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Combustion Characteristics of An Array of Energized Candle Flame

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Abstract—*The investigation addresses the heat transfer characteristics of an array of catalyst induced candle flames. The need to understand thermal and physical characteristics of energetic materials utilization and related spreading have necessitated active research efforts to understand the underlying physics. The lab scale study is carried out on magic candles where, magnesium powder is incorporated into the wick, as it has high flammability at low temperatures when compared to other pyrophoric materials. This addition of magnesium may cause potential fire hazards and hence the purpose of this study is to achieve results which can help in improving the combustion fire safety. The work centers attention majorly on three parameters, i.e., distance from the source, spread rate, and the possible orientations of an array of sources. Systematic experiments were performed with selected parameter combinations in a flow opposed combustion environment. The change in thickness and turbulence of the flames as the parameters are altered is observed. A detailed study on the Inter energy conversions taking place amongst subject candles and source candles with the help of related equations has been done.*

1. INTRODUCTION

The concept of Combustion has been a topic of interest to human kind for a long time, and the phenomenon has been comprehensively studied and understood by scientists and science enthusiasts alike. In spite of this, and the fact that this physical process is encountered by virtually everybody, the mechanics involved in it remain largely unknown to the common masses. Though simplified, the concept essentially encompasses a lot of intricacies, and it is really fascinating to learn its physics. This phenomenon has wide ranging applications in Science and Engineering. The burning of a candle is one of the prime examples of Combustion. The necessary requirements for the process of combustion to take place are Fuel, Oxidizer and Heat from some object which acts as a source. The observable flames of a candle are due to a combustion reaction taking place which leads to the formation of carbon dioxide. The heat transfer happens through conduction, convection as well as radiation. Conduction takes place through the medium in the immediate vicinity of the burning element. Convection phenomena occurs as the heated air rises up. Radiation occurs in the form of Electromagnetic Waves. In the presence of heat, wax melts and gives off wax vapors which ascend upwards along the wick and emit visible radiation, thus giving high flames, which exceed the wick height. The oxygen is brought to the low-density region created due to upward movement of burning vapors through Convection (Convective Heat Transfer). Hence the process behaves in a perpetual manner until the fuel is completely utilized. A normal candle ignites when a heat source is introduced to it, and the flame sustains as long as there is a balanced availability of the aforementioned three parameters. When a normal candle is blown, the flame gets separated from the fuel, hence depriving it of the same and the candle blows out, and requires a reintroduction of heat for it to ignite again. An Energized Candle, on the other hand, does not necessarily require this reintroduction. This type of candle is compositionally similar to a normal candle, with one critical-addition, Magnesium. When an Energized candle is blown, the Magnesium coated on the wick which was previously shielded by the flame, is exposed to the surroundings. The heat required for the candle to relight is obtained from the burning ember from the time when it was blown out. This is the basic difference between a Normal candle and an Energized Candle, also known as Magic Candle colloquially. At a grander scale, the behavior of Sun, discerns its unpredictable solar flare patterns. Flares are powered by sudden release of stored magnetic energy on the outer corona. This sudden deviation from the previously quiescent nature is termed as Flickering. Flames flicker when the amount of fuel and air in the mixture becomes disproportionate, leading to an unburned soot which gets detached from the combined flame and rises up. The topic of interest of this research paper is to determine regression rates and flame heights of Energized Candles, with differing number of heat sources placed at different distances. In the control observation, a single Energized Candle alone is placed and observed. In the subsequent observations, two main parameters are considered, which are as:

a) An array of external heat sources (here, similar energized candles of the exact dimensions as the Subject candle) at different orientations.
b) The heat sources are placed at different distances from the subject candles.

Fig. 1: Phenomenon of flickering and stratified flame.

Another noteworthy aspect to the study about heat transfer are the inter-energy conversions which take place amongst the heat sources (Fig. 1). Just as the pilot candle is affected by the presence of numerous sources, the sources are also affected in the presence of the pilot candle, howsoever small that effect may be. The subjects (candles, here) respond vigorously to this change in the surrounding which was calculated by observing the difference in regression rates and flame heights (Fig. 2).

(a) **(b)**

Fig. 2: (a) The effective increase of flame in the source candle and (b) the effective increase of flame in the pilot candle.

Following the classical work Grant, and Jones [1] on Low-frequency diffusion flame oscillations, the exploration of combustion characteristics has resulted in appreciable experimental, numerical, and analytical works. The works [2-4] provide an excellent review till the end of century.

Kitahata et. al., [5] carried out experiments using simple candles observing stable combustion with a single candle and oscillatory with three candles burning together. The mathematical model indicated that oscillatory combustion in a set of three candles is induced by a lack of oxygen around the burning point. The study advocated thermal radiation to be an essential factor in synchronization. Ghosh, et. al., [6] emphasized on studying the flickering of a candle placed in a hollow cylindrical glass tube. Variation in flame area and intensity were studied as the oscillating parameters of the flame. Tests were carried out with a range of candle diameters for the same glass tube giving similar results. A correlation dimension was determined for a number of experiments to characterize the dynamics of the signal. Saxena et. al., [7] probed amplitude death, complete suppression of oscillations. The work reasoned that the oscillations of the entire system ceases as a consequence of the interaction leading to the stationary behavior. In recently, Forrester [8], promoted synchronization of interacting dynamical sub-systems occurring as array of flames that act as master and slave oscillators with group of candles creating a synchronized motion in three-dimension

In the light of above mentioned work, the need to fundamentally under the Combustion Characteristics of An Array of Energized mixture have necessitated active research efforts. The initialization is being carried out experimentally with the quantified analysis under steady state conditions. Present work attempts to investigate experimentally on the flickering of energized candle flame. Present work, attempts to explore the combustion characteristics of energized candle Flame influenced by the presence of an external heat sources (here magic candles). Here, efforts are directed to understand the uneven heat transfer behavior which governs the burning and spreading of energized combustibles. The interest in this class of problems is primarily driven by the need to have better combustion and fire safety. The specific objectives of the present study are to.

a) Investigate influence of external heat sources on heat transfer characteristics of a magic candle and thus reasoning the optimal heat transfer conditions.

b) Analyze the role of key controlling parameters.

2. EXPERIMENTAL SETUP AND SOLUTION METHODOLOGY

The experiment was conducted in a room with all lights, doors, windows, and other openings closed to minimize the effect of outside influences such as wind and noise. The set-up was placed on a smooth plywood plank. On the plywood plank, markings were made for the positioning of the source and pilot candles as shown in Fig. 3. The candles were rectangular in cross-section, with dimensions of 0.4cm x 0.3 cm on average and a height of 5.8cm. The candles were of different colors and had white spiral strips, which ran along their lengths. Markings on the candle were etched using a CD Marker, at equal intervals of 1cm. On each Pilot candle, 4 markings were made, which translated to 3 readings per candle, at equal distances. The first marking was located at 1.5cm. from the bottom, and the others accordingly. In Fig. 3(b), the markings that were made on pilot candles is shown, the area prior to the first marking on the top was preassigned before conducting the experiments as the stabilization zone. A Scale was placed vertically on the left-hand side of the candle positions, stationed on the plank with the help of China Clay (Household clay).

(a) (b)

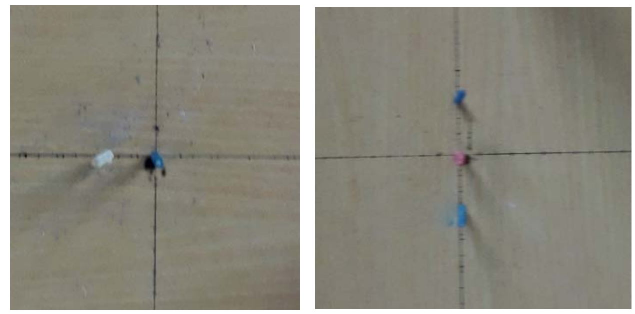
Fig. 3: The markings on the table and on the candles

(a) (b)

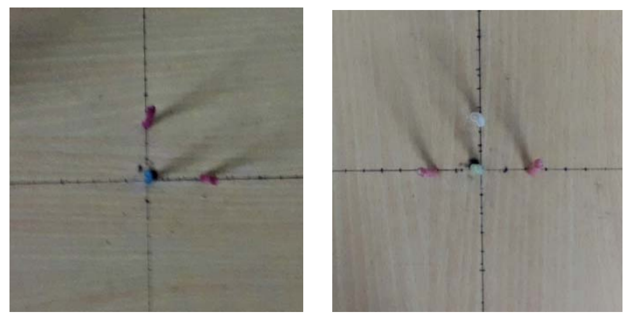
(c) (d)

Fig. 4: (a), (b)- A simple double-sided scale which was designed for taking the measurements in the experiment, (c)- The complete setup with one front camera, one side camera and a light source at a certain angle, (d)- The view from the camera placed at 45 degrees.

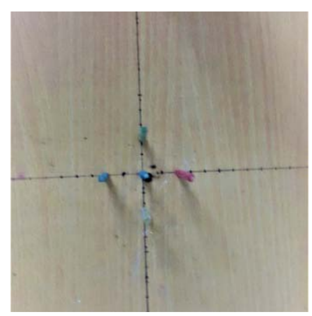
Fig. 4 shows a two-sided scale with markings on both sides, so that measurements could be taken through both cameras. The two cameras, in turn, were placed to the left and at the front respectively. The former was primarily to observe the flame heights, while the latter was mainly utilized for the determination of regression rates. However, cases where three or four source candles were interacting with one subject candle, the second camera (for measuring regression rates) was placed at an angle of 45 degrees maintaining the same distance, to obtain the desired view of the pilot candle. Lighting from another phone was used for the illumination of the set-up. Optical Videography was used to document the observations. The videos were later analyzed through a laptop, for measuring the flame height and regression rates. The videos were taken at 30 fps (frames per second). The vertical scale, visible in the videos, was used to measure Flame heights. For regression rates, a stopwatch was used to determine the time taken for burning of the pilot. As, for each candle, three markings were made, the average of the 3 regression rates were taken into account. Under the first parameter, as mentioned earlier, the following variations were exercised:



(a) (b)



(c) (d)



(e)

Fig. 5: (a) 1 source candle, (b) 2 source candles placed in a Straight-line configuration, (c) 2 source candles placed in an L-shaped config., (d) 3 candles forming a T-shaped config., (e) 4 candles forming cruciform shape.

Fig. 5 represents the configurations which were incorporated for the experimentation. Fig.5(a) is a simple configuration where only one source candle is positioned beside the pilot candle at a certain distance.

Similarly, figures 5(b) to 5(e), represent more complex configurations where the number of source candles is increased. Under the second parameter, the above-mentioned orientations were experimented at different distances of 0cm., 1cm., 2cm., 3cm., and 4cm., respectively. Using these two parameters, the trend of varying flame heights and regression rates of the Pilot candle was determined. The regression rate can be defined as the rate of decay of the subject of interest, in this case, the impure paraffin wax in the candle.

$$r = \frac{l}{T_{av}} \quad (1)$$

Where, 'r' = regression rate in millimeters per second 'l' = the portion of the candle which has been utilized. 'T_{av}' = the time taken to burn that particular portion.

From classical theory of ignition spread, assuming unity width of fuel the regression rate (r) is defined by energy balance as:

$$r = \frac{\int q_{net}}{\rho_s \tau_s C_s (T_{surface} - T_a)} \quad (2)$$

Where

$\int q_{net}$ = Net integrated heat transfer per unit time per unit area to the unburnt fuel

C_s = Solid phase specific heat τ_s = Solid fuel thickness,

ρ_s = Solid fuel density,

T_a = Ambient temperature

Ignition is primarily transition from a non-reactive material decomposition to a self-sustained reactive combustion. This transition is owing to an imbalance between the heat production and heat loss which relates to the energy stored in a volume as:

Stored energy change = Energy Production-Energy loss

$$\rho_s C_s V \frac{dT}{dt} = q_p - q_L \quad (3)$$

The energy production is based on an Arrhenius approximation as:

$$q_p = \Delta H_c V C_i A^* e^{\frac{-E_a}{RT}} \quad (4)$$

The associated heat energy loss is taken by assuming constant concentration of reactants in the volume (material not consumed prior to ignition) (Ci) indicating a uniform temperature:

$$q_L = hA(T - T_a) \quad (5)$$

q_p= Energy produced, q_L= Energy loss, V= Volume, ΔH_c= Heat of combustion, C_i = Concentration of reactants, A^*= Pre-exponential factor, E_a= Activation Energy, h= Convection factor.

It is important to note that the results represent the repeatability of the order three.

3. RESULTS AND DISCUSSIONS

An experiment was carried out on energized candles to study the variation in combustion characteristics with deviation of certain parameters viz., number of candles, orientation of candles, and distance from the pilot candle.

An energized candle has magnesium, coated on the wick of the candle, and therefore it burns at a higher rate due to greater temperatures involved in the combustion reactions taking place at the surface. Hence, the general observation has shown that the regression rate is higher for energized candles. The magnesium in the wick of the trick candle ensures that enough amount of heat is available to sustain the flame. Ideally stating, the magnesium remains shielded inside the burning wick and its temperature is kept low due to constant cooling by liquid paraffin, but due to variations in the atmosphere, as soon as magnesium is brought into contact with the surroundings, its temperature is increased abruptly which results in sudden sparks providing a rather peculiar image.

(a) (b)

Fig. 6: Spreading flame in magic candles

Fig. 6(a) highlights the spark is generated in the right-most candle. This happens due to the inter energy conversions taking place in the configuration which accelerates the rate of conductive heat transfer in the right-most candle slightly more, when compared to the other two candles. Fig. 6(b) clearly shows the propagation of spark through the surrounding, which was generated from the pilot candle. The addition of a catalyst like magnesium has consequences like growth in regression rate. A detailed analysis on comparing the average regression rates of a magic candle with that of a normal wax candle was carried out. Fig. 7 represents the average regression rate characteristics for a normal and an energized candle. The graph shows the linear increment in the average regression rate for the preassigned stabilization zone in case of both the candles. Reading '1' on the horizontal axis represents section 1. Across section 1, the regression rate for the normal candle gradually increases following the linear pattern, while that of the energized candle continues the linear increment until it reaches a maximum and then decreases abruptly.

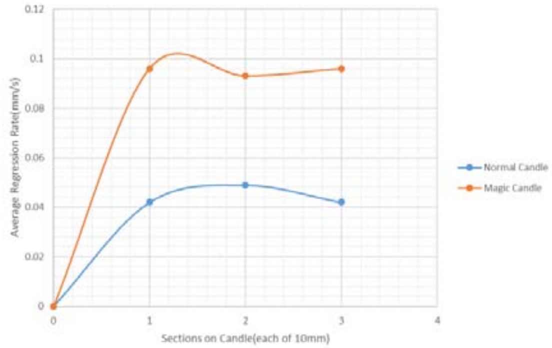


Fig. 7: The variation in regression rate for sections marked at equal intervals on the candles.

Across sections 2 and 3, the characteristics are almost constant. This contradistinctive nature of the energized candle can be attributed to the presence of magnesium which acts a catalyst in the reaction and hence the mechanism involved in case of combustion of energized candle is slightly different than that of normal candle. It was observed that on average, an energized candle burns **115.64%** quicker in comparison to a normal candle. The characteristics of regression rate in the presence of external heat sources were also noted. Fig. 8 shows the variation of regression rate with increase in distance from the pilot candle keeping the number and orientation of sources constant. The graph follows a non-monotonic trend, first increasing, then decreasing, then again decreasing. The notable exception to this is the one with 3 source candles, which first decreases, then increases and then decreases at the end. This can be attributed to the different aspects of forward heat transfer. In case of one source candle, the regression rate when it is attached to the pilot candle (distance-0 mm) is less than that of an individual pilot candle (no source). As the distance is increased it follows a parabolic path until 20 mm, and then it increases gradually.

The regression rate both for attached case (at a distance of 0 mm) and at a distance of 10 mm, is maximum for four source candles with an increment of **29.06%** from the mean.

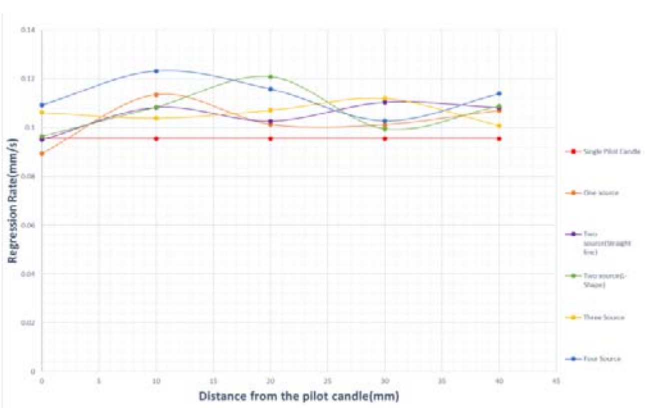
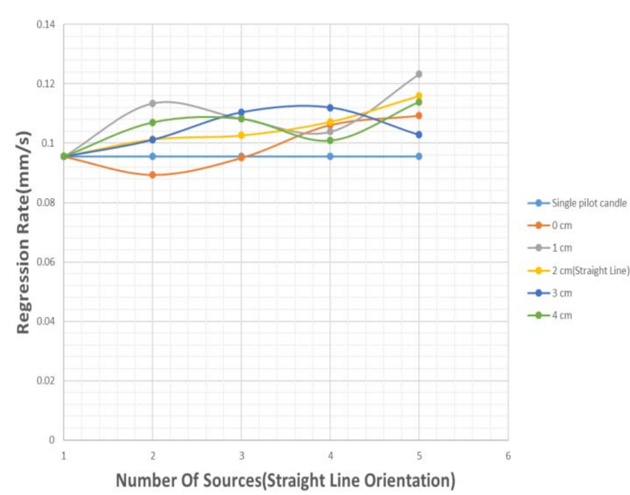


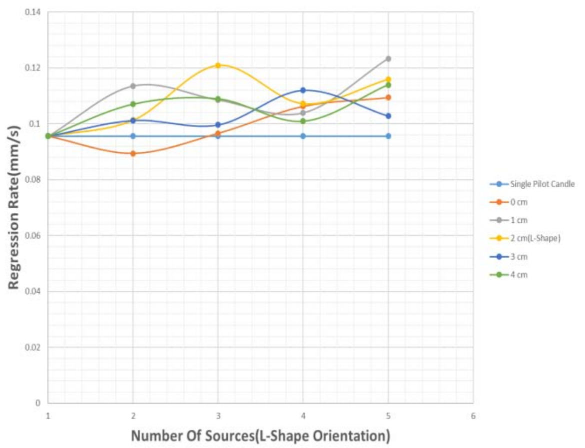
Fig. 8: Variation in regression rate with increase in distance from pilot candle keeping orientation constant

When experimented with source candles at a distance of 20 mm, the L-shape configuration of two source candles is found to have the greatest regression rate, having **26.55%** increment. When placed at a distance of 30 mm from the pilot candle, the three source candles arrangement holds the greatest regression rate, **17.23%** more than the mean. And finally, at a distance of 40 mm from the pilot, the four-source candle case with an increment of **19.22%**, has the highest regression rate. The trend followed by every curve in Fig. 8 is inconsistent to one another which directly relates to the complexity of Inter-energy conversions that occur when heat sources are arranged in the aforementioned orientations. The characteristics of regression rate v/s the number of sources, keeping the distance constant were also plotted. Fig. 9[(a)-(b)] represent the straight-line configuration and L-shape configuration, for the 2 source candles case respectively. On comparing, it is clear that the except for 2 source candle cases, all other cases are similar. As the number of candles is increased from 2 to 3 in both the cases, the curves meet at the same point in both the graphs. Reading '1' on the horizontal axis represents single pilot candle, '2' represents one source candle, and so on. For 0 mm case, when one source candle is placed next to pilot candle, the regression rate experiences a decrement of **6.43%** from the mean. The maximum value of regression rate is obtained when four source candles are placed at a distance of 1 cm. from the pilot candle and the increment observed was **29.06%**.

Therefore, it can be stated that regression rate increases with increase in number of heat sources. However, this statement cannot be justified as the other curves show contradictory trends. For 20mm (L-Shape) case in Fig. 9(b), the maximum value of regression rate is observed when 2 sources are placed with the pilot candle rather than for 4 sources case, with an increment of **26.55%** from the mean. Apart from regression rate, maximum flame height of the burning candle flame was also measured and plotted against the distance from the pilot candle:



(a)



(b)

Fig. 9: Variation in regression rate with increase in number of sources keeping distance from the pilot constant. In (a), Straight Line Config. is considered; and in (b) L-shaped Config. is considered.

When the distance between the pilot and source candles is 0, the readings obtained were in correspondence to the predicted ones. The highest flame height obtained was in the case of 4 source candles standing attached to the pilot candles. The flame height measured was **242.83%** greater than the flame height in case of an individual pilot candle. This was followed by the 3 source candles case, which saw an increment of **199.97%** over the single pilot candle case. The experiment yielded that the effect of external heat sources over the flame of the pilot candle gets diminished as the distance of the heat source from the pilot candle goes on increasing. From Fig. 10, it can be seen that all the curves converge as the distance between the sources and pilot candle is increased beyond a certain boundary (here about 40 mm).

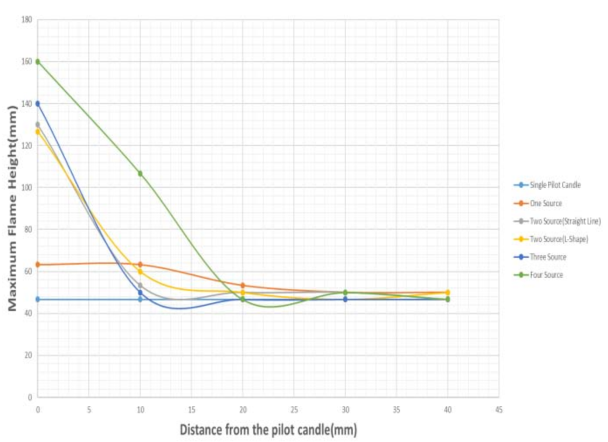


Fig. 10: Characteristics of maximum flame height v/s the distance from the pilot candle, keeping the number and orientation constant.

The quantitative analysis of an array of energized candle flame reveals the aspect that catalytic chemicals do vary the combustion characteristics. Under circumstances of an array of external heat sources, the governing physics may be attributed to the uneven changes in the forward heat transfer owing to the presence of external heat sources. The forward heat transfer in this case, originates as a cumulative sum of the inter-energy interaction of the pilot fuel and the external heat source(s). The experiment discloses that the nature of respective changes follows a close form solution however, is associated with non-linearity. The resulting energy transfer substantiates the enhanced spreading rates and related consequences.

4. CONCLUSIONS

Experiments were conducted on an array of Energized Candles under controlled environment to investigate their unusual combustion characteristics, and their inconsistent nature. Based on the observations the following conclusions may be drawn:

a) Enhanced spread rate of energized Candle compared to that of a Normal candle corroborates the presence of catalyst magnesium.
b) At low distances, the spread rate of an energized candle is less dependent on its distance from the heat source(s), but more on the orientation of the same, which is directly associated with the forward heat transfer.
c) A direct correlation exists between the flame heights and the separation distance of the heat source(s). The flame height highlighted average highest when the distances were minimum (0 cm.), and became constant after a certain distance (2 cm.).
d) The inter-energy conversions taking place have a deciding impact on the maximum flame heights observed in the readings.
e) The predictions of the experimental setup were validated with the benchmark heat transfer theory and matches reasonably well.

Applications of the work: The basic concept of energized propellant and combustion is similar to that of energized candles, hence the observations presented in this paper will find relevance in the above-mentioned field. The energized combustibles can find their applications in fire safety, and better, efficient combustion in various fields of science and Engineering. The controlling science of energetic combustion can be utilized to entail a good physical insight to design and validate the existing fire systems, to improve their reliability. The inefficiency of hybrid propellants due to their low regression rates can be tackled by the introduction of a suitable catalyst which is experimentally verified in this paper.

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