Synchronization of dual diffusion flame in co-flow

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ABSTRACT

In this study, the interaction of two adjacent diffusion flames (dual flame) were experimentally investigated using the direct imaging method and particle image velocimetry (PIV) measurements for varied distances between the two flames under the influence of the co-flow. The direct imaging method indicates the presence of various synchronization modes, such as merging, in-phase synchronization, amplitude death, anti-phase synchronization, and desynchronization, as the distance between the flames was increased. The dual flame synchronization was characterized using an image analysis of the time-series variation of flame heights summarized by the mean flame height, root-mean-square of the flame height, Strouhal number, and the cross-correlation coefficient of flame heights against the burner distance. Furthermore, the unsteady velocity fields of the synchronized flames were measured using PIV combined with the proper orthogonal decomposition (POD) analysis to extract the flow structure of the dual flame. The experimental results indicated that the in-phase mode is characterized by the formation of symmetrical vortices, whereas the anti-phase mode features the formation of asymmetrical vortices inside and outside of the flame. The POD analysis demonstrated higher fluctuating energy in the anti-phase mode than in the in-phase mode, which suggested the formation of a highly organized flame structure in the anti-phase mode.

1. Introduction

The instability of the flame is a fundamental topic of interest in combustion science. It is also practically important to design high performance burners for combustor. Flame flickering is one of the instability modes and has been studied in literature due to fundamental interests in combustion science. This phenomenon is known as the periodic oscillation of the flame, and the flickering frequency is observed mostly at 10–20 Hz. This frequency is weakly dependent on the Froude number and insensitive to the fuel type [1,2]. The mechanism of flame flickering is caused by the fluid dynamic instabilities, such as the Kelvin–Helmholtz and Rayleigh–Taylor instabilities in the shear layer between the flame and the surrounding fluids of different densities, because the buoyancy forces arising from the high-temperature flame acts as the driving force of instability [3–7]. The periodic behavior of the flickering flame is caused by the large-scale structure in the outer layer of the flame called the toroidal vortices oscillating slowly along the flame [1,8]. The scale of the toroidal vortices extends up to several diameter of burner in lateral direction [8]. Therefore, flame interaction is enabled, when another flame is located adjacent to it.

The velocity field of the flame has attracted considerable interest due to the importance of convective transport of heat and momentum transfer across the flame. In recent times, the particle image velocimetry (PIV) method has been introduced for the unsteady velocity field measurements in the flame [9–11]. This system enables two-dimensional instantaneous velocity fields across the flame by illuminating the cross-section of the flame with a laser light-sheet and capturing the visualized tracer images in the cross-section of the flame. This experimental technique of PIV combined with the proper orthogonal decomposition (POD) analysis provides a powerful tool for investigating the flow physics of the flickering flame [8,12].

Flames that are placed adjacent to each other exhibit the phenomenon of flame interaction, which is often called the “synchronization”. This is a topic of interest in this research and has been studied by several researchers in literature [13–21]. These studies show the in-phase and anti-phase synchronization of the dual flame, where the flame interacts with each other and the flickering frequency changes from the case without synchronization.

A literature survey on flame interaction indicates that two candle flames that are placed adjacent to each other exhibit in-phase and anti-phase synchronizations [13,14]. The in-phase synchronization is the symmetrical flame oscillation mode with respect to the centerline of the dual flame, while the anti-phase synchronization is the asymmetrical flame oscillation mode, where the flames exhibit anti-phase periodic motion with respect to the dual flame centerline. Furthermore, a similar
flame interaction pattern was observed among three candles placed in a triangular arrangement [15]. The dual flame exhibits in-phase and anti-phase synchronizations, when the distance between the flames is increased. Therefore, the variations in the synchronizations depend on the distance between the two flames.

The mechanism of synchronization of the two flames located adjacent to each other has been a central topic of interest in recent times. Kitahata et al. [13] observed the synchronization of the dual flame and examined the mechanism by proposing a nonlinear oscillator model. On the other hand, vortex dynamics is another possible mechanism of flame synchronization of a pair of flames, as suggested by Forester [14] and Okamoto et al. [15]. They argued that the synchronization of the in-phase and anti-phase synchronization through the vortex dynamics that exists between them. The observation of the dual flame behavior has been carried out in recent years to understand the mechanism of dual flame. Manoj et al. [16] showed the presence of amplitude death (AD) between in-phase and anti-phase mode along with the variation in frequency and correlation coefficient with distance between the flames. Further experimental studies [18–20] were carried out for the flow field using schlieren and infrared imaging [18], shadowgraph imaging [19] in the candle flame, and direct imaging [20] in a burner flame. They demonstrated the physics behind the occurrence of the dynamical states in two coupled flames. Furthermore, numerical studies were carried out on the interaction mechanism of coupled turbulent fires [17] and the dynamical behavior of pool flames [21]. However, the physics behind the flame synchronization is still not completely understood because of the complex mechanism of synchronization associated with the flame flickering phenomenon.

The purpose of this study is to investigate the mechanism of synchronization in the dual flame from the point of flow field using the direct imaging method and PIV velocity field measurements in combination with the POD analysis that enables the visualization of the flame structure inside and outside the dual flame.

2. Experimental apparatus and procedure

2.1. Experimental setup

The experiments are carried out in a test section, as illustrated in Fig. 1. The dual pipe-burner is situated in the test section and the two pipe burners located adjacent to each other supply the fuel methane for flame. The length of the pipe is 700 mm, and it possesses a straight exit section of length 200 mm. The pipe diameter \(d\) of the dual burner was set to 11.4 mm. It is noted that the distance between the centers of the two burner pipes \(l\) could be varied from 13 to 120 mm using the traversing mechanism. The temperature of the fuel and surrounding air were constant at approximately 290 K. The dual burner was set in the co-flow of 250 mm in diameter. The co-flow was added to the dual flame to eliminate the unsteadiness in flickering flame [22–25]. The co-flow velocity ratio \(V_c\) was set to 0.9, where \(V_c\) is the co-flow velocity and \(V_f\) is the fuel flow velocity. It is known that the co-flow of this velocity ratio can eliminate the unsteadiness in flickering flame without changing the flickering frequency [25]. The flow rate of fuel methane was set to 0.5 l/min in this experiment, which corresponds to the Froude number \(Fr\) \(= V_f^2/gd\) = 0.06 (g: gravitational acceleration).

2.2. Flame characterization

The flame characterization was performed using the direct imaging of the dual flame. This technique allows the visualization of flame luminosity arising from the soot formation. Flame characterization of the dual flame was performed by evaluating the mean flame height \(H_m\), root-mean-square (RMS) of the flame height \(H_{rms}\), flickering frequency \(f\) (Hz), and the cross-correlation coefficient of dual flame heights \(C\) \(= \overline{H_L H_R}/H_{rms\,rms}\), where \(H_L\) and \(H_R\) are instantaneous heights of left and right flames, respectively, and the overbar shows the time-averaging property. These characteristics were obtained from the direct flame images captured by a camera, which operates at a frame rate of 60 fps with the spatial resolution of 480 × 640 pixels and produces a
flame image of size 180 mm × 180 mm. To characterize the dual flame, the edge detection method was conducted on two adjacent pixels of the flame image using the gray-level ratio technique, and the mean and RMS flame heights were obtained. The flickering frequency $f$ (Hz) was obtained from a fast Fourier transformation analysis of the average intensity of images, and was converted into the Strouhal number $St (=fd/V_f)$. Furthermore, the cross-correlation coefficient $C$ was evaluated using the instantaneous flame heights of the dual flames that quantify the flame behavior.

Fig. 2. Direct images and the time-series variations of flame height of the single and dual flames. (a) Single flame images, (b) In-phase mode ($l/d = 2.6$), (c) Anti-phase mode ($l/d = 4.4$), (d) Amplitude death ($l/d = 3.0$).
2.3. Measurement of velocity field

To characterize the velocity field of the dual flame, the instantaneous velocity field was measured by the PIV system, which includes the CW Nd:Yag laser (8 W), a high-speed camera (1200 fps, 1024 × 1024 pixels, 8 bits), and a pulse controller. Note that the time interval of a set of two images is set to 1/6000 s. The flow visualization was conducted using the SiO₂ tracer particles of 5 μm in diameter illuminated by the laser light sheet of 1-mm thickness. Tracers were supplied to the fuel flow and co-flow using two rotary mixers driven by a DC motor, which combines the gas and tracers in the container using the rotating propeller. The tracer concentration can be controlled by the rotational speed of the propeller. A total of 12,000 images were captured over a duration of 10 s by the high-speed camera operating at 1200 fps. The instantaneous velocity field was evaluated with the sequential two images using the direct cross-correlation algorithm and a

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(c) Amplitude death ($l/d = 3.0$)

(d) Anti-phase mode ($l/d = 4.4$)

Fig. 2. (continued)
sub-pixel interpolation method for the PIV analysis [26]. The interrogation window size was set to $31 \times 31$ pixels with 50% overlap in the analysis. The maximum displacement of the PIV images was set to approximately 4 pixels by controlling the time interval of the sequential two images. The invalid velocity vectors were less than 3% of the total velocity vectors. The uncertainty interval of the PIV analysis was 3.7% at 95% coverage, in which the majority of the errors comes from the sub-pixel analysis errors arising from the non-uniform seeding density of the tracers [8,27].

2.4. POD analysis

Snapshot POD analysis is one of the most efficient statistical methods for detecting the energetic flow structure in the instantaneous velocity fields measured by the PIV. In this analysis, the fluctuating velocity fields are decomposed into linear combinations of orthogonal eigenfunctions of temporal and spatial correlations [25,28–30], which enables the evaluation of the mean velocity field in the 0th POD mode and fluctuating velocity field in higher POD modes. Therefore, the lower POD modes contain higher fluctuating energy of the velocity fields. The details of this analysis has been described in literature [25], and therefore, it is not repeated in this study.

3. Results and discussions

3.1. Direct observations of single and dual flame

Fig. 2(a)–(d) show the time-series observations of the single flame, in-phase mode, amplitude death mode, anti-phase mode of the dual flame, respectively. The in-phase mode is observed at the burner distance of $l/d = 2.6$, the anti-phase mode is at $l/d = 4.4$, and the amplitude death is at $l/d = 3.0$. These are the direct images of luminosity distribution of the flame captured by the camera operating at 60 fps, while the time-series variation of the flame height is shown below the flame images for comparison. The time-series images and flame height variation start at the minimum flame height ($t = 0$ s) and shown for every 1/60 s, while the normalized time $t/T$ is shown for comparison, where $T$ is a cycle period of flame flickering. It is noted that the range of normalized time changes for each flame configuration, which reflects the minor change in the cycle period of flame flickering in agreement with the Strouhal number variation in Fig. 3(c).

A clear symmetry of the flame behavior is caused by the influence of the co-flow surrounding the flame. Otherwise, the flickering behavior suffers from the influence of random motion, which results in an asymmetric behavior of the flame [25]. In order to demonstrate the influence of the co-flow, the time-series observations of a single and dual flame without co-flow (in-phase and anti-phase modes) are shown in Appendix 1 for comparison. These visualizations indicate that large-scale unsteady fluctuation arising from the flame instability is highly magnified in the dual flame without co-flow. The comparative study indicates that the co-flow acts to stabilize the large-scale unsteady fluctuation of the flame, which was similarly observed in the single flame in co-flow [22–25].

The single flame pictures in Fig. 2(a) demonstrate the periodic flame oscillation caused by flame flickering. This figure shows an iteration of the periodical flame behavior including the growth of the flame height ($t = 0–2/60$ s), suppression of flame width in the mid flame (3/60 s), the flame detachment (4/60 s), and the flame returns to the shortest flame again. It can be observed that the flame luminosity is the highest at the instant of flame detachment, which agrees with the previous observations [8]. The time-series variation of the flame height shows the corresponding periodicity of the flame.

The dual flame pictures in Fig. 2(b) show the flame behavior in the in-phase mode. This figure demonstrates a symmetrical flame shape with respect to the centerline of the dual flame. It is observed that the two flames approach each other near the burner exit at the minimum
The dual flame attains the highest luminosity before the detachment of the flame (\(t = 3/60\) s), which is similar to the observation of single flame in Fig. 2(a). It is noted that the flame height is defined by the height including the detached flame. The time-series variation of the flame height shows the overlapped traces here, suggesting the repeatability of the same motion of each flame in the in-phase mode.

The dual flame pictures in Fig. 2(d) show the anti-phase mode of the flame. This figure demonstrates the asymmetric flame formation with respect to the dual flame centerline. When the left flame is the shortest (\(t = 0\) s), the right flame exhibits high flame height. Therefore, the flame behavior of the dual flame repeats a periodic motion with a half-cycle difference. When the elapsed time is increased, the left flame initiates a clip-off motion and becomes detached at \(t = 3/60\) s, while the right flame starts to grow and becomes detached immediately after the elapsed time \(t = 5/60\) s. Thus, the dual flame indicates a half-cycle phase difference between the left and right flames. However, there is a minor difference in the flame shape between the left and right flame due to the complex flame behavior. The time-series variation of the flame height shows the opposite traces in the flame oscillation, suggesting the opposite phase motion of the flame in the anti-phase mode.

These flame observations on the in-phase, amplitude death, and anti-phase mode of dual flame look similar to the previous results [16,18–20]. However, the flame behavior in the amplitude death observed here is slightly deviated from that of the candle flame. In the amplitude death of the candle flame, the flame oscillation is highly damped with slender and long flame [15,16], while it is slightly damped in the present burner flame. Therefore, the flame behavior of the amplitude death in the present experiment qualitatively agrees with the previous observations in the candle flame.

With further increase in the burner distance, two flames behave independently and returns to the single mode in Fig. 2(a). The time- variations of the single flame and the desynchronized two flames are shown in Appendix 2 for comparative purpose. It should be mentioned that the transition of the dual flame from one mode to another is highly related to the burner distance, which may be due to the variation of global instability of the dual flame [31].

### 3.2. Characterization of dual flame

Fig. 3(a)–(c) show the mean, RMS flame heights and the Strouhal number variations of the dual flame for varied burner distances \(U/d\), which are measured at the volume flow rate \(Q = 0.5\) m\(^3\)/s. The results corresponding to the single flame are shown in the figures along the line \(U/d = 0\). Note that mean and RMS flame heights are normalized by the mean height of a single flame \(H_0\), which is 123 mm.

It is observed from the results of the mean flame height \(H_m\) variations (Fig. 3(a)) that a merged flame appears, when the burner distance is less \((U/d < 2)\). At this point, the flame height of the dual flame is higher than that of the single flame, which is caused by the increased volume flow rate of fuel. With further increase in the burner distance, the mean flame height decreases and becomes constant, which is followed by a minor flame height variation in the anti-phase mode. The high flame height in the anti-phase mode closely agrees with that in the desynchronization at a higher value of burner distance. It should be mentioned that the boundaries of the mode change are determined from the flame observation by direct imaging.

Similar results were obtained for the RMS flame height variations across different burner distances \(U/d\). These results are shown in Fig. 3(b). It is observed that the RMS flame height attains a high value in the merged flame at a smaller burner distance, which is followed by a lower value at the in-phase mode and the anti-phase mode. Note that the RMS flame height in the desynchronization is the same as the single flame. The RMS flame height indicates a local low value during the transition of the in-phase to the anti-phase mode, which is the amplitude death mode, and the flame oscillation is weakened, while the flame height is approximately equal to the single flame (Fig. 3(a)).

It is observed from Fig. 3(c) that the Strouhal number (St) demonstrates a low value in the merged flame and in-phase mode and then a sharp increase during the transition from the in-phase to anti-phase modes, followed by a gradual decline in the anti-phase mode and desynchronization. These observations of the dual flame characteristics agree well with those of the former qualitative flame images of the dual flame at various burner or candle distances [13,16,19,20].
correlation coefficient \( C \) was evaluated using the direct flame images. Fig. 4 shows the cross-correlation of the dual flame for varied burner distances \( l/d \), where the flow rate is fixed at \( Q = 0.51/s \). The experimental results demonstrate a positive correlation for the in-phase mode, a negative correlation for the anti-phase mode, and a zero correlation in the desynchronization. The amplitude death at the transition of in-phase to anti-phase modes shows a low correlation near the intersection of the positive and negative correlations, which is similar to the behavior of the desynchronization at larger values of burner distance. It is interesting to observe that the correlation magnitude is higher in the in-phase mode and lower in the anti-phase mode. This is because, the similarity between the shapes of the two flames declined in the anti-phase mode, as observed from the direct flame images in Fig. 2(c). Therefore, the scattering of the detached flame height is higher in the anti-phase mode, as these flames appear more frequent in the flickering cycle. This results indicate that the cross-correlation coefficient is a good indication of the flame behavior of the dual flame synchronization.

3.3. Mean velocity fields of dual flame

Fig. 5(a) and (b) show the mean velocity fields obtained from the PIV measurements for the in-phase \((l/d = 2.6)\) and anti-phase \((l/d = 4.4)\) modes of the dual flame, respectively. It is noted that the mean velocities are estimated from the time-averaging 600 instantaneous velocity fields of the PIV measurement taken in a period of 10 s. The mean velocity field of the in-phase mode (Fig. 5(a)) is featured across the small burner distance of the dual flame, which is observed in the merged mean velocity downstream. In contrast, the mean velocity field of the anti-phase mode (Fig. 5(b)) is featured across the large burner distance, which results in a low velocity between the flames. Furthermore, the mean velocity spreads outward, as the distance from the burner increases, which results in the divergence of the two flames in the downstream. The position of high velocity magnitude in the anti-phase mode is lower than that of the in-phase mode, which agrees qualitatively with the observation of lower flame height in the anti-phase mode in Fig. 3(a). It is noted that the mean velocity distributions of a single flame have been reported in Ref. [8], which shows a symmetrical velocity profile with respect to the centerline. Note that the results apply to the single flame in the desynchronization, too.

To clearly understand the difference of the mean velocity fields of the in-phase and anti-phase modes, the local maximum mean velocity and the centerline velocity of the dual flame are plotted against the downstream distance \( y/d \) from the burner, which is shown in Fig. 6. The experimental result indicates that the maximum velocity increases up to \( V_{\text{vmax}}/V_f = 31 \) for the single flame \((V_f \text{ fuel velocity at the burner})\), whereas the anti-phase mode is \( V_{\text{vmax}}/V_f = 27 \) and that of the anti-phase mode is \( V_{\text{vmax}}/V_f = 23 \). Moreover, the peak position for the single flame occurs at \( y/d = 10 \), while that of the in-phase mode is at \( y/d = 11 \) and that of the anti-flame mode is at \( y/d = 8 \). These experimental results indicate that the maximum mean velocity field of the dual flame declined due to the interaction of the two flames, which is observed mostly in the anti-phase mode. This interaction effect is not observed near the burner at \( y/d < 4 \). The interaction effect of the dual flame is also observed in the centerline velocity variation, as shown in Fig. 6. The experimental results indicate that the centerline velocity of the anti-phase mode is much lower than that of the in-phase mode, which is due to the divergence of the two flames downstream in the anti-phase mode, as observed in Fig. 5.

3.4. Phase-averaged velocity and vorticity contours

Fig. 7(a) and (b) show the contour maps of the phase-averaged velocity vectors and vorticity contour \( \zeta \left( = \partial U/\partial x - \partial V/\partial y \right) dV/dT \) for the in-phase mode, respectively, at four different normalized time \( t/T = 0, 0.25, 0.5, 0.75 \), and the color contour shows the velocity magnitude \( V_{\text{vmax}} \). These results were obtained from the snapshot POD analysis of 1000 velocity fields using the two major energy modes reconstruction [8,32]. The phase-averaged velocity contour (Fig. 7(a)) shows that the high velocity region moves upward along the dual flame with an increase in \( t/T \). The high velocity region is located at the edge of the soot formation region in the direct images. This phenomenon is observed in the single flame as well [8]. The high velocity region of each flame is located close to each other in the in-phase mode, which is caused by the approaching behavior of the two flames, as observed in the direct images shown in Fig. 2(b) and the mean velocity values shown in Fig. 5(a). Thus, the velocity field of the in-phase mode shows a converging behavior \((t/T = 0 \text{ at } y/d = 7)\) after the initiation of the high velocity region adjacent to the burner exit at \( t/T = 0.5 \left( y/d = 3 \right) \), which is followed by the upward movement of high-velocity region at \( t/T = 0.75 \left( y/d = 5 \right) \).

In contrast, the phase-averaged vorticity contour (Fig. 7(b)) shows the formation of positive and negative vorticity on both sides of the flame. The high vorticity region is formed on both sides of the high velocity region. This indicates that the vorticity generation is closely related to the high velocity region, in which the velocity gradient is higher than others. The high magnitude of vorticity is generated along the inner flame as well, where the high velocity gradient is observed along the inner side of the high velocity region. The vorticity in the inner layer of the dual flame is highly observed along the flame axis on both sides of the high velocity region.

Fig. 8(a) and (b) show the corresponding velocity and vorticity fields for the anti-phase mode, respectively, at four normalized time \( t/T = 0, 0.25, 0.5, 0.75 \). The velocity field (Fig. 8(a)) shows the formation of high velocity regions in each flame, which demonstrate a staggered arrangement of the high velocity regions in the dual flame. A detailed examination of the vorticity field shows that the high velocity region on the left flame is generated adjacent to the burner exit \((t/T = 0)\) and moves vertically. It is also revealed that the velocity magnitude increases with an increase in the normalized time \( t/T \). However, the growth of the high velocity region on the right flame is delayed by a half-cycle, and a growth similar to that of the high velocity region on the left flame is observed. Furthermore, the high velocity region on the left flame expands to the right and that of the right flame expands to the left near the centerline of the dual flame, where the low velocity region prevails. This interacting motion of the dual flame is clearly observed between the flames in the anti-phase mode, which is different from that in the in-phase mode. These results indicate that the interaction of the two flames is more evident in the anti-phase mode. The vorticity field of the dual flame in the anti-phase mode shows the formation of high vorticity on the outer layer of the dual flame, which demonstrates a positive vorticity on the left flame and a negative vorticity on the right flame. The high magnitude of vorticity is generated near the high velocity region because of the presence of high velocity gradient. Therefore, the high vorticity regions prevail over the dual flame in a staggered arrangement. The examination of the vorticity contour in the inner side of the dual flame shows the formation of a negative vorticity along the left flame and a positive vorticity along the right flame. Moreover, the magnitude of the vorticity in the inner layer is less than that of the vorticity in the outer layer. It is noted that the inner vorticities appear in a staggered arrangement as well. These results indicate that the formation of vorticity in
Fig. 7. Phase-averaged velocity and vorticity fields for the in-phase mode. (a) Velocity field $v_{mag}/V_f$, (b) Vorticity field $\zeta$.

Fig. 8. Phase-averaged velocity and vorticity fields for the anti-phase mode (a) Velocity field $v_{mag}/V_f$, (b) Vorticity field $\zeta$. (a) Velocity field $v_{mag}/V_f$, (b) Vorticity field $\zeta$. 

the dual flame is highly different in the in-phase and anti-phase modes. However, the interaction of the two flames are highly magnified in the anti-phase mode compared to the in-phase mode, which can be observed in the color contour of vorticity magnitude. This result suggests that the entrainment of the surrounding air from the outside is increased for the synchronization of dual flame in the anti-phase mode.

3.5. Consideration on vorticity field by POD analysis

To examine the flow structure of the synchronized dual flame, a snapshot POD analysis was performed on 1000 instantaneous velocity fields and the first and second POD modes were evaluated. The results of the in-phase and anti-phase modes are shown in Figs. 9 and 10, respectively.

Fig. 9(a) and (b) show the first and second POD modes for the in-phase mode of the dual flame, respectively. Each POD mode is shown by the x, y components of velocity vector, and the color contour shows the vorticity of each POD mode normalized by the maximum. The first and second POD modes contain 18.3% and 16.3% of fluctuating energy, respectively. The results indicate that the velocity field of the dual flame consists of a large-scale vorticity in the outer layer of the dual flame, which corresponds to the toroidal vortices. The vortices are located symmetrically with respect to the centerline of the dual flame. However, the inner-layer vortices are generated between the flames, which induces the upward and downward flows depending on the combinations of the signs of vortices. The downward flow is observed at y/d = 7, and the upward flow is observed at y/d = 10 in the first POD mode, while the downward flow at y/d = 5 and the upward flow at y/d = 8 are observed in the second POD mode. These features of the POD modes and the vorticity in the in-phase mode are similar in the single flame, as described in the literature [8].

Fig. 10(a) and (b) show the first and second POD modes in the anti-phase mode of the dual flame, respectively. The first and second POD modes contain 22.9% and 21.9% of fluctuating energy, respectively. Therefore, the relative fluctuating energy in the anti-phase mode is higher than that in the in-phase mode. These results indicate that the vorticity formation is a staggered arrangement in the outer layer of the dual flame, and the vorticity is widely distributed in comparison with that in the in-phase mode. This is due to the varied behavior of the phase-averaged mean velocity fields in the in-phase and anti-phase modes of the dual flame. The vorticity magnitude in the anti-phase mode is magnified in the region far from the burner, where the detached flame is highly deformed by the synchronization. However, the clockwise and counter-clockwise vorticities are formed along the centerline of the dual flame. Therefore, the dual flame becomes asymmetrical to the centerline and a staggered arrangement of the vorticity field is generated along the dual flame, as observed in the flow visualization pictures in Fig. 2(d). The inner vortices are located at y/d = 8, 11, 13 in the first POD mode, while they are shifted to y/d = 6, 9, 12 in the second POD mode without any structural change. These results indicate that the symmetrical mode of flickering is formed in the in-phase mode, while the asymmetrical mode is formed and magnified in the anti-phase mode. The scale of the vortices along the centerline of the flame is larger in the anti-phase mode than those in the in-phase mode. Furthermore, more vortices are observed along the flame in the anti-phase mode than the in-phase mode, reflecting an increase in the Strouhal number in the anti-phase mode in Fig. 3(c). It should be mentioned that the in-phase and anti-phase modes of the dual flame is controlled by the burner distance. Therefore, it can be concluded that the synchronization of the dual flame depends highly on the burner distance, which controls the dynamic behavior of vorticity formation pattern inside and outside the dual flame.

4. Conclusions

In this study, the interaction of two adjacent diffusion flames in the coflow was studied from the point of flow field using the direct imaging method and PIV velocity field measurements to understand the synchronization mechanism of the dual flame. The direct imaging of the dual flame demonstrated the presence of various synchronization modes, such as the merging, in-phase, amplitude death, anti-phase, and desynchronization, with increasing burner distance. These flame variations were characterized by the image analysis of the time-series flame images, in which the mean flame height, RMS flame height, Strouhal number, and the cross-correlation coefficient were considered with respect to the burner distance. Furthermore, the unsteady velocity fields of the in-phase and anti-phase modes of the dual flame were studied by the PIV combined with the POD analysis to extract the flow structure of the flame interaction. The experimental results indicated that the in-phase mode was characterized by the formation of the symmetrical vortex pattern, while the anti-phase mode was featured by the asymmetrical vortex pattern between the two flames. The POD analysis indicated that a higher fluctuating energy was observed in the anti-phase mode, which suggested the presence of highly energized flame interaction in the dual flame. Therefore, it is confirmed that the synchronization of the dual flame is highly magnified the vorticity formation pattern in the anti-phase mode, which is larger than the in-phase mode.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1

(See. Fig. A1)

Fig. A1. Direct images and the time-series variations of flame height of the dual flame without co-flow.
Appendix 2

The time-series variation of the flame height of the single flame and desynchronized two flames \((l/d = 7.9)\) are shown in Figs. A2 and A3, respectively. Note that three enlarged views of the single and dual flames in a period of 0.5 s are compared with those of the first period 0 to 0.5 s for each flame observation. These results indicate that the single and desynchronized flames consist of various phases of flame oscillation, which may be caused by a chaotic variation of the flickering frequency. These results suggest that the single and desynchronized flames behave similarly within a range of experimental uncertainty. (See Figs. A2 and A3)

Fig. A2. Time-series flame height variation for single flame in co-flow.

Fig. A3. Time-series flame height variation for desynchronized dual flame in co-flow \((l/d = 7.9)\).
References