How to Burn? Straight vs Horizontal vs Suspended

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Abstract. Burning is an inevitable process that happens in nature and has a massive impact on life. Technically, burning or combustion emphasizes on the reaction process that consumes oxidizer and fuel to deliver heat and burnt products. Based on the direction of reaction propagation and fuel orientation, burning or combustion is classified in to forward or reverse combustion. Forward combustion is a process which comprises of movement of air and the propagation of ignition zone in the same direction while in reverse combustion, air moves opposite to the direction of the propagation of the ignition zone. Forward combustion escalates rapidly in solid fuels when compared to reverse combustion. The conductivity of the burning solid fuel, convection due to the atmospheric air around and buoyancy effects which takes place due to the difference in air densities plays a major role in the forward combustion process. In this work, thin uniform cross-sectioned solid materials such as matchsticks, candles and incense sticks have been considered as fuel to investigate forward flaming and smoldering. The experiments were carried out in ambient atmospheric conditions. The results based on visualizations suggest that the orientation of the fuel has a greater impact on burning rates and provides us the information on how to burn it in a beneficial way.

1. Introduction
Origin of fire initially started with the lightning from the sky, which struck a tree that caught fire later on. The early men who noticed this phenomenon didn’t know that it was fire and assumed that it was some kind of creature. And so, they approached it with the intention of knowing what it was, with the spears, but they noticed that it started spreading all over. When they tried to destroy it with the spear, they observed that it started to borne to the spear. They tried to touch it with their hands but they aren’t able to do so as it is very hot and burning their hands. At this point, they finally found out the sniff of the burning material. Once when they were sharpening their weapons by means of filing with the stones, a spark of fire fell on the ground. This led to smoldering which slowly turned out to give fires. This was observed by the early man and they started to use the fire to scare the wild animals away. Homo erectus who lived as long as 500,000 years ago in the Palaeolithic period was the first kind of man who got to know the uses of fire. The oxygen maxima (Carboniferous) came into existence after the Palaeolithic period [1,2,3]. Fire has even completely transformed the diet of humans by playing a major role in the food system [4]. They used fire to cook meat as they found chewing meat cooked using fire is easier is chew and tasted better than raw meat.
As years passed by, different ways of initiation of the fire were discovered. One such method which was widely used is the hand drill method. This method used a wooden drill against a wooden board to create fire by friction. Another group of early people created a fire spark by rubbing stones against hard rock. The discovery of fire has become more and more numerous in many sites mostly in Africa, Europe, Asia and the middle east [5, 6, 7]. Archaeologists have found ashes of wood, charcoal in the caves that existed about 400,000 years ago. From this, it is clear and evident that early men used fire to produce light as it would be dark inside the caves. They used fire to clear trees and bushes by burning them to ease hunting. This changed the living conditions and environment and gave rise to the development of mankind.

The intensification of the use of fire in humans profound the different ways of execution of fire in everyday life [8]. In the prehumanera, the evidence of fire came to existence which is essentially due to the oxygen, heat and fuel, apart from that it has become socially embedded and have a major impact on the environment [2]. Early human society started to develop only when they practiced control over fire. The discovery of fire by early men is the reason for great inventions and developments to date. The standardized global charcoal values indicate a drastic change in the usage of fire from 170,000 to 500 years and the origin of agriculture had first begun in the East [2]. 4000,000 years ago, the discovery of fire has become more and more in numerous in many sites mostly in Africa, Europe, Asia and the Middle East [6, 7, 8].

The scientific development of combustion studies is classified into Flaming and smoldering. Smoldering is a form of combustion that burns slowly without flame and it's the major cause for the initiation of flame by the heat sources and also causes fuel to transform into toxic compounds leading to fire [9]. Oxidation process utilizes the alkali metal impurities which are derived from the plants and by the enhanced surface where oxygen attacks [10]. The time taken by the smoldering zone to penetrate through the layers is proportional to the twice of the layer depth [11]. The configuration of smoldering is classified into forward and reverse smoldering, propagation of smoldering reaction front as the airflow and opposite direction respectively [12]. The propagation of smoldering velocity increases with the depth of the layer [13]. In experiments that were carried using polyurethane foam, it was found that within the reaction zone the dominant supply of oxidizer propagates the downward smolder. It was also found that not only the temperature of the surrounding but also the temperature at a point on the fuel which is ahead of the reaction zone increases and when the oxygen supply is less, the reaction is weakened [14].

The present work has been carried out exclusively to find out at which surface orientation the combustion process is beneficial. The results obtained from this work can be used in effective burning and also in the investigation of naturally occurring fire accidents like forest fires, industrial fires, residential fires, and building fires.

2. Methodology
Visualizations and calculation of regression rates were supported by an experimental setup. Wood-based match sticks, wax-based match sticks, and candles were used as a fuel to visualize flaming combustion and incense sticks were used as a fuel to visualize smoldering combustion. The fuels used in this work has a thin uniform cross-section to facilitate uniform burning. In this work, the flaming and smoldering combustion on the different fuels has been visualized when the fuel is placed at three different surface orientations viz., straight/vertical (burning from the top end), horizontal and upended (burning from the bottom end), that is, 90°, 180° and 270° respectively. The regression rate of the fuel has been calculated along the longitudinal axis of the fuel.
The regression rate variation has been calculated for the varying surface orientation of the fuel. To calculate the regression rates of the incense sticks, it was marked for a 3 cm distance with a regular interval of 1 cm. The average time taken to burn 1 cm of the fuel for all 3 surface orientations were calculated. To calculate the regression rates of the match sticks and the candle, they were allowed to burn completely and the time taken by it to burn 1 cm was averaged for all 3 surface orientations. The height and the diameter of the wood-based match sticks, wax-based match sticks, and the candles were measured to be 4.69 cm, 2.70, 5.27 and 0.19 cm, 0.13 cm, 0.68 cm respectively. Simple fuels like the candle, match sticks and incense sticks were used due to its easy availability. These fuels were dried prior to experimentation to remove excess moisture from it. The fuel samples were ignited manually using a pilot fuel. All the experimentation was done in a closed room under ambient conditions.

The regression rates of the fuel used were calculated using the formula,

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 r = \frac{\text{length of fuel burned (l)}}{\text{time taken to burn 1 cm of the fuel (t)}}
\]

3. Results and discussion

This experimental study was carried out to understand the role played by surface orientation on forward and reverse combustion processes. Regression rates were measured and calculated for all the flaming and smoldering fuels. These values were calculated for 3 different surface orientations of the fuel [15]. The fuel is positioned vertical, horizontal and upended which is 90°, 180°, 270°. The consequence of orientation on the regression rate values of the fuel was observed and calculated.

3.1. Smoldering

Incense sticks were used to compare the regression rate values at all 3 surface orientations for smoldering combustion. When the fuel is oriented vertically, it was observed that the transfer of heat to the fuel behind the reaction zone (unburnt fuel) is mainly due to conduction. The ash produced by the burning fuel has a convective nature which produces shot smoke that moves across it due to buoyancy. This results in reduced heat loss to the surroundings. When the fuel is orientated horizontally, the regression rates are wholly found to be a result of conductive heat transfer to fuel behind the reaction zone, which is a result of zero buoyant velocity on the surface of the unburnt fuel. In this case, horizontal and vertical orientations of the fuel are found to have similar regression rates [15]. This is primarily due to the loss of heat from the ash to the surrounding which causes reduced loss of heat from the smoldering part of the fuel to ash.

![Figure 1. Smoldering of an incense stick oriented straight (top), horizontal (middle) and upended (bottom).](image-url)
The reason for the peak in regression rates is the sharp increase in heat transfer to the unburnt fuel. The rise in conductive heat transfer in the horizontal orientation of the fuel is purely due to the presence of ash across which hot smoke passes. When the fuel is oriented at 270°, that is, when the fuel is placed upended, it tends to burn faster than the other two cases [12]. This is primarily because of the preheating of the fuel due to buoyancy [14]. When the fuel is burning upended, it gives out hot smoke which rises up due to buoyancy. The smoke moves in the direction of propagation of the ignition zone. This smoke preheats the fuel through convection and makes the unburnt fuel to reach its ignition temperature faster than the other cases. Fig. 1 shows the smoldering of an incense stick oriented at 90°, 180°, and 270° respectively.

3.2. Flaming

3.2.1. Wood-Based match sticks. Match sticks made out of wood were used to compare the regression rate value at 3 surface orientations. When the match stick is oriented vertically, it was observed that the transfer of heat to the fuel behind the reaction zone (unburnt fuel) is mainly due to conduction. The flame produced by the burning fuel is convective in nature which produces hot smoke that moves across it due to buoyancy. This results in reduced heat loss to the surroundings. This buoyant force is stronger than the conductive heat transfer rate of wood which causes the match sticks to burn only at the match head, that is, the fuel part of the match stick. In other words, the buoyant force is not allowing the ignition zone to propagate farther than the zone at which the fire [6] was initiated.

At the horizontal orientation of the match sticks, both conductive and convective heat transfer takes place. The flame slowly stabilizes after ignition and the ignition zone propagates through the preheated match stick. The sticks get preheated by the flame and the combustion gases such as smoke. As the combustion process is stable, the flame propagates throughout the stick and burns it completely [8].

When the match sticks are oriented upended, that is, at 270°, the flame and the smoke move in the direction of the propagation of the ignition zone. This preheats the match sticks to an immense level causing it to burn completely. From the experiments that were carried out, it was observed that the upended flaming on the wooden match sticks was faster than the other two orientations. Fig. 2 shows the flaming of a wood-based match stick oriented at 90°, 180°, and 270°.

![Figure 2. Flaming of a wood-based match stick oriented straight (top), horizontal (middle) and upended (bottom).](image-url)
3.2.2. **Wax-based match sticks.** Match sticks made out of wax[8] were used to compare the regression rate value at 3 surface orientations. When the match stick is oriented vertically, it was observed that the transfer of heat to the fuel behind the reaction zone (unburnt fuel) is mainly due to conduction. The flame produced by the burning fuel is convective in nature which produces hot smoke that moves across it due to buoyancy. This results in reduced heat loss to the surroundings.

Unlike the wooden match sticks, here, wax serves as a fuel to propagate the flame downward. That is, the conductive heat transfer rate of wax is high and is sufficient enough to overcome the effect of buoyancy on heat transfer. This allows the match sticks to burn completely even when it is oriented vertically. It should be noted that the wax evaporates as it gets hotter due to flame.

In the case of horizontal orientation of the match sticks, both conductive and convective heat transfer takes place similar to the wood-based match sticks. The sticks get preheated due to the conductivity of the wax and also due to convection because of the flame and smoke generated by it. Owing to this, the flame propagates throughout the stick and burns it completely.

When the match sticks are oriented upended, that is, at 270°, the flame and the smoke move in the direction of the propagation of the ignition zone. This preheats the match sticks to an immense level causing it to burn completely within a few seconds. The combustion process is very swift when compared to the other two surface orientations of the match sticks. Fig. 3. Shows the flaming of a wax-based match stick oriented at 90°, 180°, and 270°.

![Figure 3. Flaming of a wax-based match stick oriented straight (top), horizontal (middle) and upended (bottom).](image)

3.2.3 **Wax candles.** Wax candles were used to compare the regression rate value at 3 surface orientations. When the candle is oriented vertically, it was observed that the transfer of heat to the fuel behind the reaction zone (unburnt fuel) is mainly due to conduction. The flame produced by the burning fuel has a convective nature which produces hot smoke that moves across it due to buoyancy. This results in reduced heat loss to the surroundings. In this case, wax serves as a fuel to hold the stabilized flame on the wick. Here the solid wax initially melts due to convection and it evaporates to take the gaseous state as it gets hotter due to flame.
In the case of the horizontal orientation of the candle, both conductive and convective heat transfer takes place. The candle gets preheated by the flame and the combustion gases. The candle is observed to burn in an inclined manner as the wax melts down to a liquid state.

The evaporation of the wax is not observed as the liquid wax drips down owing to gravity. Fig. 4 shows the flaming of a candle oriented at $90^\circ$ and $180^\circ$. When the candle is oriented upended, that is, at $270^\circ$, two different cases are observed. First, the wick of the candle is positioned in line with the axis of the candle. When the wick of the candle is lit up, the flame heats up the wax and melts it through convection and partial conduction and because of this the melted liquid wax starts dripping down through the wick and puts off the flame.

![Figure 4](image1)

**Figure 4.** Flaming of a candle oriented vertically and horizontally.

Next, the wick of the candle is inclined to the axis of the candle. In this case, the flame does not touch or trace the wax but it is away from the wax. The solid wax melts completely due to the temperature of the flame. In this case, the dripping liquid wax does not come in contact with the flame and hence does not put off the flame. Fig. 5 shows the flaming of a candle oriented upended with wick positioned inline to the axis of the candle.

![Figure 5](image2)

**Figure 5.** Flaming of a candle oriented upended (red candles are with wick positioned inline to the
axis of the candle and green candles are with wick positioned inclined to the axis of the candle).

4. Summary
From the experimentations that were performed, it was observed that the surface orientation of the fuel is found to have a remarkable effect on the regression rate of the fuel (refer Table. 1). In all the cases that were considered, the maximum regression rate value was observed when the fuel is oriented upended and the minimum value was observed when the fuel is oriented vertically.

| ORIENTATION        | INCENSE STICK | WOOD-BASED MATCHSTICKS | WAX-BASED MATCHSTICKS | WAX CANDLES          |
|--------------------|---------------|-------------------------|------------------------|----------------------|
| STRAIGHT/VERTICAL  | 0.26          | –                       | 3.6                    | 0.233                |
| 90°                 |               |                         |                        |                      |
| HORIZONTAL         | 0.26          | 5.21                    | 7.12                   | 0.752                |
| 0° or 180°         |               |                         |                        |                      |
| UPENDED            | 0.645         | 23.45                   | 11.74                  | 3.33 (inclined wick) |
| 270°               |               |                         |                        |                      |

In all the fuels that were considered, the maximum regression rate value was observed for an upended wood-based match stick, and the minimum regression rate value was observed for the vertically oriented candles. In the case of smoldering combustion upended burning regresses faster as the combustion smoke moves in the direction of the propagation of the ignition zone and pre-heats it to reach its ignition temperature faster. In the case of flaming combustion upended burning regresses faster but it depends on the type of fuel used. If the type of fuel used is wax, upended burning is effective only if the wick is inclined to the axis of the fuel.

5. Conclusion
In this work, the common household materials like match sticks, incense sticks, and candles were used to demonstrate how the orientation affects the burning or regression rates. The regression rates were measured by using a simple experimental set up via visualization. The results suggest that the burning in upended orientation leads to the highest burn rate which means the material burns consuming the least time. The upended burning can be used in places where rapid production of heat and light is required. Horizontal burning consumes more time than the upended burning and it better for igniting other materials like lighting a candle with a match stick. Straight or vertical burning shows the lowest burn rate which means the material takes a long time to burn. Vertical or straight burning can be used for lighting a room by using a candle flame or to keep the ambiance with the fragrance of the incense material due to its lowest burn rate.
Acknowledgment
The corresponding author wishes to acknowledge the usage of the Flow Visualization laboratory for the experiments, Advanced Computing lab for the documentation and also the help rendered by the hangar supervisor and lab assistant for the video recording reported in this paper.

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