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External Heat Source assisted Smoldering and Transitional Combustion

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ABSTRACT

Experimental setup was upraised and inferences of external heat source orientation on smoldering is explored on both modes. Physical insight into heterogeneous heat transfer phenomena of smoldering combustion over thin solid fuels is assessed. The study primarily aims at understanding the implications of an external heat source on smoldering combustion in the aid of regression rates. Incense sticks were used as potential fuel as well as external heat source. The presence of an external heat source intensifies the heat transfer drastically when oriented parallel to pilot fuel in reverse and forward mode. Results indicates deviation of heat transfer significantly with varying surface orientation and external heat source distance from the pilot fuel reflected in regression rates. Transition from flaming to smoldering combustion is aggravated intensely with the presence of an external heat source.

Keywords: Smoldering, external heat source, forward heat transfer, regression rates, transitional combustion.

1. INTRODUCTION

Smoldering phenomenon is a flameless form of combustion, deriving its heat from heterogeneous reactions occurring on the surface of a solid fuel when heated in an oxidizer environment (Figure 1). The ignition front formed over solid fuel spreads along the surface of the fuel by heat transfer from burning region to fuel surface ahead. The heat transferred to the fuel pyrolyzes it to vapors which upon mixing with surrounding air form a combustible mixture.

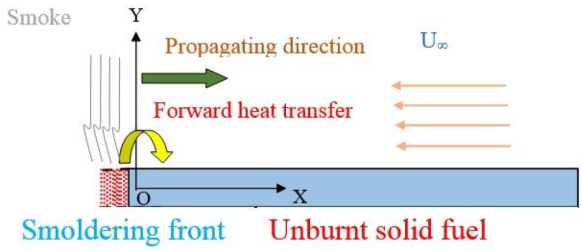

Figure 1 Schematic of smoldering combustion and forward heat transfer.

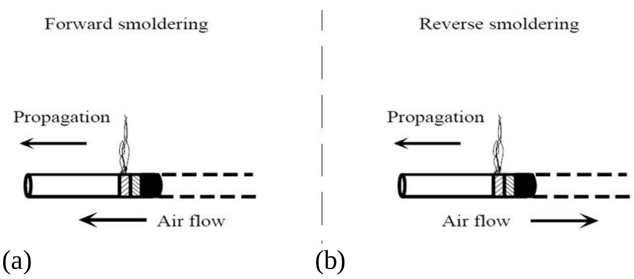

Figure 2 Schematics of (a) forward smoldering (b) reverse smoldering over thin solid fuel.

This combustible mixture is ignited by the heat transfer and hence advances forward over the surface of the fuel. The characteristic temperature and heat released during smoldering are low compared to those in the flaming combustion of a solid. Smoldering combustion is broadly studied and defined according to the direction in which the smolder reaction propagates relative to the oxidizer flow (Figure 2). In opposed smoldering, the reaction front propagates in the direction opposite to the oxidizer flow, and in forward smoldering, the front propagates in the same direction. These two configurations are distinguished by the roles played by the transport mechanisms and chemical reactions. In forward propagation, the fresh oxidizer flows through the char, reacts at the ignition zone and then the oxidizer-depleted flow goes through the virgin fuel. This configuration favors that the oxidation reactions occur at the rear of the ignition zone and pyrolysis at the front. In opposed propagation, the fresh oxidizer flows through the virgin fuel and reacts at the smolder zone favoring that both the oxidation and the pyrolysis reactions occur at approximately the same location. It is of interest both as a fundamental combustion problem and as a practical fire hazard. In spite of its weak-combustion characteristics, smoldering is a significant fire hazard. Smoldering can be initiated by weak sources of heat; yields a high conversion of fuel to toxic products per unit mass smoldered (particularly CO and heavy molecules); is difficult to detect and extinguish; and it can abruptly transition to flaming combustion. The study of smoldering combustion phenomena is primarily driven by the need to have better fire safety, by means of enhanced understanding of the mechanisms that control the spread and extinction. One of the major lessons learned is that it is impossible to eliminate all ignition sources, so fire inhibition is achieved through use of fire resistant materials and external resources to eliminate excessive spread. Hence, fundamental understanding of smoldering spread over solids is important in proficient design of materials for efficient scientific and engineering applications.

Following the classical work of Kinbara et al., [1] highlighting the downward propagation of smoldering combustion through solid materials. In the last five decades' research works have contributed significantly to the advancement in understanding of the smoldering combustion. The contributions have been reported in several reviews like Chan and Napier [2], McCarter [3], Ohlemiller ([4], [5], [8]), Beever [6], Alexopoulus and Drysdale [7], Badr and Karim [9], Atreya [10]. The works provide an excellent review on the developments up to the end of the century.

In the last decade appreciable advancements have occurred. Leach et. al., [11] studied the kinetic and fuel property effect on forward smoldering combustion from a one-dimensional transient model. The effects of the inlet gas velocity, kinetic frequency factors, inlet oxygen concentration and fuel properties such as specific heat, density, conductivity and pore diameter were studied. Krause and Schmidt [12] presented a mathematical model which allows one to treat the combined phenomena of heat, mass and species transfer by diffusion as they occur within smoldering fires in accumulations of dust or other solid bulk materials. Rein et al., [13] developed a one-dimensional computational model of smoldering combustion. The heterogeneous chemistry was modelled with a 5-step mechanism, so the model was able to predict qualitatively and quantitatively the smoldering behavior, reproducing the most important features of the process. The fact that it was possible to predict the experimental observations in both reverse and forward propagation with a single model was a significant improvement in the development of numerical models of smoldering combustion. Rein [14] attempted to synthesize a comprehensive view of smoldering combustion bringing together contributions from diverse scientific disciplines. Tiwari et al., [15] worked on the effect of surface orientation on smoldering regression rates using standard cigarette sticks and incense sticks. Results showed that the regression rate increases non-monotonically standing maximum at 45 degrees and qualitatively similar trends were observed for different smoldering fuels. Tiwari and Malhotra [16] worked on the external heat source effect which is kept on two side and the separation distance varies. Aldushin et al., [17] tries to find out the transition from smoldering to flame. The work was completely analytical and theoretical. They took a constant wave and tries to find out the transition zone. The complete work was carried in forward heat transfer. Aldushin et al., [18] again took the work and repeat with a little different setup for reverse heat transfer and tries to get the answer is it possible or not. Bar-Ilan et al., find out the transition from forward smoldering to flaming combustion using the small polyurethane foam samples.

Although much has been done but complexity of the problem has prevented a complete understanding due to interaction between flow, heat and mass transfer. Therefore, a systematic study is needed to understand mechanisms controlling the behavior of smoldering combustion. In light of above mentioned works, an important feature to note is that almost all of smoldering spread studies are carried out with a single fuel to understand the spreading mechanism. However, in almost all of practical situations spreading front may interact with nearby surfaces or potential heat sources which can influence the regression rates. This has not been investigated and such interaction can have major implications. Hereby in this work, the effect of external heat source on smoldering spread behavior is investigated experimentally. Interaction of smoldering spread with an external heat source is likely to alter the spreading behavior from that of a single fuel. External heat source releases heat from the heated surface and can enhance heat feedback to the pilot unburnt fuel. This heat feedback is likely to increase pyrolysis of fuel resulting stronger ignition front. The increase or decrease of regression rate can have significant effects and applications in engineering background. The objectives of the present study may be summarized as:

a) To study effectiveness of the oriented external heat source in parallel on smoldering regression rates.
b) To investigate the transition length at which flame combustion diminishes and convert to smoldering combustion.

2. EXPERIMENTAL SETUP AND SOLUTION METHODOLOGY

A simple apparatus (Figure 3) was upraised for the present study. The apparatus comprised of a) base made of hard thermocol (here placed vertical) b) protractor fixed on thermocol c) thin iron sticks pierced through thermocol to fix it d) marked dark sheets to capture the smoke pattern and additional weight to support the assembly. The experiments were thoroughly carried out in a quiescent room under normal gravity conditions. The solid fuel assembly comprised of dried incense sticks in 6.9 cm × 0.20 cm specification. The composition of incense sticks is sawdust (30 %), charcoal (30 %) and cow dung (38–39.5%) and incense chemical (< 1.5%). Fuel specimen strips are made to ensure uniform burning across the width of fuel as the front propagates along the length of fuel specimen and to remove the moisture which can affect ignition and front spread rate. The regression rate is very sensitive to the gas and the surface temperatures which are a part of solution procedure. In order to facilitate uniform horizontal ignition across the width, the fuel strip was cut at the top and ignition was done by exposing it to a pilot flame (please see figure 4).

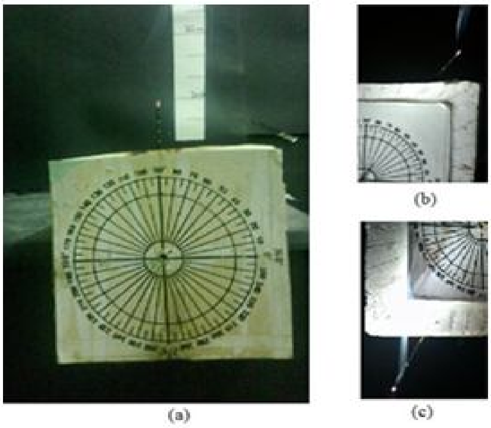

Figure 3 Pictorial view of (a) Complete experimental setup (b) reverse smoldering (c) forward smoldering over thin solid fuel.

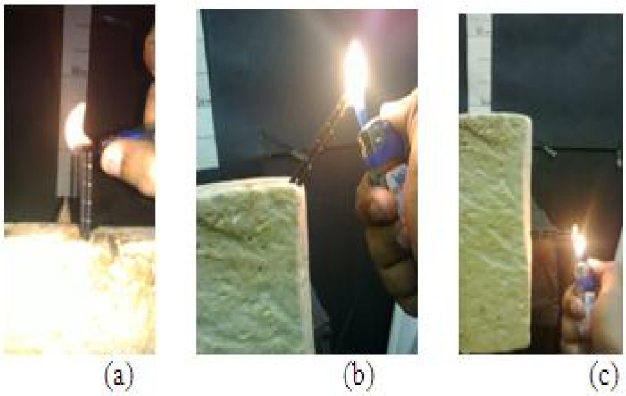

Figure 4 Pictorial view of external heat source and pilot fuel configuration with at varying orientation location (a) 90° (b) 45° (c) 0°.

The solid fuel strips were marked at regular intervals of 1.5 cm to track the smoldering front propagation with time. Every experiment was carried out within a range of 5 minutes to bring room atmosphere back to normalcy. Stopwatch was used to measure the split times across the markers. An optical setup was made to obtain shadowgraph of the propagating front which was digitally video graphed. The readings were taken thrice for same distance and the average repeated value with was accounted. Therefore, to ensure regression rate (*r*) does not go out of bound, linear method is used as:

$$r = \frac{l_s}{t_{av}} \qquad (1)$$

Where, "l_s" is the standard length of fuel taken (here, 1.5 cm) and "t_{av}" is the average time taken for all three marked distances. From classical theory of ignition spread, assuming unity width of fuel the regression rate (*r*) is defined by energy balance as:

$$r = \frac{\int q_{net}}{\rho_s \tau_s c_s (T_{Surface} - T_\infty)} \qquad (2)$$

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.
$T_{Surface}$ = Surface temperature.
$T_{Ambient}$ = Ambient temperature.

3. RESULTS

Experiments were carried out in purely natural convective atmosphere with 21 % oxygen concentration. According to classical heat transfer theory over thin solid fuels, the propagating front spreads by heat feedback (forward heat transfer) from the burning to the unburnt solid fuel upstream. The heat feedback content will be reflected in increase or decrease in regression rates (refer equation 2). Most of all conventional studies on smoldering have been confined to surfaces oriented horizontal or vertical (downward/upward spreads). It owes to convective buoyant flow, localized velocity and temperature fields are formed on the fuel surface. High temperature smoke carries heat moving parallel to fuel surface supplying additional energy and preheating. High cumulative heat transfer to the unburnt fuel can be attributed as the reason for high regression rates in forward smoldering. The spread in this configuration is so fast that it is difficult to prevent forward smoldering fires in inclined orientations. First, we look at the effect of external heat source on reverse smoldering at an orientation. Figure 5 shows the variation of regression rate with surface orientation of the external heat source and the pilot fuel. Any increase or decrease in forward heat transfer owing to external heat source will be reflected in the regression rate value. Looking at the plot one can note the varying reverse heat transfer with the heat source orientation indicating significant impact. For better simplicity to understand the effect of the external heat source the heat source are kept at both the end of the pilot fuel at three different separation distance **widely-spaced (10 mm)**, **intermediately-spaced (5 mm)** and **narrow-space region (1 mm)** respectively.

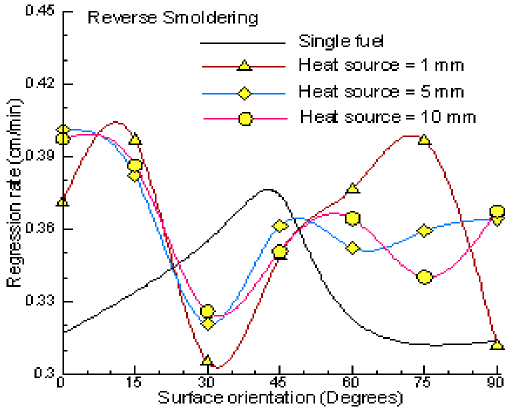

Figure 5 Effect of external heat source and pilot fuel configuration orientation on reverse smoldering. mm.

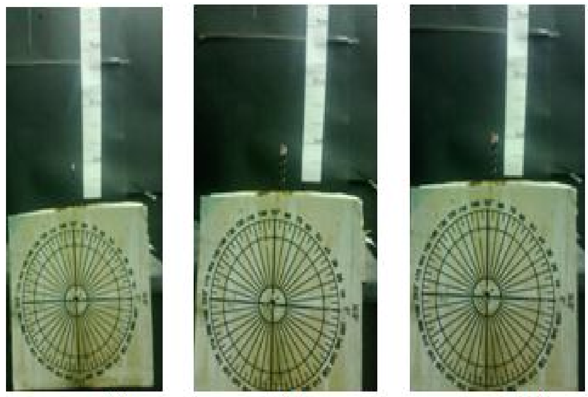

Figure 6 Pictorial view of external heat source location effect on reverse smoldering at 90o(a) single fuel (b) 1 mm (c) 5

Looking at the plot one can notice that regression rate increases at every regime and enhancement of heat transfer is significantly observed. Regression rate higher than the single fuel were noted. Even though the regression rate is higher than the single fuel the magnitude of regression rate at 0 degree is lower than the intermediate and far region for the very near regime. Interestingly, as orientation increase to 15 degrees a significant drop is noticed for 5 mm and 10 mm regime whereas the regression rate increases for the 1 mm. The highest regression value is obtained by separation distance as well as the orientation for different regime. As it is shown in the plot that the increment in the value is obtained at 0 degree for intermediate regime i.e. **29%**. Another interesting point to note is that the value of 10mm and 1mm is equal but for different surface orientation i.e. 0 degree and 15 degrees respectively. This results owes to the strong convective heat transfer which is clearly dominates between (0-15^{o}) surface orientation. As soon as we move from (15-30^{o}), we noticed a sudden drop in the regression rate which is even less than the single fuel value for all the regime. Another surface orientation which show the decrease in the regression rate is 45 degrees. However, for single fuel the value of regression rate was obtained maximum. The maximum drop is noticed at 30 degrees for 1 mm regime which is **14.01%.** This surface orientation is termed as **"Heat Sink zone"** (30 degrees and 45 degree). The heat transfer in this regime is decrease due to the decrease in the localized temperature around the pilot fuel. The results can be owing to the reason that not enough oxygen get enters to fume the pilot fuel. It can be seen easily from the experimentation picture as the external heat source and pilot fuel make a **'M'** shape which tells that near region propagates but due to the property of regaining symmetry it decreases the regression rate. Another point to notice here is the smoke which carries the heat to the unburnt fuel also not playing their part which reduces the convective heat transfer. The very near regime (1mm) drastically drop after that till 75 degrees. Which make it as **"Enhanced heat transfer zone"**. The connective heat transfer is dominating in this region because of buoyancy that carries the heat to the unburnt fuel. The value of enhanced heat transfer is approx. **26%** at 75 degrees which is equal to the value of 15 degrees for same regime as well as for 10 mm at 0 degree. Interestingly the value for very near regime start decreasing after this and shows exact value of single fuel at 90 degrees. Which makes it as **"No effect zone"**. Another interesting point to note is that at the same surface orientation which is 90 degrees we obtained same value regression rate for 10 mm and 5 mm. Which also justify that the separation distance more than 1 mm will enhance the heat transfer but will become insensitive with the distance more than 5mm.

The result also indicates that the radiation start dominated at this surface orientation which further lead to the poor heat transfer in the opposed smoldering combustion. With reduction in spacing, heat transfer to the unburnt fuel takes a significant role as conduction and convection are proportional to the first power of temperature (~T) but radiation is proportional to the fourth power (~T^4). Results certifies that the presence of an external heat source very nearer in opposed smoldering affects heat interaction drastically. The important result obtained from the plot is that 1mm can be used as Heat Sink, Heat Source and Insensitive at different surface orientation. For better understanding the

experimentation pictorial view is given figure 6. The pictorial view shows how the smoke carries in different orientation as well as the surface orientation. The radiation effect in 90 degrees can be understand from this.
The 10 mm and 5 mm are enhanced heat transfer zone. For better heat transfer this result can be used as well as it is used for fire safety as well. The no effect zone helps us to build a better understanding to improve the knowledge of heat transfer as how to utilize the external source for various application that ranges from our daily life to vast engineering.

Next, we will look at the effect of heat source orientation effect on forward spread rate. For the case of smoldering in the forward mode (upward spread), figure 7 shows the variation of regression rate with heat source orientation. Similar to the reverse mode, variation of forward heat transfer with external heat source distance is classified in three regions as wider spaced region (10 mm), intermediate spaced region (5 mm) and narrow space region (1 mm). Looking at the plot one can notice that, the heat transfer varies substantially with the location of heat source. In the wider spaced region, drastic enhanced regression rates were noted. The increment in the regression rate is noticed up to **~51%** for 5 mm placement of external heat source at 270 degrees. The experiments were carried out at lab scale and the quantity and the pilot fuel is small, the result shows huge development of heat transfer in forward spread rate. However, this can be more drastic and can be a game changer when the quantity of the fuel is large.

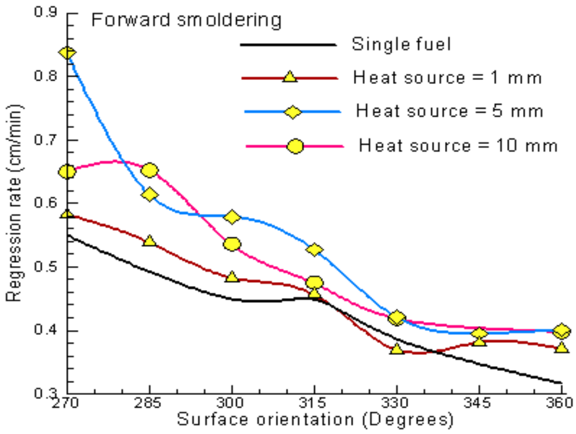

Figure 7 Effect of external heat source and pilot fuel orientation on forward smoldering.10mm.

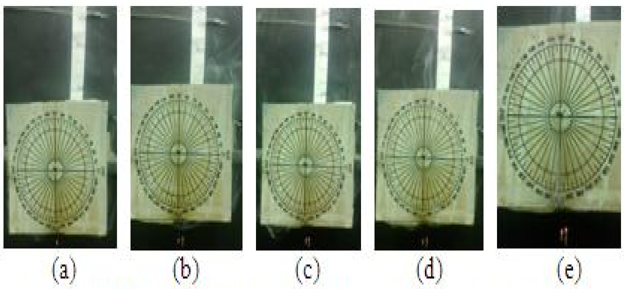

Figure 8 Pictorial view of external heat source location effect on forward smoldering (a) single fuel (b) 1mm (c) 3mm (d) 7mm (e)

The forward regression rate enhanced in the presence of an external heat source which make this as **"Enhanced heat transfer zone"**. The reason attributed for the results are due to the strong convection heat transfer and buoyant forces which states that the heated gas goes up and interacts with the virgin fuel and this interaction add the additional heat to the fuel. This additional heat further helps in a better regression rate. The most interesting point to observe in this plot which is highly dominated by convection heat transfer is at 330 degrees which shows Heat Sink zone where the heat transfer reduced by **5%**. Another point to be noted from this plot is that there is no **"Insensitive"** or **"No effect zone"** present throughout the forward smoldering combustion. However, regression rate increases from 270-285 degrees for the intermediate regime (5 mm). At 330 degrees and 360 degrees the value is insensitive to the external source separation distance as we move from intermediate regime to very far. Very far reason show a monotonic decrease in regression rate after 270 degrees. Whereas intermediate takes a jump at 285 degrees and then follows the same trend. This results states a strong presence of an external heat source and hence referred to enhanced heat transfer zone. The phenomena is largely dominated by the convection heat transfer. The smoke generated in the process can be termed as the heat carrier in forward smoldering combustion. These results can be used in various application viz., in engineering, daily life and environmental pollution control. Hence, better understanding of the smoldering combustion phenomena its effect with and without an external heat is needed. Results indicates the norm of smoldering combustion being more harmful than the normal combustion.

To understand the reasons for the peculiar trend in regression rate with separation distance next, we examine at the experimental images. Figure 8 shows the images of smoldering experimentation with an external heat source for upward spreading at varying heat source location. Looking at the images one can note that the wider space region entertains minimum heat and mass interaction in the form of smoke emanating. As the upward buoyant convection currents assists the heat transfer higher spread rates were noted. Conduction and radiation heat transfer assumes usual roles as in opposed spreading however, convection undertakes the dominating part in the heat transportation. The localized velocity and temperature fields are formed on the fuel surface and assists in forward heat transfer. Significant convective flux, but uneven heat and mass transfer stances for the stability of propagating front. In the narrow space region, along with convection, radiation contributes profoundly (fuel strips placed closer) in heating unburnt fuel so regression rate jumps to a very high value. However, when placed very close (> 2 mm), limited oxygen is diffused or difficult to diffuse so regression rate drops from maximum to very low value. Forward smoldering is highly affected with source placed close and related implications (please see figure 7).

Further, the transition of flaming to smoldering combustion is addressed in terms of Transition Length which represents distance where normal combustion diminishes and converts to smoldering. Experimentation were carried out on same incense stick marked in 10 segments of 1 cm each. The fuel is exposed to pilot flame and the distance where it diminishes and becomes smoldering from flame is noted.

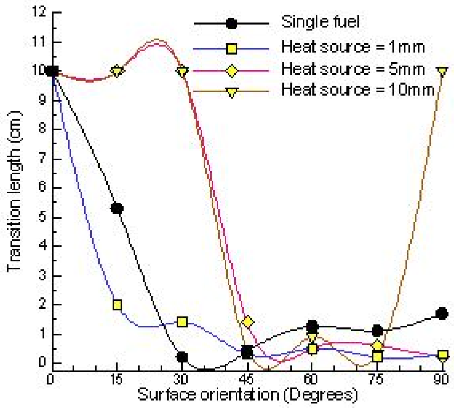

Figure 9 Effect of external heat source and pilot fuel configuration orientation on transition length.

(a) (b) (c)

Figure 10 Pictorial view of external heat source and pilot fuel transitional effect (a) 90° (1 mm) (b) 0° (1mm) (c) 0° (5 mm).

Figure 9 represents the transition length with the surface orientation with and without external heat source. External sources are kept in all three regimes. The distance is taken from the outer surface of the pilot fuel. One can notice that there is no diminishing of the flame when it is kept at 0 degree. This results states that there will no loss of heat transfer when we keep it at horizontal unaffected to the separation distance of the external fuel. The pilot flame gets stabilized and a continuous heat transfer prevent it from diminishing is the reason for the obtained results. There is a continuous support for each other (flames) will be seen which enhances the heat transfer. As we move further and increase the surface orientation there is a drastic drop in the transition length for the very near regime (1mm). The length decreases by ~3.5 cm and further follows a monotonic decrease in the trend but the length is greater than the single fuel for 30 degrees by ~1.1 cm. Except for intermediate regime the transition length is same for very near, single fuel and very far regime at 45 degrees which makes this surface orientation insensitive to the heat transfer. And thus termed as “Insensitive Zone”. The most interesting result obtained is at 75 degrees where for 10mm separation distance “Insensitive Zone” is seen. Figure 10 shows the illustrative pictorial view of experimentation for better clarification. “Heat Sink Zone” is obtained after 45 degrees for all regime where the heat transfers decreases. Intermediate separation distance is insensitive to the transition effect till 30 degrees. The transition affect also dictates that there will be combustion happening but the heat transfer will have reduced and smoke presence will be there.

4.CONCLUSION

The experimental smoldering combustion investigation focusses on evaluating the effects of an external heat source orientation on smoldering and transition from flaming to smoldering. Based on the investigation it can be concluded that external heat source effect is reflected in modified regression rates owing to altered forward heat transfer to the unburnt pilot fuel. In reverse smoldering mode, regression rate decreases with surface orientation till 30 degrees and then increases monotonically and at 90 degrees become insensitive to the separation distance for intermediate and very far regime. For very near separation distance it increases monotonically with surface orientation for 15 degrees and then fall at 30 degrees and then increases and at 90 degrees it is insensitive to the presence of an external heat source. For 75 degrees the value of regression rate is almost equal to the value of 15 degrees for very near regime and of 0 degree of the intermediate regime. till peak at 45 degrees and then decreases sharply close to horizontal. Forward smoldering mode depicts higher regression rate and diverse variation than reverse. There is more than 50% enhancement in the regression rate is noted in the forward whereas in reverse the maximum increment was 29%. If we talk about the transition length in presence of an external fuel with fuel surface orientation some interesting results are found. For intermediate regime and very far there will be no transition as the flame stabilize the heat transfer and the pilot flame does not extinct. But for very near separation distance it continuously drops. At 45 degrees except for 5 mm the value of all others are equal. There is a sudden and huge increment in the transition length when the separation distance is too far at 75 degrees. Conduction heat transfer dominates with radiation evenly contributing in both the modes. However, forward smoldering is controlled by convective heat transfer resulting drastically enhanced regression rates. The experimental predictions were validated with the conventional heat transfer theory and established smoldering work and matches reasonable well. External heat source results in increasing regression rate owing to enhanced heat transfer to unburnt fuel. In reverse smoldering, the effect monotonically and steadily rises with reduction in separation distance. Forward heat transfer with a parallel heat source is mostly dominated by conduction from pilot fuel and radiation from external heat source. However, when placed very close, radiation assumes principal role. Nearby placement of any external heat source may lead to hazardous threats necessitating proper prevention. Forward smoldering is momentously affected with the presence of an external heat source. Reduction in heat source separation distance from pilot fuel results as drastic rise in regression rate. Conduction and radiation contributes evenly as in reverse mode conversely, convection dominates in this mode leading to severely enhanced forward heat transfer owing to convection domination and radiation contributing evenly. Regression rate rises extremely with reduction in spacing but drops radically to minimum when placed very close (~1 mm) owing to limited oxygen diffusion for combustion. Presence of an external heat source in forward smoldering is a potential source of extensive hazards and may transit to disastrous fires. The transition affect commands that there will be combustion happening but the heat transfer will have reduced and smoke presence will be there.

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