Burning, Fluttering, and Extinguishing of a Candle Flame in a Tube

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In this article, we report some experimental results on the behaviour of the flame of a candle kept at the bottom of a glass tube, which is open at the top and closed at the bottom. Thus, the supply of oxygen for the continuous burning of the flame is possible only from the top open end of the tube. We find that the candle burns steadily below a critical tube height. Above this height, the flame oscillates in size, and a further increase in tube height leads to the flame extinguishing quickly.

1. Introduction

There is no more open door by which you can enter into the study of natural philosophy than by considering the physical phenomenon of a candle. – Michael Faraday

Burning of a candle is a phenomenon that has intrigued both children and adults alike since aeons. When we light a candle, we see at first, the formation of a beautiful cup-like flame. As air flows near the candle flame, it cools the sides of the wax more than the part within the candle. As a result, the part within the candle melts while the part outside doesn't. If the cup is unsymmetrical or the air stream is irregular, we do not get to see the beautiful cup on the candle, rather guttering (flowing of liquid wax from the sides) occurs. The fluid formed on the top of the cup flows to the wick due to capillary action. This melted wax climbs all the way upto the wick where it is burnt, acting as a fuel. If too much of the melted wax goes to the top, the candle extinguishes, as you may have noticed when we turn a candle upside-down. When we blow out a candle, we can see a stream of vapour oozing out of the wick end and, if we put a lighter near those vapour streams, we can see that the candle starts burning again. The only condition is that the vapour must be lighted quickly for the candle to burn again as the vapour tends to cool fast and codense into a liquid or

Keywords
Candle, flame, convection, plume, air stream.

solid.

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Have you ever wondered how the flame sustains itself in the air? What is the role of ambient air in the burning of a candle? What if we constrain our candle flame in such a way that only a limited supply of air is available to it? Will the flame sustain itself and if it does, will its nature change? We have tried to answer some of the above discussed questions in our experimental study. In our study, the candle flame was enclosed in a glass tube open at the top and closed at the bottom. This configuration is different from the common one like a kerosene lamp where the air is allowed to enter from the sides and bottom, and the burnt gases escape from the top.

2. Experimental Setup

The experiments were performed in a glass tube of diameter 58.6 mm and different heights. Two different candles of diameter 1 and 2.5 cm with corresponding wick diameters 1 mm and 2 mm respectively were used. The length of the candle used was nearly 2 cm, and the wick height was kept at 8–10 mm during all the experiments. Following is the experimental procedure.

Water was filled to a height of 5 mm in a container of about 1 cm tall and diameter slightly larger than the tube. The candle was then placed in the middle of the container and lit. The glass tube was then placed coaxially with the candle. Presence of water in the container ensures that ambient air does not enter from the tube bottom. A schematic of the setup is shown in *Figure* 1. Flame characteristics were captured using an optical camera (Nikon Coolpix P7800) placed along a plane perpendicular to the flame. Temperature distribution on the outer surface of the tube was obtained using a thermal camera (Fluke Ti400).

3. Results and Observations

Let us first discuss the behaviour of the flame as the tube height is changed. The following discussion is for a 2.5 cm diameter

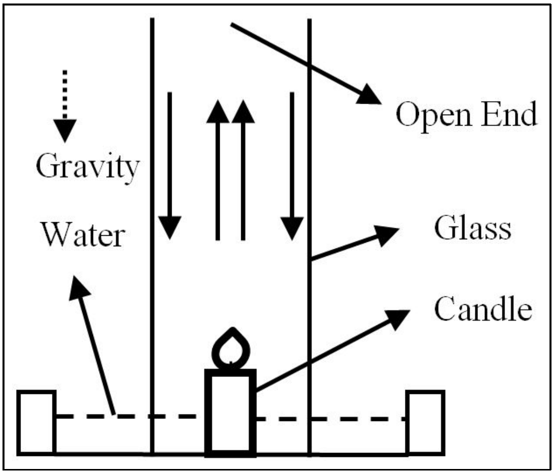

Figure 1. Schematic of the experimental setup. Candles used were 1 and 2.5 cm in diameter with 1 and 2 mm thick wicks, respectively. Diameter of the glass tube was 58.6 mm and their heights used were 24, 30, 38, 43.5, 48, 55.5, and 60 cm.

Candle diameter (cm)	Glass tube height corresponding to			
	Fluttering (cm)	Steady (cm)	Oscillation (cm)	Extinguished (cm)
2.5	24	30	38, 43.5	48, 55.5, 60
1	24	30, 38	43.5, 48, 55.5	60

Table 1. Characteristics of the candle flame at different tube heights and candle diameters.

candle, but the behaviour is qualitatively similar to the 1 cm diameter candle. For a tube height of 24 cm, a considerable amount of flame fluttering (a swift quivering movement in the horizontal direction) was observed. As the tube height was increased to 30 cm, the candle flame became nearly steady. As the tube height was further increased to 38 cm, the flame began oscillating, i.e., the flame height increased and decreased with time, the optical camera indicated a time period of 20–50s. The amplitude of oscillation of the flame tip varies with time. For a 43.5 cm tube height, the flame oscillated a few times and then it extinguished. The flame even became nearly spherical for some instances of time during its oscillation. In case of 48 cm, 55.5 cm, and 60 cm tube heights, the flame extinguished immediately. The characteristics of the candle flame with the change in tube height and the candle diameter are given in *Table* 1.

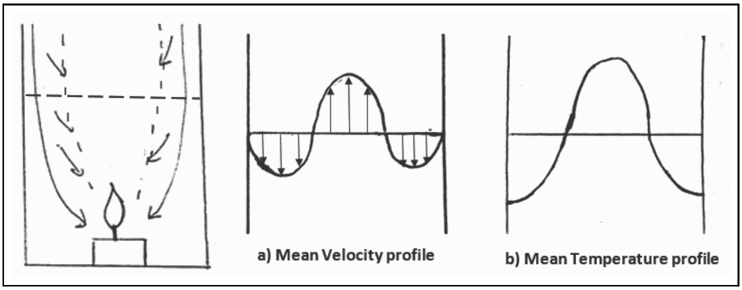

Figure 2. Schematics showing the entrainment of ambient air into the tube and the expected **(a)** mean vertical velocity and **(b)** mean temperature profiles along the cross-sectional area of the tube. The hot plumes will emerge from the middle of the tube and the cold ambient air will be entrained along the circumference of the tube.

The necessary condition for the flame to burn is that ambient air should enter from the top of the tube. Note that the continuity equation or mass conservation for the flow of gases at any tube cross-section must be satisfied at all instants. The volume of gases (cold + hot) inside the tube is constant. This implies that the flow rate of gases exiting the tube must be compensated by the flow rate of ambient air entering the tube. In effect, there is a counter current of up-flowing and down-flowing gases at any cross-section (*Figure* 2). To understand the flame behaviour, we used the shadowgraph technique (*Figure* A, *Box* 1) to observe the air current inside the tube. We could observe the cold stream of air getting in from the top of the tube, and a hot plume formed due to the combustion of the candle rising up in the centre. The plume was highly turbulent and three-dimensional in nature.

In case of small tube heights, ambient air enters from the top of the tube along its circumference and reaches the flame, whereas, hot gases escaped predominantly from the central region of the tube top. The rate of air (oxygen) consumption by the flame and the rate of incoming ambient air are equal in this case. In fact, the incoming cold air which is consumed near the flame base has a high velocity causing the observed 'flame fluttering'.

For slightly longer glass tubes, the incoming ambient air flow near the flame is not sufficiently strong to cause it to flutter. Hence, the candle flame is steady. This situation is similar to the condition where a candle is burning in a quiescent atmosphere.

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A further increase in the tube height results in the oscillation of the candle flame which is explained as follows. When the flame is

Box 1. Shadowgraph

The density of a fluid varies with the temperature or with the concentration of a dissolved species (like salt in water) and there is an associated change in its refractive index. Variations in the refractive index deflect (or phase shift) the light passing through the fluid. If a screen is placed opposite to the light source, these effects create shadows on the screen creating an image, visible to the naked eye, called a shadowgraph. The schematic of the experimental setup for shadowgraph imaging is shown in *Figure* A.

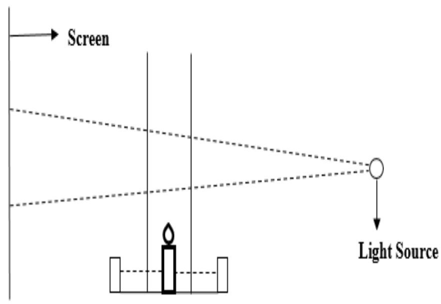

Figure A. Schematic of the shadowgraph experimental setup. The glass tube had a square cross-sectional area of 25 cm^2 and a height of 30 cm. The light source creates a shadow of the hot and cold air currents on the translucent screen. The optical camera (Nikon Coolpix P7800) was behind the screen to record the shadow patterns.

at its peak, there is insufficient incoming ambient air (and hence oxygen) to burn, and its length is reduced. A smaller flame allows more ambient air which causes the flame height to increase. This pattern keeps repeating itself and hence the observed oscillations in the flame size. *Figure* 3 shows photographs of the flame and the plumes schematically indicated by dotted lines at two instants.

On further increasing the height of the tube, the flame extinguishes because the cold fresh air is unable to reach the candle flame and provide the required oxygen.

The surface temperature measurements using the IR camera give further insights (*Figure* 4). It is evident that the maximum surface temperature is not near the flame. We observe one global maximum and one local maximum in the temperature versus height

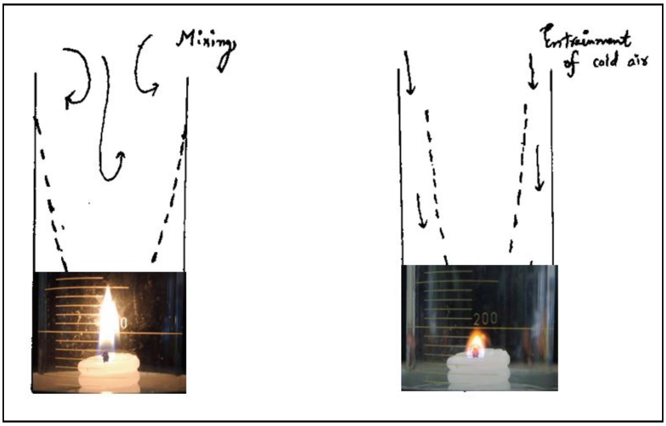

Figure 3. Two images of the candle flame during its oscillation.

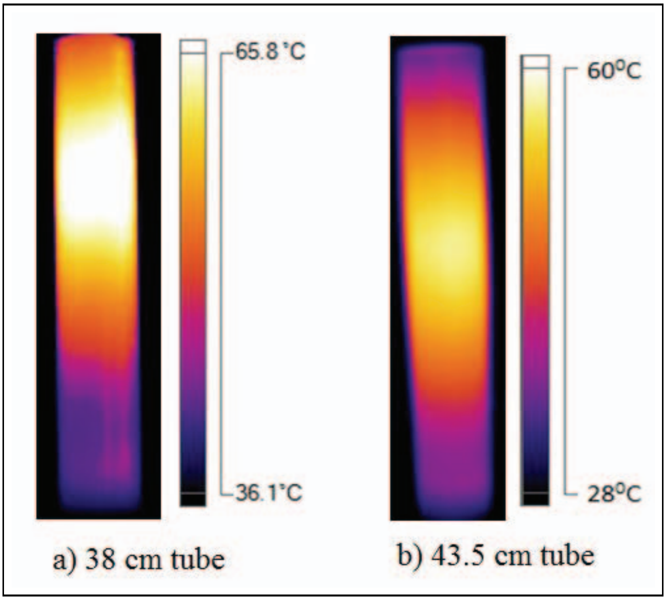

Figure 4. Thermal images of tubes with two different heights but the same glass tube diameter (58.6 mm) and the candle diameter (2.5 cm).

plot (*Figure* 5). The global temperature maximum, observed at some height away from the flame rather than near it, is due to the mixing of the hot burnt gases and the cold ambient air away from the tube bottom. The global temperature maximum coincides with the point of maximum gas temperature near the tube surface, and the value and location is determined by the complicated mixing process in the counter flow in the tube. The local maximum occurrs near the candle flame due to the heat radiating from it. The local maximum and the candle tip almost coincide.

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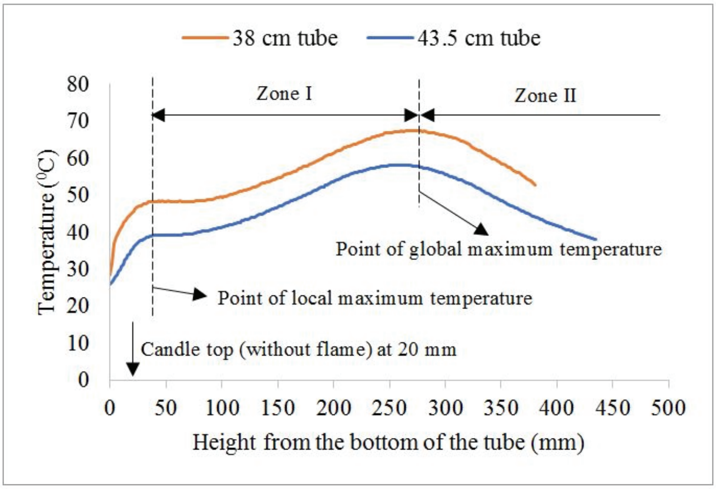

Figure 5. Tube outer surface temperature *vs.* height from tube bottom during steady state. Two maxima are observed in surface temperature – a local one near the flame and a global one at about 275 mm.

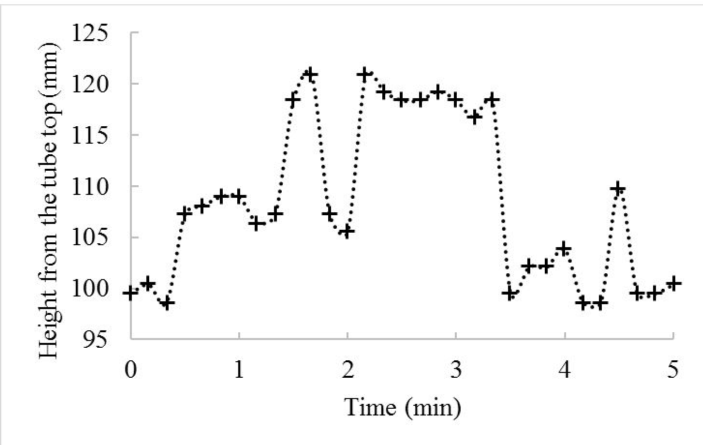

Figure 6. Variation of the point of maximum temperature with time (38 cm tube height, tube diameter 58.6 mm and 2.5 cm diameter candle). Note that the variations in position of the temperature maxima are approximately equal to the flame height.

In the case where the flame oscillates, the position of surface temperature maximum also changes with time (*Figure* 6). The pattern of flame oscillation captured by the optical camera matches with the temperature maxima oscillation of the outer wall of the glass tube captured by the thermal camera. Note that the thickness of the glass tube was 3 mm, and the time taken for heat to get conducted through it would have been nearly 3–4 seconds, much lower than the time period of oscillation of the flame.

4. Conclusion

The behaviour of a candle flame, with the candle placed in a tube open at the top and closed at the bottom, was studied with varying tube heights. The novelty of the current configuration is that the air required for combustion can only enter the tube from the top since the tube bottom is sealed. It was observed that when the tube height was increased, the flame changed its behaviour from fluttering to steady state burning, to oscillation, and finally to it being extinguished rapidly. The downward flow of ambient air resulted in flame fluttering and the communication time gap between the ejection of hot air and entrainment of cold ambient air resulted in flame oscillation. Shadowgraph revealed that the flame released hot plumes which hit the glass wall at a certain height; where we recorded the maximum wall temperature. The temperature distribution of the outer glass tube revealed two temperature maxima – one global which was formed due to the convection and mixing of hot burnt gases with ambient air, and the other is the local maximum formed due to the heat radiating from the flame.

5. Acknowledgments

It is a pleasure to thank Shashikant Pawar for his help in performing shadowgraphy and Deepak G Madival for discussions in preparing the manuscript.

6. Supplementary Material

Supplementary videos of the experiment are available at:
`https://figshare.com/s/8c6f5e76abd4b69f47e1`.

Suggested Reading

[1] M Faraday, *Faraday's Chemical History of a Candle*, Chicago Review press, Chicago, IL, p.124, 1988.

[2] Biman Nath, A Note on the Chemical History of a Candle – Michael Faraday, *Resonance: Journal of Science Education*, Vol.7, No.3, pp.90–98, 2002.

[3] Anthony Hamins, Matthew Bundy and Scott E Dillon, Characterization of Candle Flames, *Journal of Fire Protection Engineering*, Vol.15, No.4, pp.265–285, 2005.

[4] Murali R Cholemari and Jaywant H Arakeri, Experiments and a Model of Turbulent Exchange Flow in a Vertical Pipe, *International Journal of Heat and Mass Transfer*, Vol.48, No.21, pp.4467–4473, 2005.

[5] Jaywant H Arakeri, F E Avila, J M Dada and R O Tovar, Convection in a Long Vertical Tube Due to Unstable Stratification – A New Type of Turbulent Flow?, *Current Science*, Vol. 79, No.6, pp.859–866, 2000.