Research on the Synchronization Problem in the Combustion of Candles

Desheng Cheng*, Bo Shi, Shenghao Wang, Lingling Huang and Guohao Qiu
Foundation Department, Academy of artillery and air defense, Huangshang Road 451, Hefei, China
*Email: 455611846@qq.com

Abstract. In 2020, IYPT question 5 "synchronized candles" describes an interesting common phenomenon in life. The so-called synchronous candle refers to the flame that can be observed to oscillate when several adjacent candles are burning. Two such oscillations can be coupled with each other, leading to in-phase or reverse phase. In this paper, the control variable method is used to study the reason of the oscillation of a single oscillator and the phenomenon of in-phase or anti-phase oscillation of candles with different separation distance. It is found that the phenomenon of the oscillation coupling of regular candles is related to the distance between candles. Considering that the gas diffusion coefficient of the air is too low and the isotherm of the candle is relatively stable, the most likely cause of synchronization or inverse synchronization is thermal radiation. Finally, FDS software is used to simulate the combustion of the flame, and the results of in-phase and inverse vibration are also obtained.

1. Introduction
The flame is the vaporization of the object after burning. The main component of the candle is paraffin. Which is vaporized to produce gas, “Synchronous Candle” in question 5 of IYPT2020 (The International Young Physicists’ Tournament) describes flame phenomenon which is often overlooked in life: When the candle is lit, a single candle flame is stable in a windless environment and does not oscillate, but the oscillating flame can be observed when several burning candles are close to each other. Two such oscillations can be coupled to each other, leading to in-phase or out-of-phase synchronization, and their oscillations depend on the distance between the candles. In order to investigate this phenomenon, the control variable method was used to investigate the cause of oscillation of a single oscillator and the in-phase or in-phase Oscillation of candles with different spacing. The main focus of the experiment involves two aspects: one is to observe the flame oscillation of a single
oscillator in the experiment, and to analyze the reasons for the oscillation of candle combustion; the other is to observe the oscillation of the same oscillator at different distances, and the cause of coupling oscillation of candle combustion is analyzed.

2.1. Flame Vibration of Single Vibrator

The diameter of the candle used in the experiment is 1cm. When a single candle burns, the candle flame burns smoothly without oscillation. In the experiment, the number of candles is changed, and the displacement mode is shown in figure 1 (a). The flames of different oscillators (2, 3, 4 and 5 candles) are observed respectively. In order to unify the experimental environment, the influence of oxygen content on the flame temperature is ignored during the experiment. It is assumed that the paraffin in the candle reacts fully, there is no paraffin residue in the burning flame and the paraffin is enough, and the paraffin gas can be supplied at a constant rate, and the disturbance of non experimental air flow to the flame is minimized, excluding the influence of accidental factors and individual differences of candles, then it can be found that the candle flame constituting the oscillator begins to oscillate regularly, And the number of single vibrator candles will affect the oscillation frequency of the flame. The more candles, the lower the oscillation frequency.

Figure 1. Flame oscillation of single vibrator: (a) Arrangement of single vibrator candles; (b) Flame oscillation of 3 candle.

2.2. Flame Vibration at Different Vibrator Distances

In order to observe the interaction of different oscillators, the 3 + 3 mode is adopted to explore the oscillation phenomenon of the two oscillators. As shown in figure 2, the distance between the oscillators is 6 different distances (5, 10, 20, 30, 50, 60mm). When changing the distance between the oscillators, try to reduce the disturbance of non experimental air flow to the flame and eliminate the influence of accidental factors and individual differences of candles, The experimental recording video is completed continuously at one time to reduce the impact of different experimental environments in different time periods on the experimental results. The flame with typical characteristics is intercepted from the video. The flame oscillation phenomenon is shown in figure 2. The flame oscillation phenomenon is different at different distances of the vibrator. The statistical results of experimental phenomena are shown in table 1.

It can be seen in table 1 that when the distance between the two oscillators is less than 20mm, the candle flame of the two oscillators oscillates in phase. When the distance between the oscillators is equal to 30mm, the candle flame oscillates in Anti phase and in phase at random. When the distance between the oscillators is equal to 50mm, the candle flame oscillates in Anti phase, and when the distance is greater than 60mm, the oscillation of candle is the same as that of single oscillator model. Compared with the simulation results of 10mm and 30mm, it can be seen that the air temperature between candle flames is not affected by candle combustion because of the increase of the distance between candles. At this time, there is no coupling between a pair of candle oscillators.
Figure 2. distance between different oscillators: (a)5mm; (b)10mm; (c)20mm; (d)30mm; (e)50mm; (f)60mm.

Table 1. Variation relationship between flame oscillation law and vibrator distance.

| Vibrator distance (mm) | 5   | 10  | 20  | 30  | 50  | 60  |
|------------------------|-----|-----|-----|-----|-----|-----|
| Oscillation phenomenon | In phase | In phase | In phase | random | Anti-phase | No dramatic relationship |

3. Theoretical Analysis

The combustion of flame oscillator is an open system [5, 6]. During the combustion process, reactants and products spread freely through molecular diffusion movement. The outside of the flame is ambient air, which provides oxygen supply for flame combustion. Oxygen is continuously transmitted to the reaction area. In the flame reaction area, carbon, oxygen and hydrogen are mixed and react with each other. The products of the reaction diffuse into the surrounding environment. Because the temperatures in different areas of the flame are different, the colors we see are also different. From the color of the flame of a single candle, we can see that the temperature distribution of the candle flame is hierarchical, the temperature around the flame is close to the ambient temperature, and the flame combustion products diffuse upward. Therefore, it can be seen that heat conduction and heat convection will not become the main cause of flame oscillation.

H. Kitahata et al. Put forward hypothesis [3]: 1. Candle oil is vaporized and mixed with oxygen; 2. The supply of Candle oil is sufficient, but the oxygen supply rate is constant; 3. Oxygen is delivered to the candle from an infinite distance, and the heat generated by the combustion reaction is transferred by convection. Based on the above three assumptions, the following equation is constructed:

$$C \frac{dT}{dt} = \omega_1 \left[ h(T_0 - T) + \beta an \exp \left( -\frac{E}{RT} \right) \right] - \sigma T^4$$  \hspace{1cm} (1)

$$\frac{dn}{dt} = \omega_2 \left[ k(n_0 - n) - an \exp \left( -\frac{E}{RT} \right) \right]$$  \hspace{1cm} (2)
In the formula, $T(t)$ is the temperature of the flame, $n(t)$ is the oxygen concentration of the air, $C$ is the specific heat capacity of the gas, $R$ is the gas constant, $E$ is the active energy, $T_0$ is the ambient temperature, $n_0$ is the external oxygen concentration, $h$ is the convective heat transfer coefficient, $K$ is the oxygen supply rate, $\beta$ is the heat production per unit volume of paraffin, $\sigma$ is the Stephen Boltzmann constant, $\omega_1$ and $\omega_2$ is the characteristic time constant of temperature and oxygen concentration respectively. In formula (1), the three terms at the right end of the equation respectively represent the heat loss caused by gas convective flow, the heat generated by combustion and the heat loss caused by radiation. In formula (2), the two terms at the right end of the equation represent the oxygen brought by gas flow and the oxygen consumed by combustion respectively.

When the parameter $a$ is small, the combustion flame temperature $T(t)$ of a single candle does not change, but maintains a constant value. When $a$ is large, the time series of temperature $T(t)$ shows oscillation behavior corresponding to the combustion of three candles. Therefore, by changing parameter $a$ in formula (1) (2), two modes of steady combustion and oscillating combustion can be obtained. Further, considering the coupling between the two groups of candles, the following equation can be obtained:

$$C \frac{dT}{dt} = \omega_1 \left[ h(T_0 - T_i) + \beta n_i \exp \left( -\frac{E}{RT_i} \right) \right] - \sigma \left( \frac{\mu}{L^2} \frac{T_j^4 - T_i^4}{T^4} \right)$$  \hspace{1cm} (3)

$$\frac{dn}{dt} = \omega_2 \left[ k(n_0 - n_i) - an_i \exp \left( -\frac{E}{RT_i} \right) \right]$$  \hspace{1cm} (4)

Where $L$ is the distance between two oscillators, $\mu$ is the light absorptivity in the gas, and the radiation coupling is expressed as $\sigma (\mu/L^2) (T_j^4 - T_i^4)$.

For $i, j = 1, 2, (i \neq j)$, the temperature and oxygen concentration of oscillator 1 are $T_1(t)$ and $n_1(t)$ respectively, and the temperature and oxygen concentration of oscillator 2 are $T_2(t)$ and $n_2(t)$ respectively.

The change law of flame temperature and oxygen concentration can gotten by the theoretical formula. For a single candle, the oxygen supply is sufficient, and the flame keeps burning smoothly. However, when two or three candles are close to lighting, the candle combustion oxygen supply is insufficient, which cannot maintain constant combustion, and the gas flow changes, resulting in the oscillation behavior of combustion.

However, for the synchronous oscillation phenomenon of multiple flame oscillators, the main function of the flow of air flow is to release the heat of combustion and supplement the oxygen required for combustion, and the characteristic length of air flow diffusion can be negligible relative to the distance between oscillators, so the flow of air flow is not the cause of in-phase or anti-phase oscillation of flame oscillators [7, 8].

It can be found from the experiment that the coupling phenomenon of the two oscillators is only related to the distance between the oscillators, the in-phase or anti-phase oscillation of the flame can be seen as long as the distance between the two oscillators is changed. Considering the distance and oscillation period of the flame oscillator, and for the gas diffusion coefficient of combustion products is too low, the most likely cause of flame oscillation is thermal radiation [9].

According to the analysis conclusion, Ting Chen et al. Proposed a "overlapping peak model" based on infrared temperature distribution [10], which successfully explained the phenomena observed in the experiment of different number of flame oscillators, and some evolution laws of flame oscillators also is found that were not observed in the experiment, It is revealed that the relationship between the in-phase or anti-phase of the flame oscillator and the flame oscillator spacing is basically consistent with the experimental phenomenon, which proves the applicability of the overlapping peak model in explaining the synchronous oscillation of the oscillator spacing and the flame oscillator.
4. Numerical Simulation

In order to more intuitively study the characteristics of flame oscillation, in this paper, the fire dynamics simulator simulation software was used to simulate the oscillation and synchronous coupling of candles. We set the calculation area in the calculation area of 0.1m * 0.1m * 0.1m, set TWFIN as 10s, grid size as 200 * 100 * 120, set the combustion reaction material as paraffin wax, and default INERT (inert surface). The ambient temperature is set to 22 °C, and the initial wind speed is 0 by default. The SURF related parameters are set to cotton object combustion. The VENT and MODEL related parameters are set according to the actual size of candles and combustion flames. The SLICES interface parameters were set to temperature and velocity. The number and specification of candles are consistent with the experiment. For a single flame oscillator, the gas flow and temperature distribution as shown in figure 3 simulated.

![Gas flow and temperature distribution of a single flame oscillator.](image)

Figure 3. Gas flow and temperature distribution of a single flame oscillator.

Due to the large amount of heat released by the combustion of paraffin vapor, it can be seen in figure 3 that the temperature distribution of the surrounding air is uneven. The oscillating flame air flow is divided into two parts, one is the turbulence formed by the disturbance of hot air, and the other is the laminar flow of air formed by the need to supplement oxygen during the combustion process. When the three candles burn together, the turbulence in the upper layer diffuses rapidly, and part of the air flow rotates downward and contacts the flame in the lower layer, causing the flame to bifurcate and form oscillation. According to the simulation results, the causes of flame oscillation may come from two aspects: first, when multiple candles are combined and arranged, the internal oxygen supply of candles is insufficient, the central area forms a low-pressure area, and the surrounding cold air flows towards the low-pressure area, squeezing the flame; Second, the main products after paraffin combustion are water and carbon dioxide, and the oxygen content of the combustion gas flow is relatively low. When this part of the heat flow rotates downward and contacts the flame, it can also cause the bifurcation of the flame.

The temperature distribution and flame shape of the vibrator at different distances was shown in figure 4. From the shape of the flame, the vibrator is different from different distances. In the figure, the flame oscillation shape of the flame vibrator is basically symmetrical at 5mm, 10mm and 20mm, while at 30mm, there are two cases of flame oscillation. The flame oscillator oscillates synchronously as shown in figure 4 (d), while the flame oscillator oscillates in phase in figure 4 (E). The anti-phase oscillation and in-phase oscillation of candle flame appear randomly. The flame oscillator oscillates in anti-phase was shown in Figure 4 (f) when the vibrator is 50mm, and there is no coupling phenomenon in the flame oscillation as shown in Figure4(g) when the vibrator distance is 60mm. From the simulation result of FDS, it can be obtained that the simulation results consistent with the experimental phenomena, which verifies the reliability of the experimental and theoretical analysis. However, from the simulated temperature distribution, the overlapping phenomenon caused by thermal radiation is not very obvious.
Figure 4. flame temperature distribution and flame shape at different distances of vibrator: a) 5mm; b) 10mm; c) 20mm; d) 30mm (in-phase); e) 30mm (anti-phase); f) 50mm; g) 60mm.

Figure 5. vector diagram of air velocity distribution at different distances of vibrator: a) 5mm; b) 10mm; c) 20mm; d) 30mm (in-phase); e) 30mm (anti-phase); f) 50mm; g) 60mm.

The velocity vector of gas flow is shown in figure 5. It can be found that when the vibrator is close, the gas flow velocity of the flame vibrator is generally larger than that when the vibrator is far away. When the vibrator is close, the turbulent layer of the flame gas flow is more intense. It can also be seen from the discontinuity of the change of the flow velocity of the flame gas that the flame oscillates in the combustion process. The velocity direction of air flow reflects the direction of air flow. It can be found that the air flow has obvious bifurcation and supplement during flame oscillation.
5. Conclusion
In this paper, according to the physical phenomenon described in the IYPT title "synchronous candle", the experimental scheme is designed to carry out the experiment, and the physical phenomenon consistent with the title description is obtained. Which the following conclusions can be obtained:

1. The number of single vibrator candles will affect the oscillation frequency of the flame. The more candles, the lower the oscillation frequency.
2. For the synchronous oscillation of multiple flame oscillators, the main factor affecting the in-phase or anti-phase oscillation of flame oscillators is the distance between the oscillators.
3. The characteristic length of gas flow diffusion is negligible relative to the distance between oscillators, so the flow of gas flow is not the cause of in-phase or anti-phase oscillation of flame oscillator. Considering the distance and oscillation period of flame oscillator, and because the gas diffusion coefficient of combustion products is too low, the most likely cause of flame oscillation is thermal radiation.

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