Smoldering Combustion of Hexagonal Incense Material with Forced Airflow

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Abstract. Most of the forest fires and building fires are occurring due to the low-temperature flame-less phenomenon called smoldering combustion. The present study is carried for the understanding of fluid flow patterns over the fuel and also fuel under smoldering combustion. The fuel equipped here is a hexagon since most of the modern architectural shapes for buildings, parking lots, hexagon-shaped houses, honeycomb-patterned facades, etc. Regression rates are calculated for the fuel under smoldering. For experimentation, a tabletop wind tunnel is fabricated, and an axial fan is fixed with a speed regulator to investigate the smoldering combustion under the flow and behavior of the fluid flow. The results suggest that the smoldering phenomenon is significantly dependent on the orientation, flow speed and the direction of smoldering with respect to the flow.

1. Introduction
Smoldering is a key phenomenon that plays a major role in the production of smoke and the same results in environmental pollution. The complete combustion results in less smoke and the same is not seen during smoldering. The effect of air on the smoldering phenomenon has a significant effect on the burn rate and the smoke production process. In this regard, the present manuscript focuses on the experimental study of the smoldering phenomenon subjected to airflow under various conditions. The literature on the smoldering phenomenon of various materials is presented in the following paragraphs.

Experiments on the transition from forward smoldering to flaming were reported by Bar-Ilan et al [1]. The experiment was carried out on the polyurethane foam in order to find the effect of velocity flow, concentration of oxygen and the radiation flux on the transition of smoldering to flaming at microgravity and low gravity environment. The samples of small size are selected because the smoldering combustion can self-propagate as the heat is lost to the environment. The experiments are carried out in a wind tunnel where the fuel is placed vertically. The lateral sides of the three samples are maintained at elevated temperature whereas the other three sides were exposed to the upward flow and radiation flux. From these experiments, it was found that there is a delay in the transition of smoldering to flaming by decreasing the flow velocity, increasing the concentration of oxygen and by increasing the radiation flux.
They concluded that the transition can occur in the char region left behind by the smoldering reaction with the appropriate external conditions.

D.A. Schult et al [2] studied forced forward smoldering combustion, where cylindrical samples were considered with gas forced into the samples through one of its ends. Two different structures were used to find smolder wave solutions. Each had two interior layers. Combustion reaction in one layer and heat transfer between the solid and fuel in the other. Marco Zanoni et al (2018) worked on “Fundamentals of Applied Smoldering Combustion”. They concluded that for the self-sustaining cases, the net energy balance is constant with time and it can be achieved by increasing the air flux or fuel saturation. And for the smoldering extinction, the decrease in temperature with time occurs.

T.J. Ohlemiller et al [3] worked on experimental comparison of forward and reverse smolder propagation. The two types of permeable fuels used were wood fiber and polyisocyanurate. The sample bed of 16.2 cm diameter and 17.8 cm deep is peripherally insulated in the dispersion section where the uniform flow of oxygen or nitrogen mixture takes place. This study showed that the reverse smolder is 10 times faster than the forward smolder because of conduction and radiation (note: the flow velocity is less than burn rate). And also concluded that the higher flow rate of oxygen increases the char consumption in both the forward and reverse smoldering.

Y. Gao et al [4] reported a discussion on Buoyancy, Turbulence, and Combustion. The main purpose of this study was to know the effect of buoyancy, turbulence and combustion on the fire field model, for example, a test section in the form of a compartment with a window inside and door in front. Simulations were carried out using Computational Fluid Dynamics (CFD). Two cases were studied under different operating conditions. Case A simulations were carried out with fire at the center of the room. Case B simulations were carried out at the corner of the room. Both cases were compared. The flame height is determined by knowing whether the fuel is burnt or not. The results from case B showed that because of the closed surface area the flame is height is more thereby increasing the upper ceiling temperature. Whereas in the case of A the flame height is less and doesn’t reach the ceiling as the combustion propagates uniformly in all directions. They concluded that this is the reason for the combustion reactions to take place at the ceiling where the heat release rates are higher.

Bar-Ilan [5] performed experiments on “Transition from forward smoldering to flaming in small polyurethane foam samples” to know that there is a delay in the transition of smoldering to flaming by decreasing the flow velocity, increasing the concentration of oxygen and by increasing the radiation flux.

Kenji Sato et al [6] performed experiments on “Smolder Spread in a Horizontal layer of Cellulosic Powder”. The experimental set up involved a high bulk density cellulosic powder bed over which a stream of air was supplied in order to study the smolder spread in a horizontal layer. The results involved the 2D structure of a spread zone, spread rate, cross-sectional views of the burning region and temperature distributions. From this experiment, it was observed that for forward smolder spread as the airstream velocity increases, spread rate increases at first, but above a critical airstream velocity the spread rate becomes independent of the airstream velocity and complete extinction of the smolder zone occurs. From experimental data, it is found that the heat balance around the intersection zone between the oxidation zone and virgin part of the bed is very important to the smolder spread behavior. They also concluded that the aerodynamic effects over the smolder zone also control the spreading behavior through heat transfer processes.

T.J. Ohlemiller [7] did research on “Smoldering combustion propagation through a permeable horizontal fuel layer”. The experiments were carried out on a cellulosic loose-fill material under natural convection air supply condition. The results were produced on temperature profile, the mole fraction of oxygen and residues left out after combustion. The results indicated that a complex smolders wave structure which depends on the balance between the stages of oxidation. The steady-state of the oxidation is reached with the forward smolder rate. And also found that more the wave more the heat is released. They concluded that by decreasing the char oxidation stage we can decrease the dangerous fire accidents.
The literature on smoldering combustion effectively misses out the study on the effect of flow on smoldering combustion and hence the present manuscript will throw some light on the phenomenon. The following section will describe the experimental setup and procedure followed for the experiments conducted in the present study.

2. Methodology
A fuel (Incense Material) of finite length and hexagon shape (fig.1) is chosen for the experimentation. To allow the Forced flow in a closed place over the fuel under smoldering an experimental setup table top wind tunnel [9] is fabricated to study the effect of flow over the fuel under the smoldering condition. The typical incense material chemical composition is of sawdust, charcoal, cow dung and incense chemical. As shown in fig.2 wind tunnel is fixed with axial fan for the forced flow to pass inside the test section. Mesh is fixed before the honeycomb structure for compartment next to an axial fan for the airflow to be laminar since most of the fires and smoldering phenomena arise with the unsteady flow.

![Image](image1)

**Figure.1** Pictorial view of Hexagonal shaped Incense Material.

![Image](image2)

**Figure.2** Pictorial view of the wind tunnel used for the present study.

The axial fan is fixed with the five-speed regulator for varying speed inside the test section (for different Reynolds numbers) and the Reynolds number for flow over the bulk hexagonal incense material fuel was calculated as shown in table.1. The flow inside the test section is made to be asymmetry laminar flow which almost equalizes the unsteady flow. A fuel holder is made to attach the fuel and to withstand the flow and heat. Each Fuel is marked 1cm distance at the centre to calculate the spread rate. Fuel is ignited on top of the surface and allowed to burn uniformly. The fuel is placed
inside the test section and forced flow is introduced inside the test section by means of an axial fan. A laser is made to shine from the top of the wind tunnel to study and see the flow pattern over the fuel. Experiment is carried both with and without the effect of flow, the effect of forced smoldering combustion over the fuel is studied and compared with the base cases (without flow). Three possible cases are chosen for the experimentation with the flow, as opposed to the flow and transverse to the flow. A digital microscope is used to record the video and to carry the observation and investigation.

| Speed (m/s) | Test Section Reynolds Number | Hexagonal Fuel Reynolds Number |
|-------------|------------------------------|-------------------------------|
| 0.8         | 10.256 *10^3                | 769                           |
| 1.8         | 23.077*10^3                 | 1731                          |
| 2.2         | 28.205*10^3                 | 2115                          |
| 2.3         | 29.487*10^3                 | 2212                          |
| 2.4         | 30.769*10^3                 | 2308                          |

3. Results and discussion
Smoldering of hexagon material without any external flow is carried out first in normal conditions and the results are tabulated as shown in table 2. The regressions rates [8] are calculated for distance burnt to the time taken according to the markings made on the fuel. It is found that without the external flow the smoldering of fuel at normal atmospheric conditions it burns uniformly (fig.3). From the regression rates the hexagonal fuel ignited smoldered and placed inverted has the highest regression rate as the smoke and the direction propagation are in the same direction enhancing the heat transfer in the form of convection and conduction respectively, this phenomenon is called as forward smoldering.

![Figure 3. Reverse natural smoldering (top), horizontal natural smoldering (middle) and forward natural smoldering (bottom) of the hexagonal fuel.](image-url)
For the fuel placed vertically the regression rate is found to be related to the fuel placed horizontally as this phenomenon is called reverse smoldering since the smoke moves in the opposite direction of the smolder propagation reducing the enhancement of heat transfer. Fig.3 shows the natural burning of the hexagonal fuel without any external flow.

Table 2 Regression rates of Natural Smoldering.

| Position | Regression rate (cm/min) |
|----------|--------------------------|
| Vertical | 0.2                      |
| Horizontal | 0.189                   |
| Inverted | 0.276                    |

As the fuel is bulk with a diameter of 14.63 mm the time taken to smolder is more and the important aspect was the fuel after smoldered is being left with ash, but it seems to be still smoldering inside so to calculate regression rates consideration has been done where the smoldered particle touches the marking.

To introduce the flow over a bulk incense material with hexagonal shape in a closed environment the fabricated wind tunnel for smoldering combustion is used. A ramp is made in such a way that the boundary layer develops over the ramp and the effect the forced flow over the smoldering material can be studied. Since hexagon has 6 corners and 8 faces, the faces and corners play a crucial when the flow is forced to pass over it. The four cases for experimentation opted are hexagonal fuel placed with the flow, opposite to the flow and placed vertically 90° to the flow, but when placed vertically there is a concern for the effect of corners and edges. So, when placed vertically two cases are considered facing corner and face to the flow.

3.1 Hexagonal Fuel placed along with the flow (Forced Reverse Smoldering)

Fuel is fixed to the sample holder on the ramp and placed inside the test section axial fan is turned on and a laser is shined from the top to visualize the flow pattern and the effect of smoldering combustion with the forced flow. Since the fuel is placed along with the flow when it is ignited it undergoes a forced reverse smoldering phenomenon. For forced reverse smoldering along with the flow of the combustion gases, the heat released from the fuel and smoke from the fuel will be carried along with the flow. So, the burn rate will be either less or slightly more than the base cases considered. The experimentation was carried out for all five speeds. The observation was made for the flow over the fuel under smoldering and the regression rates were calculated for all the speeds. At low velocity, the regressions rate for hexagonal incense material is almost the same as the base case. It is observed that the regression rate at intermediate velocities has higher regression rates and the highest velocity is with a lower regression rate when compared to the intermediate speeds. From observations, it is found that for low velocity the enhancement of heat transfer is very less when the smoldering material is placed along with the flow. The occurrence of convection phenomenon is very less for the forced reverse smoldering when the flow is long with the heat generated from the fuel as the flow carries away all the heat generated from the fuel. But for the intermediate speeds, the flow is enhancing the conduction to propagate and make the fuel smolder faster. For the maximum velocity, the again the decrease in the heat transfer takes place since the more velocity over a bulk material under smoldering along the flow makes very difficult for the heat propagation since all the heat is carried along with the flow. The change in percentage for regression rates has been calculated with the base case and for the better understanding of the change and the effect of forced reverse smoldering combustion over a hexagonal incense material. The percentage changes are slightly more as the hot gases released from
the reaction front is carried away by the forced flow over the flow, the change in percentage of regression rates are found to be ~13% for 0.8m/s, ~19.5% for 1.8m/s, ~57% for 2.2m/s, ~65.5% for 2.3m/s and ~39.5% for 2.4m/s. the highest being at 2.3m/s as the flow at that speed enhances the heat transfer. Fig.4 shows the smoldering of the hexagonal fuel when placed along with an external flow at velocity 2.2 m/s and fig.5 shows the variation of regression rate of the hexagonal fuel placed along with the flow with respect of the flow velocity.

Figure 4. Smoldering of the hexagonal fuel when placed along with an external flow at velocity 2.2 m/s.

Figure 5. Speed m/s (vs) regression rate cm/min when fuel is placed along with the flow.

3.2. Hexagonal Fuel placed at Vertical Position at 90° to the flow
The important aspect when fuel is placed at 90° to the flow is that the faces and corners play a major role. Two cases have been considered for the experimentations one is the impact of flow on the flat faces and corners. The fuel is fixed to the ramp in such a way to withstand the flow. The experiment was first performed for the flow facing the flat face and later by corner facing under smoldering. So, this phenomenon is considered as forced reverse smoldering and there is a more impact on corners when compared to faces as for the forced flow over the hexagon material to the flat face acts as a blockage to the flow and decreases the spread of flow over the material. But for the corner, the spread of flow is faster and enhances the flow over the material. The ramp fixed with fuel ignited is placed
inside the test section and forced flow is let over the fuel. The experiment was performed for both face and corner facing and the results show a great impact for corner facing flow under smoldering. The regression rates show that the corner has more impact even when the flow is opposite the direction of fuel under smoldering. The results show a distinctive of the work that effect of corners in the field of flow and smolder spread. The experimentation results for face facing the flow under smoldering shows that there is a similarity in regression rates from initial speed to remaining speed except for the maximum speed 2.4 m/s being the highest regression rate, the alternate similarity for 0.8 m/s and 2.2 m/s, 1.8 m/s and 2.3 m/s the forced reverse smoldering combustion the flow is blocked by the face of the hexagon and thereby decreasing the heat transfer through the material with the increase in the velocity the flow characteristics seem to be similar as the flow blocks and the vortex, wake region behind the fuel by forming recirculation zones will not let the fuel burn uniformly and lead to the inclination of smoldering reaction zone. So, the regression was calculated by readings taken when the reaction touches the markings. For corners, the spread is too fast as the corners make the flow over the material to spread faster. But the flow striking the corner spreads the smolder fast and the region where flow spreads smolder faster leading to the inclination of smolder propagation. The regression rates are higher when compared to all the cases considered even fuel placed opposite to flow so for this results the effect of corner in smoldering has the major role this trend of smoldering rate is similar to that of fuel placed with the flow along the direction. This case has the highest rate of smoldering at 2.2 m/s with 5.99 cm/min and 2.3 m/s with 5.71 cm/min of all the cases chosen.

Figure 6. Smoldering of hexagonal fuel when placed perpendicular to the flow with its corner (top) and face (bottom) facing the flow.
The change in regression rate with the base case for the effect of flow on smoldering combustion when hexagonal fuel placed at corner, being highest with ~216.93% for 2.2m/s than any other cases considered for experimentation followed by ~202.11% for 2.3m/s and ~164.55% for both 1.8m/s and 2.4m/s. but when hexagonal face is placed in position to face the flow the percentage change in regression rates are less when compared to the corner effect of the fuel, ~120.1% for 2.4m/s is highest, ~105.82% for 1.8m/s, ~104.76% for 2.3m/s, ~98.41% for 2.2m/s and ~96.82%. For 1.8m/s the lowest.

3.3. Hexagonal Incense material placed opposite to the flow direction
This phenomenon is generally called as the forced forward smoldering as smoke and the reaction front propagates in the same direction. This follows an increasing sequence of regression rates with the increase in the speed except for the 2.3m/s speed because at this case the velocity at reaction front is enhancing the heat transfer and allowing to smolder faster and the spread of smoldering as the flow forced to pass through the reaction front seems to be allowing for faster propagation of smolder.

The comparisons are made with all the papers, but the uniqueness of this paper brings the fact that the fuel placed at 90° orientation to the flow facing corner has the maximum ability of faster spread of smolder. The change in regression rates was compared with base cases to see the amount of
smoldering change in percentage and the effect of flow on the smoldering material. The change in regression rates with base case is ~90.57% for 2.3m/s being highest followed by ~72.46% for 2.4m/s, ~56.15% for 2.3m/s and ~18.47% and ~18.11% almost being same for 0.8m/s and 1.8m/s respectively.

![Graph showing regression rates vs speed](image_url)

**Figure 9.** Speed m/s (vs) regression rate cm/min when fuel is placed against the flow.

Fig. 8 shows the smoldering of the hexagonal fuel when placed against an external flow at velocity 2.2 m/s and Fig. 9 shows the variation of regression rate of the hexagonal fuel placed against the flow with respect of the flow velocity.

### 4. Summary

| Speed (m/s) | Forced Reverse Smoldering | Forced Forward Smoldering |
|-------------|--------------------------|---------------------------|
|             | Along the flow direction | Face | Corner | Opposite to flow direction |
| 0.8         | 0.226                    | 0.372 | 0.353 | 0.327 |
| 1.8         | 0.239                    | 0.389 | 0.5   | 0.326 |
| 2.2         | 0.314                    | 0.375 | 0.599 | 0.431 |
| 2.3         | 0.331                    | 0.387 | 0.571 | 0.526 |
| 2.4         | 0.279                    | 0.416 | 0.5   | 0.476 |

**Table 3:** Comparison of regression rates for various conditions.
5. Conclusion

The effect of flow over the hexagon experimentation was carried out on smoldering combustion. Flow over hexagon is invested for the different cases along the flow direction, placed perpendicular flow facing face and corner, Opposite to the flow. The experimentation results show a different phenomenon when compared to the previous research on smoldering combustion. A new phenomenon is observed here that the effect of forced flow on hexagon placed perpendicularly corner to the flow, the effect is more than the forced forward smoldering. Hexagon placed perpendicularly to face and corner to the flow follows exactly the opposite trend corner being more and face being inverse. The maximum regression rates are found generally at the higher speeds for all the cases considered for experimentation. These results will be useful to study smoke generation from smoldering material subjected to airflow along various orientations.

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6. References

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