Flame synchronization and flow field analysis of double candles

Guancheng Hao 1*, Bowen Pang 2b, Qilin Zhang 3c, Fei Cui 2, Sijia Sun 4 and Shuo Liu 2.

1 Department of Vehicle Engineering, Shenyang Aerospace University, Shenyang 110136, China
2 Department of Flight Vehicle Manufacturing Engineering, Shenyang Aerospace University, Shenyang 110136, China
3 Department of Flight Vehicle Propulsion Engineering, Shenyang Aerospace University, Shenyang 110136, China
4 Department of Public Administration, Huazhong Agricultural University, Wuhan, 430070, China
*1255815019@qq.com, b1368578272@qq.com, c3255620798@qq.com

Abstract — Flame instability is an interesting topic in combustion science, and it is also of great practical significance for designing high-performance burners. In recent years, the synchronization phenomenon caused by a pair of coupled candles has aroused widespread attention, among which in-phase and anti-phase are two notable examples. In order to understand the flow structure of the flashing flame and the reasons for the synchronization of the flame oscillator, COMSOL flow field analysis technology and MATLAB grey analysis technology were used to analyze the flow field of candles in three combustion states and the change of candle combustion state respectively. By analyzing the flow structure of flashing flame, the reasons of different burning states of candles are explained. Moreover, the experimental and numerical simulation results show that the in-phase mode is characterized by the symmetrical formation of vortex concerning the centerline of two groups of flames, and the flames are vertically stretched under the vortex action. The characteristic of the anti-phase mode is that the vortex alternately forms asymmetrically concerning the centerline of two groups of flames, and the non-uniformity and asymmetry of the vortex lead to the instability of the flame surface. The characteristic of the incoherent mode is that the vortices generated by the two candle groups no longer act on each other, and the airflow field between the two candle groups remains approximately unchanged.

1. Introduction
Since the invention of the candle and its subsequent use for lighting purposes, the flickering of candle flame has long been discovered by people. The candle's high availability, low cost, and stability make it an ideal choice for people to explore flame oscillation. The principle of candle flickering is of great significance in various fields to improve combustion efficiency and stability. Flames flicker is due to the instability of fluid dynamics [1-2]. The flame oscillates periodically, and the flicker frequency is mostly 10–20 Hz. The mechanism of flame flicker is that the buoyancy generated by jet flame acts on the flame surface in an unstable form [3-4]. The flame synchronization phenomenon is caused by the structure of the outer layer of the flame, which is called the annular vortex that oscillates slowly with the flame [5].
The periodic behaviour of flashing flame is caused by the annular vortex, which oscillates slowly along with the flame. The annular vortex will extend along the diameter of the burner [6]. Based on this, when another flame is located near the flame, the interaction between the flames will be enabled.

When two candles are arranged next to each other, their flames will show in-phase and anti-phase synchronization [7]. When the positions of two flames change, the flames will change synchronously in-phase and anti-phase. It can be seen that the distance between two flames will also affect their synchronous changes [8-10].

When the flames are arranged next to each other, they will show the interaction phenomenon, which is usually called the synchronization phenomenon by the scientific community. This phenomenon is the main research content of this paper. The phenomenon of synchronization has been deeply studied in related literature. Due to the complicated mechanism of flame flicker, the physical principle behind flame synchronization is still not fully understood. The purpose of this study is to further explore the synchronization mechanism of two groups of candles from the angle of the flow field through grayscale analysis and numerical simulation.

2. Experimental instruments and procedures

2.1. Experimental device

The experimental part is shown in Figure 1(a). Two adjacent candle groups are placed on the movable platform and the stationary platform, respectively, and the distance between the two platforms. Using the transverse mechanism, the distance (L) between the centres of two candle groups can be changed from 13 mm to 220 mm. The diameter (d) of a single candle is 15 mm, and the height of the candle is 170 mm. After the experiment, it was found that the burning state is the most stable when a single candle group consists of three candles, so the candle group consists of three candles, as shown in Figure 1(a).

A high-speed camera is set up at the back of the testbed to record the candle groups in different combustion states to analyze different candle groups' greyscale and flash flame flow structure. To minimize the interference of ambient gas flow in the experiment, the experimental device was placed in a cube space with a width of 800 mm. The cube is made of a transparent acrylic plate, and there is a vent with a height of 50 mm in the front and back of the cube. To further reduce the influence of the surrounding environment on the study, keep the air temperature around the candle group stable at 290K before the experiment.

![Fig. 1 The experimental device](image)

(a) Top view of the model   (b) Overall model drawing

2.2. Characterization of flame

The change of flame combustion state is characterized by evaluating the change of flame grey-scale. This data can be acquired from pictures obtained by high-speed cameras. The frame rate of the camera is 960 fps, the resolution of the camera is 480x640 pixels, and the size of the captured image is 180 mmx180 mm. After the grey-scale processing of the obtained video, the grey-scale change images in in-phase and in-phase are obtained.
The synchronization to be mentioned first is an in-phase mode, as shown in Figure 2 (a), in which all two flames oscillate at the same frequency. Secondly, the synchronization to be mentioned is the reverse phase mode, as shown in Figure 2 (b), in which the oscillations of two flames differ by half a period.

At the same time, the velocity field is characterized. We used a device to generate low-speed smoke between the two candle groups and record the instantaneous velocity field through a high-speed camera (frame rate is 960fps) to characterise the velocity field. In this way, we can visualize the airflow around candles in different combustion states, and we can observe the change of airflow around candles caused by flame oscillation through the change of smoke shape. The results are shown in the figure below.

2.3. double flame characteristics analysis

After the experiment of candles in two states, COMSOL is used to analyze the airflow field in the combustion area, and the experimental results are used to explain the direct cause of oscillation. Set the air inlet and closed space in COMSOL as shown in Figure (4). Because the scale of the annular vortex extends to several burners in the transverse direction [6], we only pay attention to the temperature field of combustion, ignoring the influence of flame height and shape. Because there will be airflow around the flame, the change of temperature will cause the change of air density, and air convection will occur under the action of buoyancy. Therefore, we only set the ascending buoyancy airflow in the physical field and replaced the candle with the heat source condition to simplify the model.

Define the ambient temperature of the candle as 20°C and set the heat source as 400°C. The inlet
velocity is defined as 0 m/s, and the flow field is simulated in the in-phase (L/d=5.1) and the anti-phase (L/d=8.2). The physical field of fluid heat transfer and laminar flow simulates the buoyant flow, and the non-isothermal flow couples the two physical fields. The model is simplified by approximating the wall of the two-dimensional plane to thermal insulation to obtain more accurate results. The boundary layer of the grid and the grid around the heat source are encrypted. Set the solution step size as 0.01s

The schematic diagram of the model is shown in the following figure:

![Schematic diagram of airflow field simulation](image)

The simulation results are shown in the figure below.

![Velocity flow field simulation](image)

**3. Results and discussion**

The in-phase airflow around the flame causes the symmetry of flame oscillation. Otherwise, the flickering behaviour will be influenced by random motion, which will lead to the asymmetrical behaviour of flame. As shown in Figure 2 (b) and Figure 3 (b), double flame oscillation respectively characterizes the reverse phase state of flame from the angle of grayscale change and flow field. Fig. 3 (b) shows the asymmetry concerning the centerline of two groups of flames from the angle of the flow field. Two groups of flames repeatedly move periodically with a half-cycle difference. As time goes by, the left flame begins to break and separate, while the right flame grows. By processing the acquired data, it can be obtained that the phase difference between two flames is half a period. As shown in Figure 2 (a) and Figure 3 (a), double flame oscillation respectively represents the in-phase state of flame from the angle of grayscale change and flow field. Fig. 3 (a) shows the symmetry concerning the centre lines of two groups of flames from the angle of the flow field. Two groups of flames repeatedly move periodically. The two groups of flames experienced flame-cutting, separation, and growth simultaneously. It should be noted that the transition of two groups of flames from in-phase mode to anti-phase mode is related to the distance between two groups of candles, which may be due to the change of the overall instability of two groups of candles [11].

Figure 5 (a) and (b) respectively show the velocity fields in two modes obtained by numerical simulation. As shown, Figure 5 (a) shows the areas of rapid airflow regions in each flame in the in-phase
mode, and it can be obtained that the velocity flow fields on both sides are symmetrically distributed, and the annular vortices on both sides simultaneously act on the flame surface. In the experimental results of Figure 3 (a), it can be observed that the upward vortex acts on the surface of the flame at the same time, resulting in the in-phase state. In fig. 3 (b) and fig. 5 (b), two groups of flame vortices are staggered. The hot jet generated by candle burning forms an annular vortex on the flame surface, which vertically stretches the flame. It can be explained that the spatial inhomogeneity of the velocity of static air from the flame center to the surrounding leads to the instability of the flame surface. By analyzing the velocity field, it can be observed that the vortex of the left flame is generated at the bottom of the candle and transferred upwards. On both sides of the central line of the double flames, the vortex formed by the left flame is transferred to the right flame, and the vortex formed by the right flame expands to the left. The interaction between two flames can be observed in the reversed-phase mode, unlike in the in-phase mode. It can be concluded that in the reverse mode, the mutual effect between the two groups of flames is more obvious.

At the same time, we also carried out experiments and numerical simulations on two groups of candles at a very long distance (L/d = 11.5). The experimental results show no interaction between eddy currents between two groups of candles at an ultra-long distance. Through experiments, it is found that the smoke generated by the smoke generating device placed between the two groups of candles has no noticeable change. Further verification by numerical simulation shows that the flow field between the two groups of flames has no interaction, and the flow field between the two groups of candles remains approximately identical.

4. Conclusion

In this paper, the COMSOL flow field analysis method and greyscale analysis method are used to study the mutual effect between two diffusion flames at a distance from the perspective of the flow field to understand the synchronization mechanism of two flames. The main conclusions are summarized as follows:

(1) The timing diagram of greyscale changes of two groups of flames demonstrates the existence of diverse synchronization forms, for instance, in-phase, out-of-phase and irrelevant. With the increase in the distance between candle groups, there are three states: in-phase, out-of-phase, and irrelevant. The changes of these flame combustion states are characterized by the timing diagram of flame greyscale changes.

(2) The method of low-speed smoke is adopted to study the velocity field of two-flame in-phase and anti-phase patterns, and the airflow structure of flame interaction is obtained. The experimental results show that the symmetrical formation of vortices characterizes the in-phase mode, while the anti-phase mode features are the alternating formation of asymmetric vortices between two groups of flames. Incoherent mode is characterized by the fact that the vortex generated by the two candle groups no longer acts on each other, and the airflow field between the two groups of flames remains approximately identical.

(3) The experimental results are verified by numerical simulation. By simplifying the form of physical field, the velocity field changes of air in two groups of flame in-phase and anti-phase patterns are studied, and the interactive flow structure that causes flame oscillation is obtained. The results show that in the same phase mode, the vortex simultaneously acts on the flame surface and further vertically stretches the flame. In the reverse mode, the non-uniformity of vortices on both sides of the two groups of flames leads to the instability of the flame surface.

(4) In terms of future work, we should further study the influence of different arrangements and the number of single-group candles on the flow field and further explore the influence of different arrangements and numbers of single-group candles on the synchronization phenomenon.

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