SYNCHRONIZED CANDLES

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ABSTRACT

In this essay, Oscillatory flames which are observed when several candles burn next to each other. are investigated. Depending on the distance between the sets of candles two such oscillators can couple with each other, resulting in in-phase or anti-phase synchronization. We are going to find how the flames work and type of flames and relevant parameters.

Key Words: *Candles, flames, Oscillation, synchronization,*

1 Introduction

In general, heat is transferred through three methods of conduction, radiation and convection. The heat of the flame melts the paraffin of the candle due to its conduction. Melted paraffin rises from the candle wick due to its capillary properties. On the other hand, hot air rises around the flame. The volume of hot air is more than the volume of cold air and its density is less it is from the density of cold air. When hot air loses temperature, it cools down and cold air because of more density is being pulled down by gravity, and this heat transfer current continues, which is called convection. Radiation is another type of heat transfer that takes place through electromagnetic waves. In this study, loss is the most important factor. On the other hand, due to burning paraffin, carbon monoxide, carbon dioxide and water vapor, we produce Exhaust of these light gases causes the tip of the flame to stretch (Fig. 1).

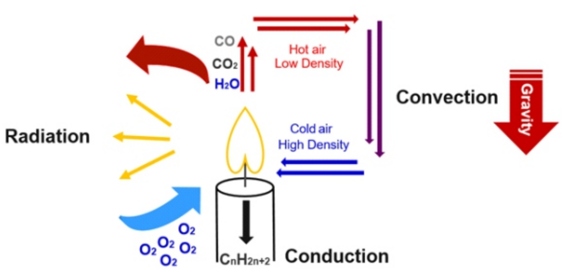


Fig. 1: Heat Transfer

2 Main Concepts

2-1 How do Flames Work and Merge?

The convection between two flames is the reason of coupling (Fig. 2). When we put two flames together, the convection flow around them continues and on the other hand, the air between the two the hotter the flame, the faster the exit and the lower the pressure. The air around the flame, which has a lower temperature and more pressure, causes it to close or so-called coupling . In this condition three types of behavior are observed, non oscillation, coordinated oscillation and uncoordinated oscillation.

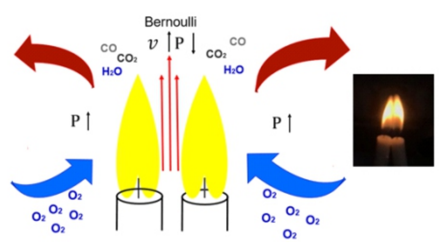
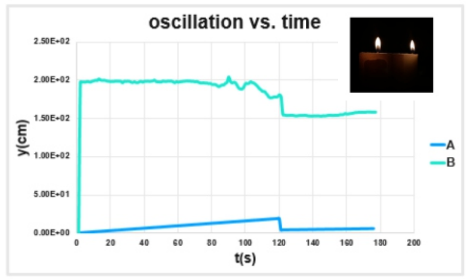


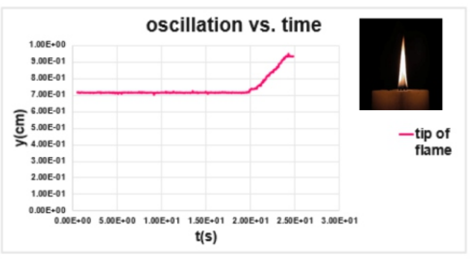
Fig. 2: The convection between two flames is the reason of coupling

2-2 Types of Behavior Observed:

In non oscillation flames there are two modes: Stable and Death modes (Fig. 3 a & b).



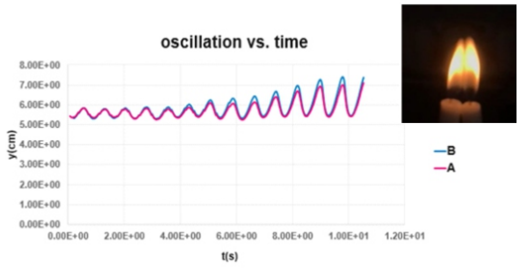
(a)



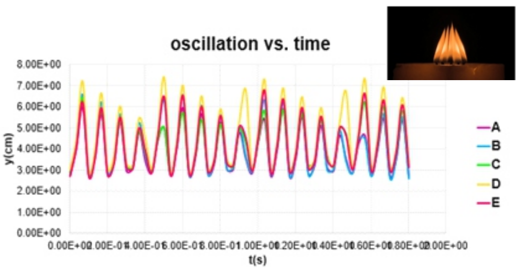
(b)

Fig. 3: Two modes in non oscillation flames, a) Stable mode; b) Death mode

In Coordinated Oscillation there are in-phase and Mexican wave modes (Fig. 4a and b).



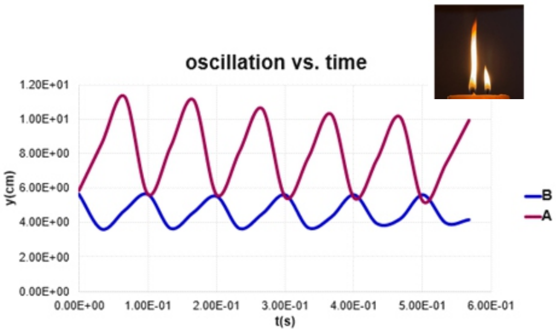
(a)



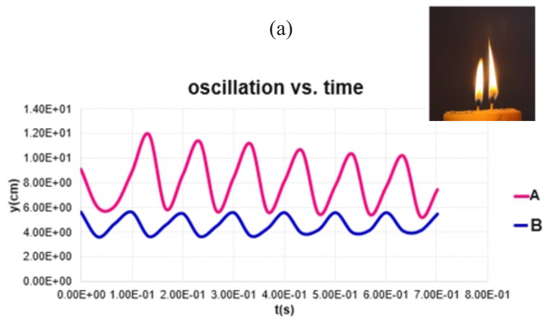
(b)

Fig. 4: Two modes in coordinated oscillation flames, a) in- phase mode; b)Mexican wave mode

In Uncoordinated Oscillation we have anti-phase and desynchronized modes (Fig. 5a and b).



(a)



(b)

Fig. 5: Two modes in uncoordinated oscillation flames, a) anti-phase mode; desynchronized mode

3 Materials and Methods

Before starting the experiment, the effective components in the phenomenon such as Number of Flames, Distance between them, Layout and Flame Level are defined. In our experiments wick thickness and Paraffin/Flame sources other than candles are investigated too.

4 Experimental Setup

To prevent the flames from disintegrating, the test space should be kept away from wind and any open air flow. To better see the flames and make the imaging clearer, the experiments were performed in a dark room and also behind the flames were also blacked out to obtain the desired distance at which the phenomenon is observed. First the flames were kept at a distance of 50 mm. They were placed together, but at this distance, the phenomenon was not observed and the distance of the flames was reduced by repeated experiments. The flames flickered at a distance of 9 mm, and at a distance of 8 mm, the desired result (flame synchronization) was obtained and when the flames got closer, they became one and behaved like a single flame (Fig. 6).

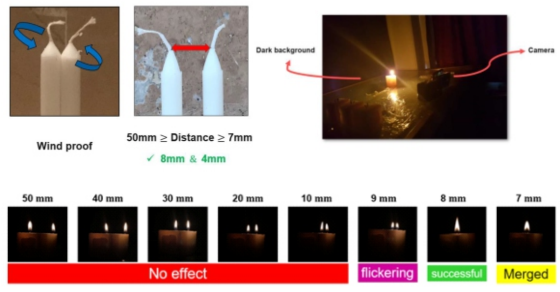


Fig. 6: Experimental Setup with candles in different distances

4-1 Two Candles: in Phase Oscillation

In the first experiment, two candles of the same size were placed at a distance of 8 mm. Due to the symmetry of the flame position, the fresh air which enters and the hot air comes out are the same and there is convection flow around them. The same thing happened and caused flames have in-phase oscillations that with increasing time, their amplitude of oscillation also increased and reached Mexican wave mode. Tracker and Excel software was used to obtain the diagram of all fluctuations (Fig. 7).

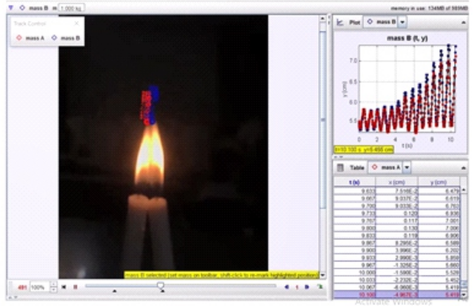


Fig. 7: Two candles in phase oscillation (d= 8mm)

As it is seen the amplitude of the oscillation increases in both phase and Mexican wave modes. These two modes are annualized by the FOURIER Transformation (Fig. 8).

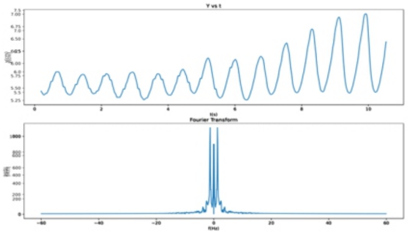


Fig. 8: Fourier Transformation, Peak frequency in two candles: A: 1.25806452; B: 1.25806452

4-2 Two Candles: Desynchronized Mode

In the second experiment, two flames of the same size on the left and another flame of the same size at a distance of 8mm were placed . Due to the fact that the temperature of the two flames on the left was higher than the single flame on the side Right, the flow around them was uneven, fresh air entering the flames and leaving the hot air was not the same between the flames. This caused the flames to oscillate out of phase.

Two flames generate more heat than one flame. Thus there is a stronger and faster convection flow. Since the two flames don't have similar shape, anti-phase oscillation happens . It is analyzed by Fourier Transformation to find the maximum peak (Fig. 9).

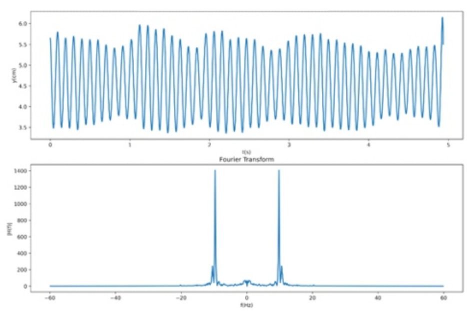


Fig. 9: Peak frequency: A: 9.72000972; B: 9.72000972

4-3 Candles in Anti Phase Mode

In the third experiment, two flames of the same size were placed at a distance of 8 mm. This time the wick sizes were fixed and the length of the right wick was 5 mm longer than the left wick. Due to the difference in the level of the flames, the convection flow around them was uneven and since the two flames did not have the same shape, this caused the flames have asynchronous oscillations (Fig. 10).

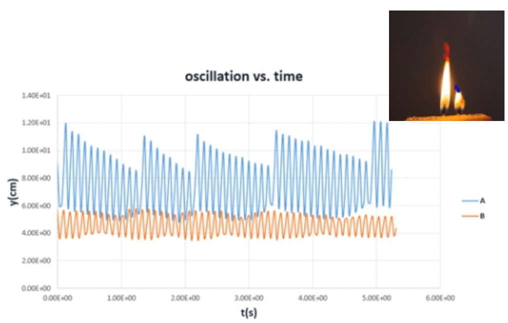
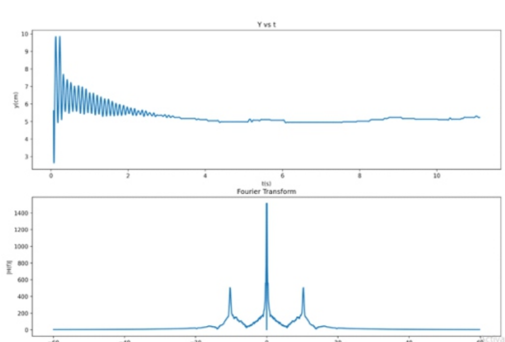
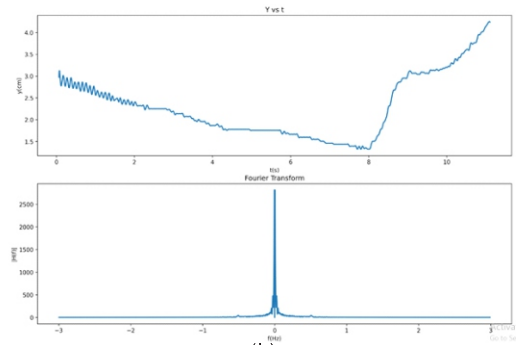


Fig 10: Anti Phase mode

The amplitude of the oscillations are short with different wavelengths (Fig. 11 a and b).



(a)



(b)

Fig. 11: Peak frequency; a) A: 0.09053022 and 0.18106044 b) B: 0.00452651 and -0.00452651

5 Comparison of the Setups

By comparing the diagrams, we found that whenever the wicks are in the same condition and at the desired distance, the oscillation is in harmony, but if the flames deviate from the symmetrical state and in different conditions such as temperature, fresh air and light gases between the flames it will be out of symmetry and there is inconsistency. So there are coordinated and uncoordinated oscillations (Fig. 12).

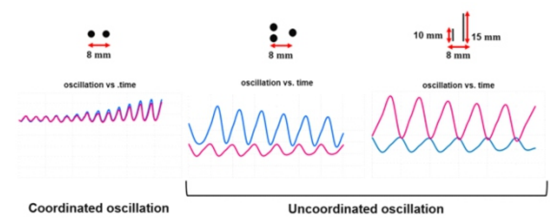


Fig. 12: Comparison of the setups

6 Making the Candles and Layout Design

The candles had to be cut to reach the desired distance for several arrangements. Therefore, special candles for this research and frequent experiments were made (Fig. 13). For proper design, the experiment first started with two wicks and the number of wicks increased and it was observed that the best result is given by five wicks.

Fig. 13: Making different candles

To design the flame arrangement, the flames were first placed symmetrically pentagonal and round, and then they were arranged in a line next to each other, and at the end, the situation was the same as the previous two arrangements Trapezius. These arrangements were tested at two optimal distances of 8mm and 4 mm (Fig. 14).

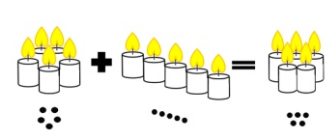


Fig. 14: Layout Designs

7 Experiment in Symmetry Situation

In this experiment, the flames of the same size were placed at a distance of 8 mm from each other (Fig. 15). Symmetry of the flames, fresh air entering the flames and hot air leaving from between them, the intensity and speed of convection, the difference in temperature, volume and pressure around the flames and inside them all caused:

- The flames have short-phase oscillations with short wavelengths and amplitude due to the high heat from the very beginning.
- Their oscillation was high and they had a Mexican wave state.

Tracker and Excel software were used to obtain diagrams of all fluctuations and Python program is used to find their frequencies .

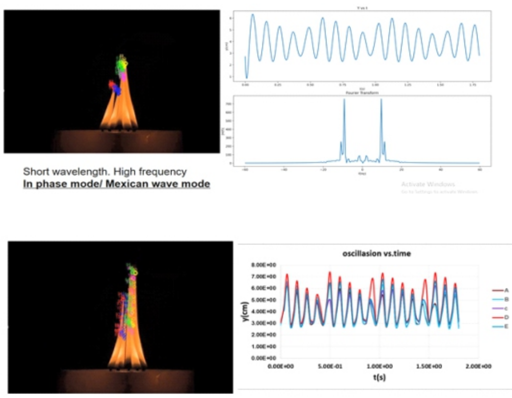


Fig 15: The oscillation in Mexican Wave (Peak: 9.43500944 cm)

In the next experiment, the flames of the same size were placed at a distance of 4mm from each other with short-phase oscillations and wavelengths . In this situation they seems calmer (Fig. 16).

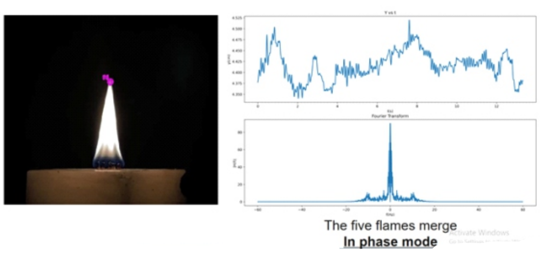


Fig 16: The oscillation in phase mode (Peak: 0.07511286 cm)

Then ;

- The same volume of fresh air entering.
- Hot air exits from the center of the candles.
- Because of the same volume of the air entering, there are same convection for each flames, so they couple equally and we have in-phase.
- In this layout they merged and act like one stable flame so we have stable form.

In other experiment, flames of the same size set side by side at a distance of 8mm and then in trapezoid shape. The condition of the flames is the same, fresh air enters the flames and hot air leaves between the two flames and intensity and the velocity of convection around the flames, which was the same, caused:

in the first shape some flames are almost without oscillation; some of them are in phase oscillations and some in non-simultaneous oscillations. Their wavelength was short and their oscillation amplitude was generally low and high in some parts (Fig. 17) .But in second one The tips of the flames should overlap; some flames had almost no oscillation and some oscillated in phase; their wavelength was short and their oscillation range was generally high (Fig. 18).

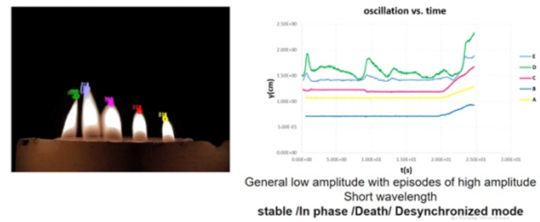


Fig. 17: flames of the same size set side by side at a distance of 8mm

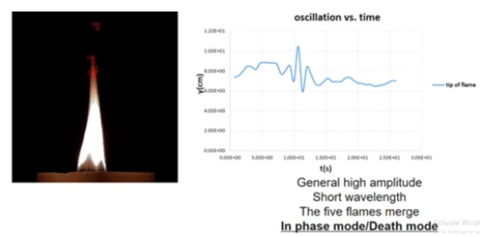


Fig. 18: flames of the same size set in trapezoid shape at a distance of 8mm

When the flames of the same size were placed side by side at a distance of 4 mm in a row fluctuated in both Mexican phase and wave state.Their wavelength is short and their oscillation amplitude was high (Fig. 19) and in trapezoid shape the tips of the flames should overlap; the flames fluctuate in phase; their wavelength are short and their oscillation range is variable (Fig. 20).

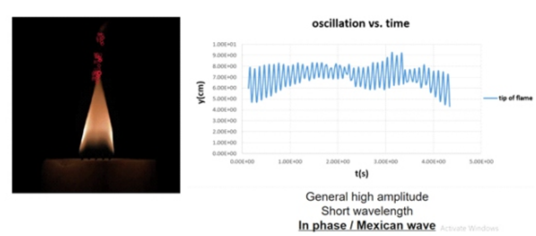


Fig. 19: In phase and Mexican Wave in flames in a distance of 4 mm

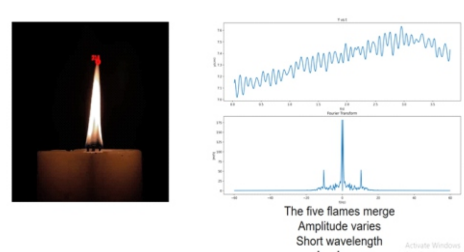


Fig. 20: In phase Wave, flames in a distance of 4 mm but with trapezoid shape

In candles set side by side:

- Hot air exits from the space between each two candles
- More air enters through asides of this layout so they are stable, but in the middle the flow of air enters from 2 sides

so it oscillates faster to suck more volume of air (Fig. 21).

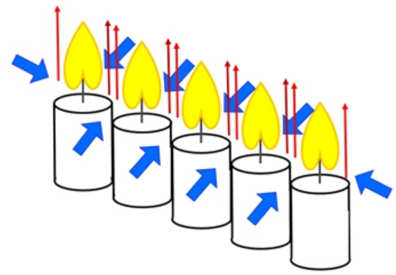


Fig 21: The oscillation in candles side by side

But in candles with trapezoid shape:
-The same volume of fresh air entering from all sides
- Hot air exits from the center of the candles
- Difference in the temperature, volume and air pressure around the flames cause the air to be sucked inside the flame arrangement and it is in phase and stable (Fig. 22).

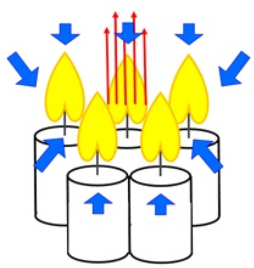


Fig 22: The oscillation in phase mode with candles in trapezoid arrangement

8 Wick Thickness

In order to observe the effect of wick thickness in this phenomenon, all arrangements made with wick with a diameter of 2 mm and 4mm (Fig. 23). Due to the intense heat, the following results was obtained:
- The candle melts faster and more
- It generates more soot and smoke
- The Combination of the states, death and the Mexican wave mode is observed

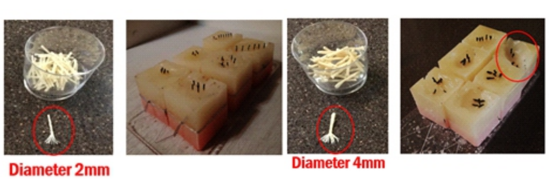


Fig. 23: Candles with different wicks

9 Conclusions

Air flow is symmetric in a single flame arrangement. So we it is a stable flame (Fig 24).

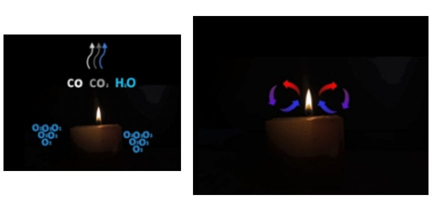


Fig. 24: Stable flame

Mexican wave is same as in phase mode but with short wavelength and High frequency (Fig. 25).

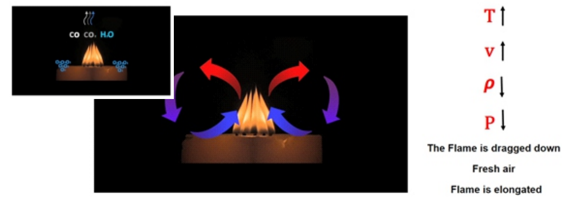


Fig. 25: Mexican Wave

When oscillations stop and show a long and slender shape, we call it Death mode . The flow of the rising hot air causes the flame to elongate (Fig. 26).

Fig. 26: Death Mode Wave

Difference of temperature causes a difference in pressure so we observe asymmetry in the flames, Anti-Phase mode / Desynchronized (Fig. 27).

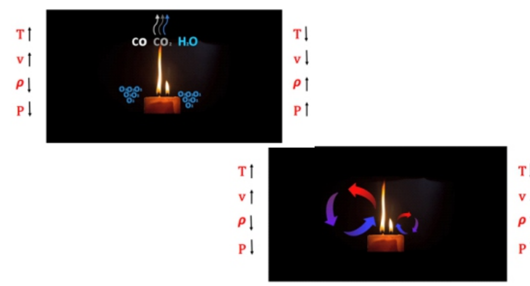


Fig. 27: Anti-Phase mode / Desynchronized

In these experiments the behavior of flames in versus different parameters were observed and analyzed (Fig. 28).

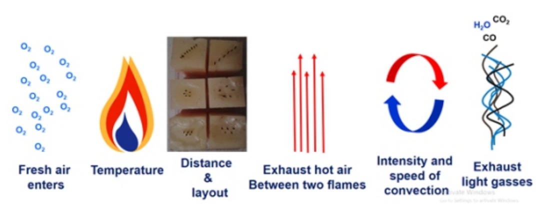


Fig. 28: Different parameters in our experiments were analyzed

Number of Flames which increased hot air and convection speed
Distance:
It was observed in the specific range of 8 mm, with the occurrence of no coupling above and merging below that range.
Layout which causes:
Difference in the volume of fresh air entering
Difference in light gas emission rate
Difference in types of flame and oscillation

Flame Level: Causes the difference in temperature and air pressure around the flame and finally the phase difference.
Wick Thickness: causes more paraffin melts

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