti-phase mode is presented, hot plumes made by each jet flame does not merge completely, rather, they are always separated at the flaming zone although they are disturbed and mixed at far downstream.

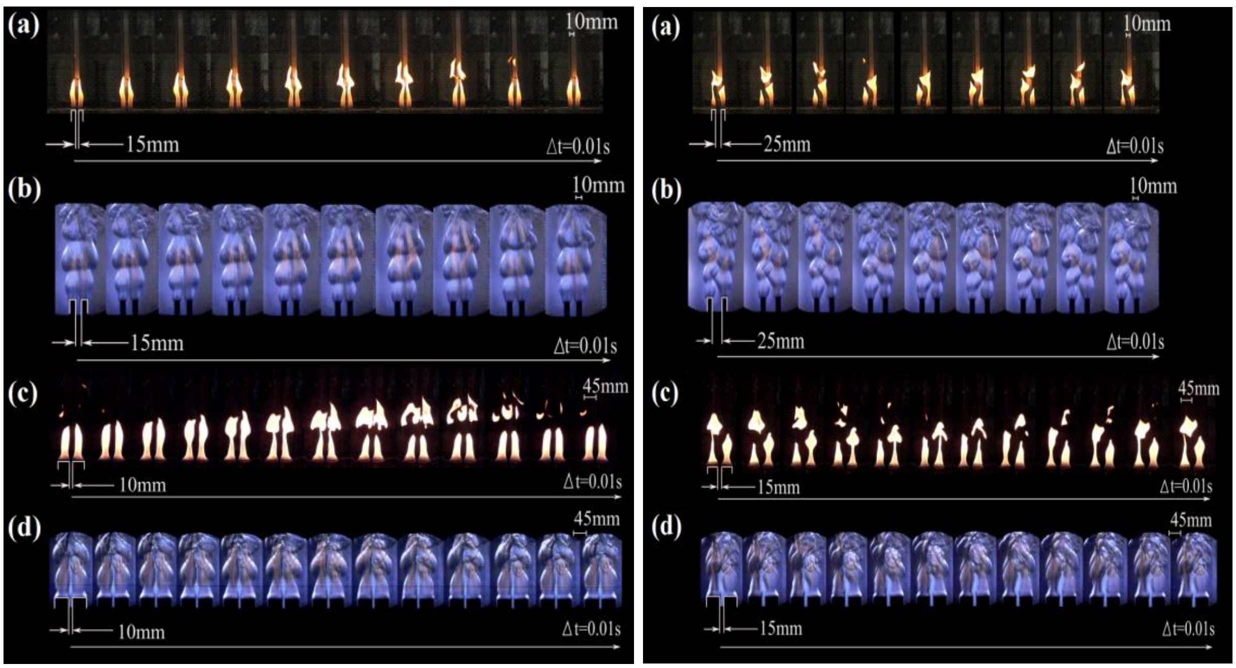

Fig. 2 Instantaneous image-sequence of pulsating methane plume and schlieren imaging under in-phase (left) and anti-phase (right) modes (a-b: d = 10.8 mm, L = 15 mm (left), L = 25 mm (right), Re = 76, Q = 1000 cc/min; c-d: d = 45 mm, L = 10 mm (left), L = 15 mm (right), Re = 37, Q = 2000 cc/min; Time interval: 0.01s)

3.2 Effect of Jet Momentum on Flickering Frequency

Figure 3 summarizes the averaged flickering frequency (*f*), which is considered as the characteristics dynamic measure of the present system, vs. the burner separation distance, *L*. In order to investigate the effect of the fuel flowrate (momentum of the jet), four cases of fuel flowrate ranging from 500 to 3500 cc/min are shown. As clearly found in this figure, sudden frequency jump was found at the critical separation distance (L_{crt}), which is nearly 20 mm in this case. At this distance, mode are changed from in-phase ($L < L_{crt}$) to anti-phase ($L > L_{crt}$), until the frequency reaches to the one found in the single burner case (~ 12 Hz in this case). More importantly, the critical condition is exactly identical for the wide range of the flowrate, confirming that the present periodic motion of the flame is governed by buoyancy under sufficiently smaller Froude number (a change of momentum is negligible since momentum of the jet isanyway much smaller than buoyancy).

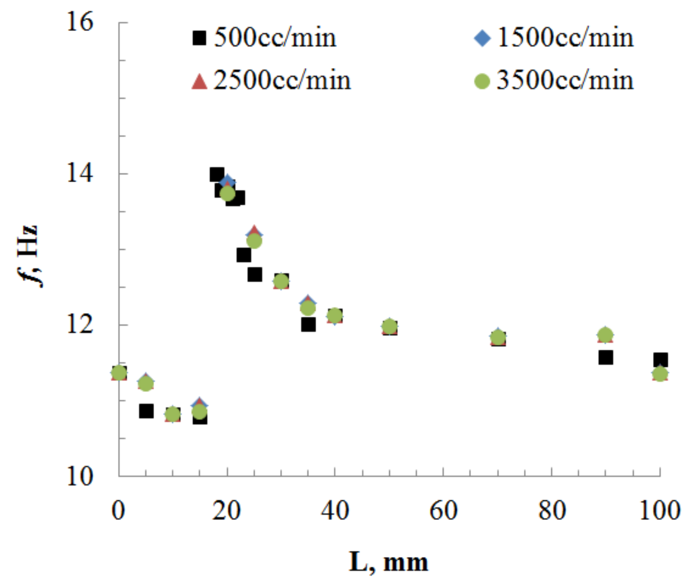

Fig. 3 Effect of burner separation distance on flickering frequency for varying of fuel flowrate. All cases shown here are at burner diameter of 10.8 mm

3.3 Effect of Fire Scale (Burner Diameter) on Flickering Frequency

Figure 4 summarizes the averaged flickering frequency (*f*) vs. the burner separation distance, *L*. In order to investigate the effect of the burner diameter, four representative cases ranging from 10 to 45 mm are shown.

As clearly found in this figure, for all cases studied here, the critical separation distance (L_{crt}) can be clearly identified, suggesting the overall trend (namely, the flame mode varies from in-phase to anti-phase when the burner separation distance is increased) is quite solid. Note that the critical separation distance (L_{crt}) was defined at the *L* when flickering mode is transit from in-phase to the anti-phase for each burner diameter case. As mentioned earlier, the condition corresponds to the sudden increase of the flickering frequency. Not likely in Sec 3.1, change of burner diameter is very sensitive to the dynamic frequency, also confirming that the present dynamics are mainly governed by the buoyancy which is controlled by the burner size (system characteristics scale).

The correlation between the critical separation distance, L_{crt}, and the burner diameter, *d*, shown in Fig, 4 (right) shows well-fit inverse of cubit power law. At present, there is no concrete theory/model to explain such correlation, however, this experimental fact suggests that there should be certain physics with critical value described by the 4th power of length scale to trigger the transition. Although not shown in the figure, it is found that the transition occurs when the boundary layers formed adjacent to the flame is merged and the merging point (height) becomes shorter as found in Schlieren images when the diameter gets larger. Because the larger diameter of the jet results in the stronger buoyancy flow, if one considers that there is certain critical condition of acceleration flow by buoyancy (namely, momentum by buoyancy) to reach transition point, at least the qualitative trend might be explained. Further study in underway and hopefully presented in the future journals.

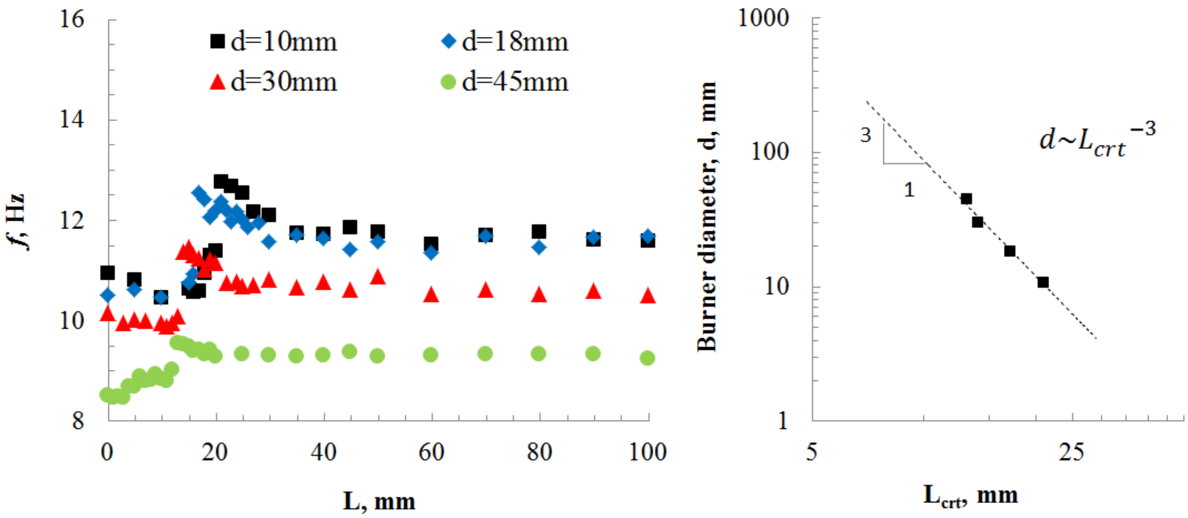

Fig. 4 Effect of burner separation distance on flickering frequency for various burner diameters (left) and dependency of critical separation distance (L_{crt}) on burner diameter *d*. All cases shown here are at fuel flowrate of 1000 cc/min except for 45 mm of 2000 cc/min

4 Remarks

An interacting behavior of two flickering jet-diffusion flames at various distances horizontally was investigated experimentally. Not only the presence of two-mode behavior, but also the transition from in-phase to anti-phase mode is successfully reproduced and investigated. Based on the systematic examination through this work, important key finding on the modeling strategy to describe the mode transition is experimentally obtained. To give the proper explanation on the present interesting flame dynamics of how the jumping condition is determined and what kind of physics lied in, further study is underway and discussions together with the numerical simulation (which is not shown in this manuscript, including the mathematical analysis) will be made in future.

Acknowledgments

This work is supported by The Toyota Physical and Chemical Research Institute, yr 2015. Assistance provided by Mr. Antoine Berthier, visiting student from University Pierre and Marie (currently, Sorbonne University) is greatly appreciated.

References

[1] Hamins A, Yang JC, Kashiwagi T. (1992). An experimental investigation of the pulsation frequency of flames. Proc. Combust. Inst., 24: 1695.

[2] Cetegen BM, Dong Y. (2000). Experiments on the instability modes of buoyant diffusion flames and effects of ambient atmosphere on the instabilities. Exp. Fluids. 28:546

[3] Toong T, Salant RF, Stopford JM, Anderson GY. (1965). Mechanisms of combustion. instability. Proc. Combust. Inst. 10 :1301.

[4] Kitahata H, Taguchi J, Nagayama M, Sakurai T, Ikura Y, Osa A, Sumino Y, Tanaka M, Yokoyama E, and Miike H. (2009). Oscillation and Synchronization in the Combustion of Candles. The Journal of Physics and Chemistry A, 8164.

[5] Fukuda M, Kudo Y, Ito A. (2003). Fire Characteristics of Subsisting Multiple Fire Sources in Three Dimensions. Bulletin of Japan Association for Fire Science and Engineering, 56.(3):45 (in Japanese).

[6] Mochizuki M, Nakamura Y. (2015). Experimental study on dynamically synchronized behavior of two flickering jet flames. Proc. AOSFST-10, Tsukuba, Japan, Poster-#062 (on USB).

[7] Mochizuki M, Matsuoka T, Nakamura Y. (2017). Study on oscillation and transition behavior of interacting flickering flames. Bulletin of Japan Association for Fire Science and Engineering, 67.(2): 21. (in Japanese).