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Implications of the external flow and acoustics on lateral upward smoldering

Ankit Rout[1], Anandita Tomar[2], Kancharla Pragathi[3], and Vinayak Malhotra[4]
Department of Aerospace Engineering, SRM Institute of Science and Technology Kattankulathur, Chennai, India, 603203

ABSTRACT :- *Combustion is a scientific term for burning. Combustion is a process of fuel reacts with the air to produce heat energy. This heat energy can produce light in the form of a flame. This is the visible part of the reaction. Smoldering is considered a type of low-intensity fire, that meaning fire slowly spreads that can be expected to last for several days, releasing small amounts of energy the most persistent type of combustion. Smoldering is a low temperature, slow, flameless form of combustion, with heat is involved with oxygen. Combustion is of two types: Flaming combustion and smoldering combustion. This type of smoldering combustion can cause number of accidents. A simple experimental setup was upraised to investigate the effect of external energy source(s) viz., air flow and acoustics on upward spread smoldering. The external energy source effect was articulated in form of different flow velocities and acoustics. The experimental predictions were systematically validated with the conventional theoretical and numerical result. A parametric investigation was carried out by linearly changing surface orientation, flow velocity, location of external source and the frequency. The results obtained so far state that the external energy source(s) have significant effect on the upward smoldering regression rate. The knowledge from the present work can be effectively applied to various functional, practical, engineering systems ranging from aircrafts, spacecrafts, buildings fires, wildfires and help us in better understanding of the phenomenon.*

KEYWORDS: *Combustion, upward smoldering, external wind energy, acoustics, regression rate.*

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I. INTRODUCTION

Fire is quite uncontrolled chemical reaction. Fire can produce light and energy sufficient. A chemical reaction involving fuel and oxidizer in the air. The present work deals with a type of combustion called smoldering that can take place very long time if there is abundance of fuel. This type of combustion causes large number of accidents and is one of the prime suspects for fire and safety hazards (fig 1). The smoldering rates of several types of dust and of a rigid combustible board were measured under various conditions, and the temperatures of the smoldering zone and the minimum depth of dust deposit required for sustained smoldering were also determined [1]. An experimental comparison of forward and reverse smolder propagation is presented; these two cases correspond, respectively, to reaction wave movement in the same and in the opposite direction of the air flow. Two types of permeable fuels were examined, a cellulosic loose fill insulation (wood fibers) and a particulate polymer material (polyisocyanurate) [2]. Smoldering combustion of various natural and synthetic solid materials constitutes a substantial fire hazard; the process itself produces copious toxic gases and it can lead to flaming combustion. This review focuses on the coupled chemical and physical processes involved in self-sustained propagation of smoldering. The potential heat sources (gas-phase oxidation, oxidative polymer degradation. char oxidation) are examined, along with the heat sinks (polymer pyrolysis, water vaporization). It is concluded that, even for the moststudied case of cellulose, the chemical mechanisms involved in these processes are both too complex and too poorly understood to be included in a smolder propagation model [3]. Measured activation energies of ignition of a wide variety of solid materials of practical importance are tabulated. The Frank- Kamenetskii model of thermal ignition was used in their determination. Comments are made on the values in terms of the nature of the respective materials and in terms of the value of the measured quantities as input to mathematical simulation of ignition [4].In recent years the National Aeronautics and Space Administration (NASA) has been concerned with the potential health hazards associated with contaminant exposure in the extended spaceflight environment such as might occur on long duration missions [5].Smoldering is a slow combustion process in a porous medium in which heat is released by oxidation of the solid. If the material is sufficiently porous to allow the oxidizer to easily filter through the pores, a smolder wave can propagate through the interior of the solid. We consider samples closed to the surrounding environment except at the ends, with gas forced into the sample through one of the ends [6]. We consider porous cylindrical samples closed to the surrounding environment except at the ends, with gas forced into the sample through one of the ends. A smolder wave is initiated at that end and propagates in the same direction as the flow of the gas [7]. Results from four microgravity smoldering combustion experiments conducted aboard the NASA Space Shuttle are presented in this work. The experiments are part of the NASA funded Microgravity Smoldering Combustion (MSC) research program, aimed to study the smolder characteristics of porous combustible materials in a microgravity environment. The objective of the study is to provide a better understanding of the controlling mechanisms of smolder for the purpose of control and prevention, both in normal- and microgravity [8].

The work detailed results from a one-dimensional transient model of forward smoldering. Fuel oxidation and pyrolysis reactions as well as a char oxidation reaction were included in the model [9]. The smouldering process of wood logs was studied experimentally in a laboratory facility and in prescribed forest burns. The main goal was to check the parameters that initiate and control the stability of the smouldering process. To do so, sample temperatures at five different locations and concentrations of CO, CO2 and O2 were measured and discussed [10].

Fig. 1: Zagros Mountains in Iran (2020). (*Al-Monitor.com)

Appreciable research efforts had been given in the past however, the effect of external energy source(s) on pure upward smoldering phenomenon is an aspect yet to be comprehensively studied and understood. Present work is motivated by the need to have enhanced fire safety through in-depth understanding of the singularity.
The specific objectives of the project are:
1) To study the effects of external energy source(s) in the form of wind and acoustics on upward smoldering.
2) To develop the suitable correlations between the fire propagation and the related energy transfer.
3) To understand the role of key controlling parameters.

II. Experimental Setup and Solution Methodology

The experimental setup comprises of a thermocol sheet with the support of two sticks, stand and a protractor sheet pasted on the surface (fig 2). The incense sticks were marked upto 3 cm with an interval of 1 cm each. First 0.5 cm was left for the ignition reaction to stabilize. The experimental samples were placed at all the orientations from 0°-90° and the time taken to burn entire 3 cm of incense stick was noted.

Fig. 2: (a) Experimental setup, (b) Incense stick Marking. (c)Lighter, (d) Table Fan. (e) Protractor.

The regression rate is defined as the rate at which flame propagates on a fuel surface specifically denoted as:

$$\text{Regression rate, } r = \frac{Distanceburntth\ eincensesticksurface\ (3\ cm)}{Timetaken\ (toburn\ 3\ cmofIncensestick)}$$

where,
ρ: Density of the solid fuel.
τ: Thickness of the solid fuel.
c: Speed of sound in that medium.
T(Surface): Surface Temperature.
T(∞): Ambient Temperature.
r: Regression rate.
∫q(net): Net energy available / Forward heat transfer andrepresents the difference between the energy generated and
the energy lost.

The experiments were carried out at normal roomtemperature and readings were taken ensuring conformity of no external disturbance in every case. *It is important to notethat every data presented here represents the repeatabilityand reproducibility of the third order.*

III. Results and Discussion:

Prior to the main experimentation, the predictions of the experimental setup were validated. The regression rate of pilot fuel for downward and upward spread was measured for varying surface orientations.
For downward spread or reverse smoldering, the pilot fuel was kept at seven different orientations (0°, 15°, 30°, 45°, 60°, 75° and 90°) and regression rate was measured for validation (fig 3)

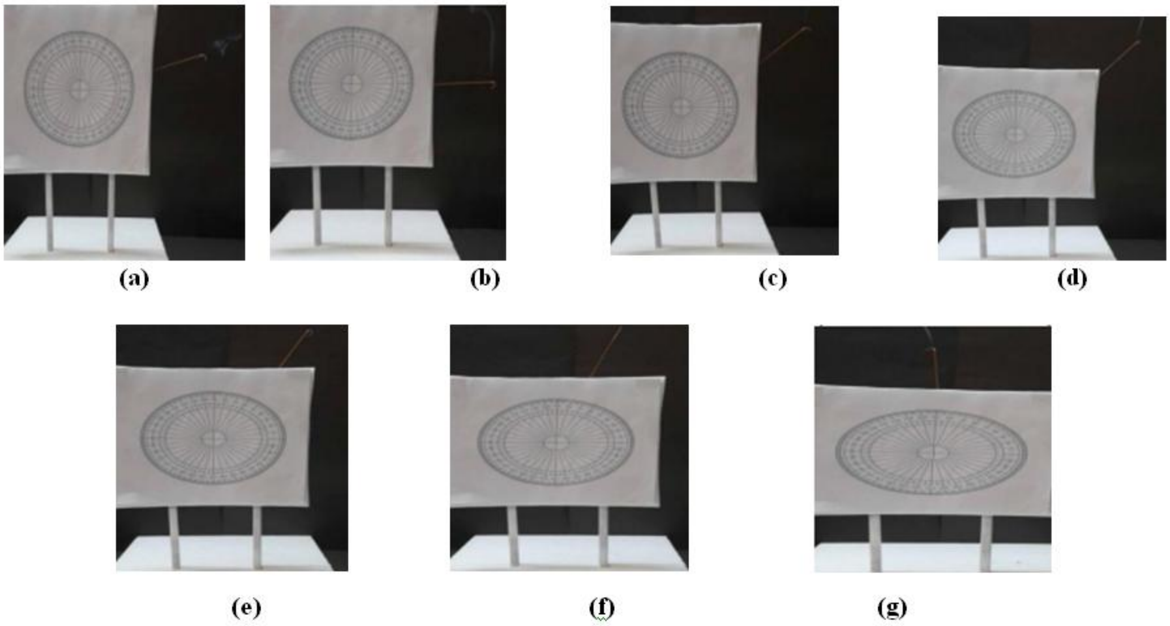


Fig. 3: Validation of the experimental setup predictions with position of incense stick at different orientations, (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, (f) 75° and (g) 90°.

During experimentation, the singularity of ash formation on the incense sticks was observed. A series of experiments were carried out to identify the role of ash formation. Figure 4 shows the first set of experimentation involving reverse smoldering where the incense stick was tapped at regular intervals of time at orientations varying from 0° to 90°. The maximum regression rate noted at 45° which resonates well enough with the conventional heat transfer theory and preceding scientific efforts.

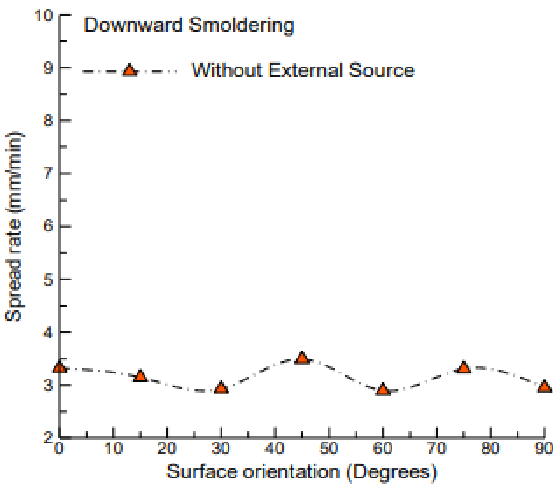


Fig. 4: Variation of downward smoldering regression ratewith surface orientation

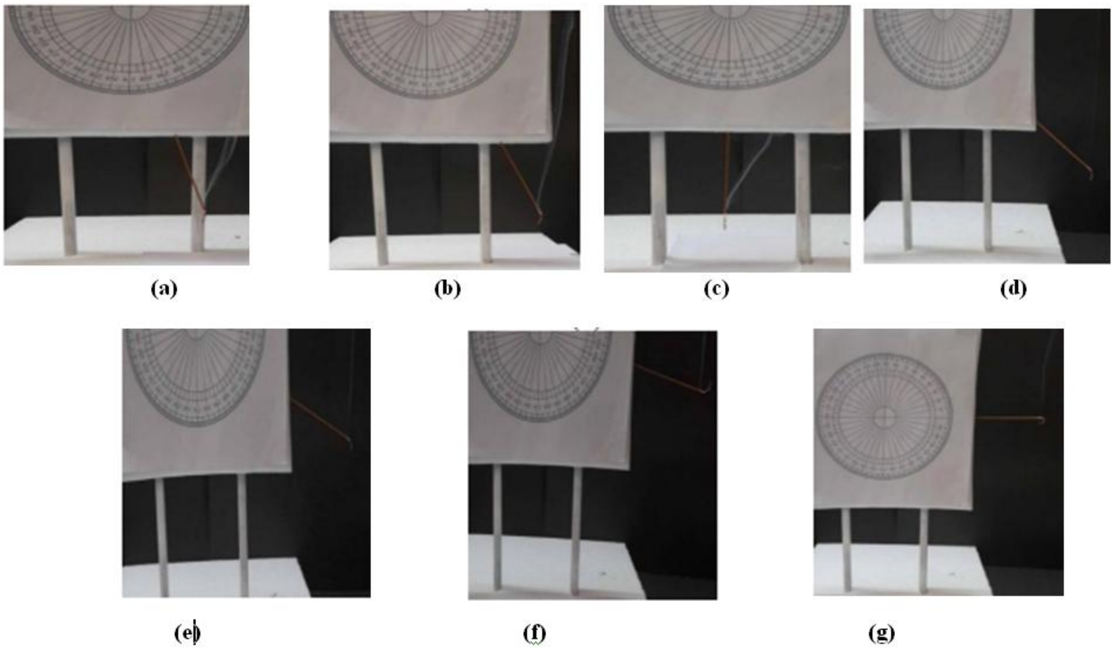


Fig. 5: Validation of experimental setup: Position of incense stick at different orientation, (a)270°, (b)285°, (c)300°, (d)315°, (e)330°, (f)345° and (g)360°.

This was followed up with experimentation involving regression rate measurement of pilot fuel for upward smoldering at orientations varying from 270°-360° (fig. 5).

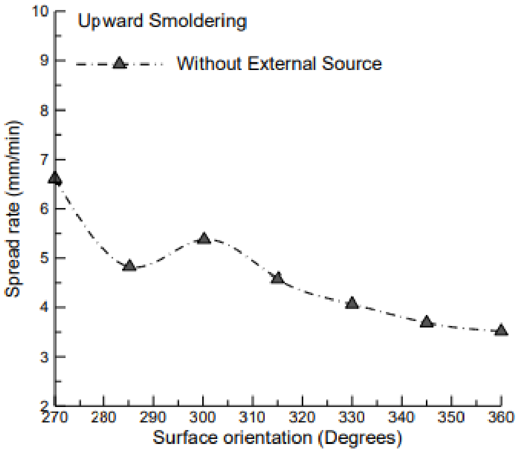
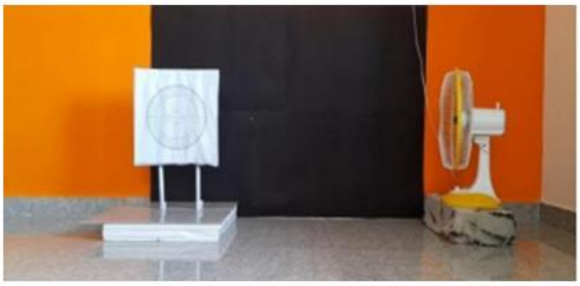


Fig. 6: Variation of upward smoldering regression rate with surface orientation.

Fig. 6 indicates the maximum regression rate of 6.607 mm/min observed at 270° which is in agreement with the conventional heat transfer theory. Thus, the predictions of the experimental setup are expected to provide a good insight of the effect of external energy source(s) on the upward smoldering phenomenon. First the effect of external flow on upward smoldering spread was articulated with varying surface orientation. The pilot was placed at surface orientations viz., 270°, 285°, 300°, 315°, 330°, 345° and 360° and subjected to the external forced flow, i.e., external flow upward smoldering takes place. The external flow source (here, fan) was placed at different locations viz., 100 cm, 75 cm, 50 cm respectively (refer fig.7). The regression rate was calculated in each case and a graph was plotted between the surface orientation and regression rate for detailed data analysis. Further, the values were compared with the base case where upward spread smoldering occurred without any external forced flow. It is important to note that, the external flow source had 3 distinct speed levels which at varying locations provided different instantaneous flow speeds (external flow speed in touch with the ignition zone).




(a) (b)

(c)

Fig. 7: Pictorial representation of the experimental setup for upward smoldering in the presence of external source flow with source location (L), (a) 100 cm, (b) 75 cm, (c) 50 cm.

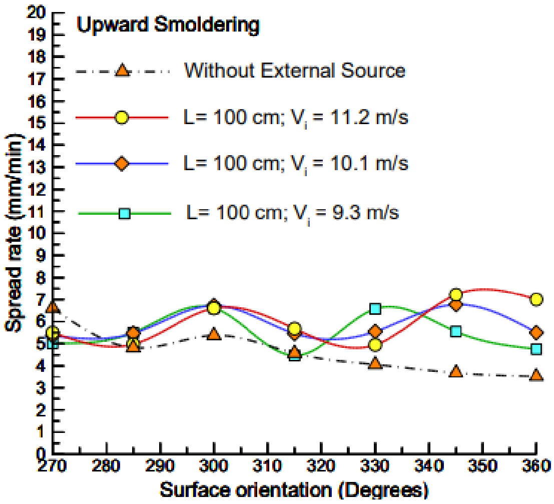
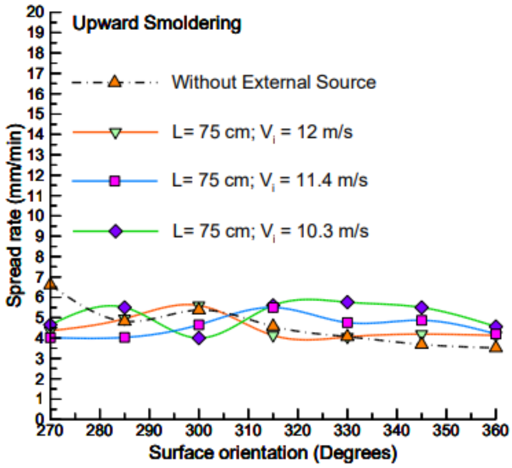
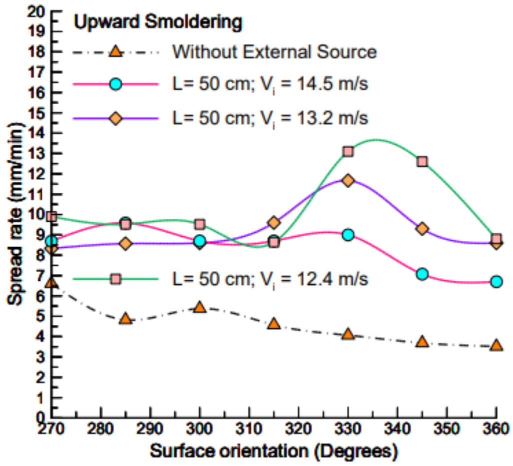


Fig. 8: Effect of instantaneous flow speed (Vi) variation on upward smoldering of faraway located external source (here, 100 cm).

Fig. 8 shows the variation of regression rates in comparison to the single pilot fuel. The variation clearly depicts that presence of external flow significantly affects the upward smoldering phenomenon. Looking at the plot one can note that, the maximum regression rate occurs at 270° surface orientation. The values for fan high speed (11.2 m/s) are 6.56 mm/min whereas, intermediate (10.1 m/s) and low speed (9.3 m/s) under similar condition result in 4.75 mm/min and 4.78 mm/min with drop of 0.71%, 28.1% and 27.65% in comparison to the base case (without external flow source).





(b)

Fig. 9: Effect of instantaneous flow speed variation on upward smoldering of intermediate located external source (a) 75 cm, (b) 50 cm.

When the external flow source was placed closer to the experimental setup at intermediate locations of 75 cm (fig. 9(a)) and 50 cm (fig. 9(b)), contrasting effect in the variation of regression rates was noted. At 75 cm, fan reported high speed of 12 m/s, intermediate speed of 11.4 m/s and low speed of 10.3 m/s. The maximum regression rate for upward smoldering were reported at 270° for different instantaneous speeds as 3.98 mm/min, 6.62 mm/min and 5.82 mm/min with -39.76%, 0.22% and -11.91% changes in comparison to the one with no external influence (fig. 9(a)). Whereas for external source located at 50 cm, fan high speed is 14.5 m/s, intermediate speed is 13.2 m/s and low speed is 12.4 m/s. The maximum regression rate occurred at 270° as 5.63 mm/min, 5.88 mm/min and 5.54 mm/min respectively with -14.71%, -11.0% and -16.14% difference from the reference (refer fig. 9(b)).

Following the external flow, the effect of acoustics on upward smoldering phenomenon was investigated. Similar to the preceding experimentation, a pilot incense stick was placed at various surface orientations viz., 270°, 285°, 300°, 315°, 330°, 345° and 360° and the system was subjected to the external acoustics of varying frequency viz., 1000 Hz, 500 Hz, and 250 Hz at different source location(s) viz., 100 cm, 75 cm, and 50 cm. Similarly, the effect was noted in the form of regression rate measurement in each case and comparison with the one without any external influence. First, the effect of varying acoustics on upward smoldering was investigated for the faraway located external source i.e., 100 cm (see fig. 10).

(a) **(b)**

(c) **(d)**

(e) **(f)**

(g)

Fig. 10: Pictorial representation of experiments for upward smoldering in the presence of external acoustic source placed at a distance of 100 cm for varying surface orientations
(a) 270°, (b) 285°, (c) 300°, (d) 315°, (e) 330°, (f) 345° and (g) 360°.

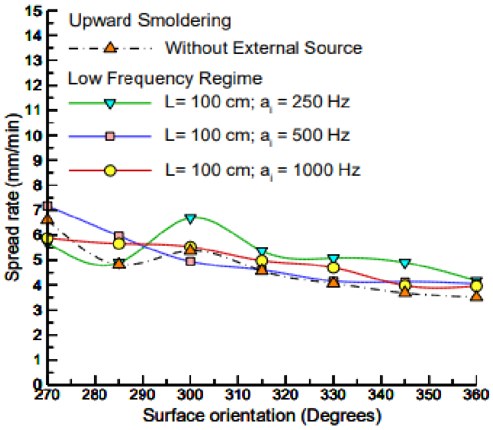
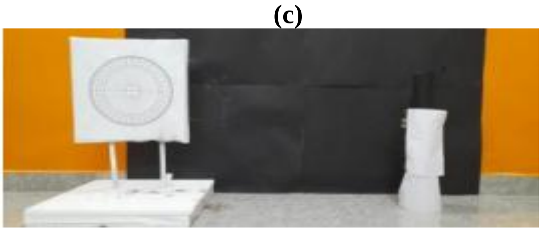


Fig. 11: Effect of low frequency acoustics variation on upwardSmolderingof faraway located externalsource (100cm).


(a)

(b)

(c)

(d)

(e)

(f)

(g)

Fig. 12: Pictorial representation of experiments for upward smoldering in the presence of external acousticsource placed at a distance of 75 cm for varying surface orientations
(a) 270°, (b) 285°, (c) 300°, (d) 315°, (e) 330°, (f) 345° and (g) 360°.

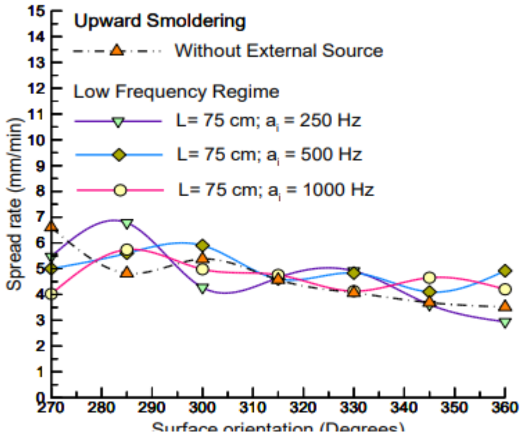


Fig. 13: Effect of low frequency acoustics variation on upward smoldering of intermediate located external source (75 cm).

(a) **(b)**

(c) **(d)**

(f)

(e)

(g)

Fig. 14: Pictorial representation of experiments for upward smoldering in the presence of external acoustic source placed at a distance of 50 cm for varying surface orientations (a) 270°, (b) 285°, (c) 300°, (d) 315°, (e) 330°, (f) 345° and (g) 360°.

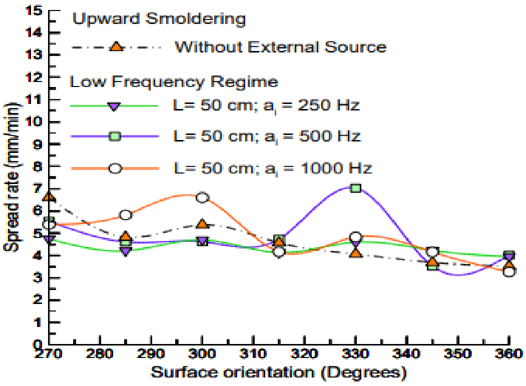


Fig. 15: Effect of low frequency acoustics variation on upward smoldering of intermediate located external source (50 cm).

To understand the role of external source location, the acoustic frequency was fixed and effect of varying source location was observed.

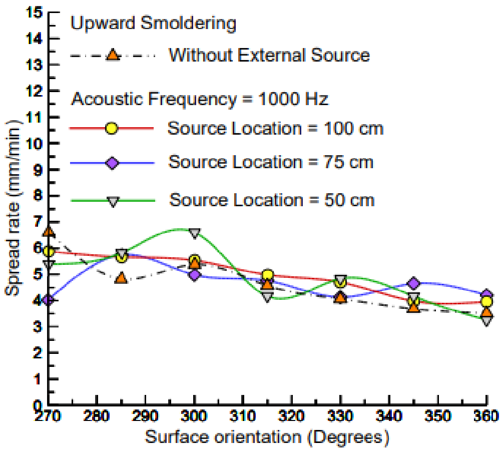


Fig. 16: Effect of acoustics source variation on upward smoldering for acoustic frequency of 1000 Hz.

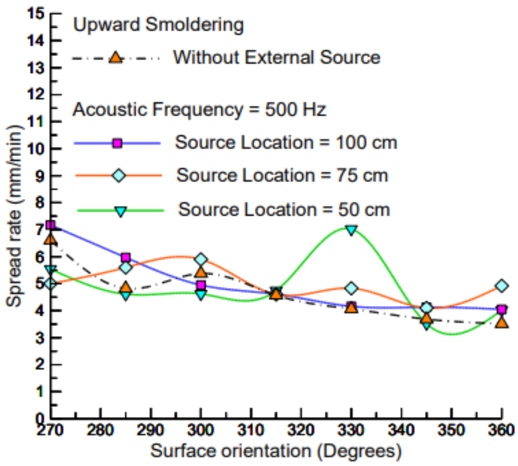


Fig. 17: Effect of acoustics source variation on upward smoldering for acoustic frequency of 500 Hz.

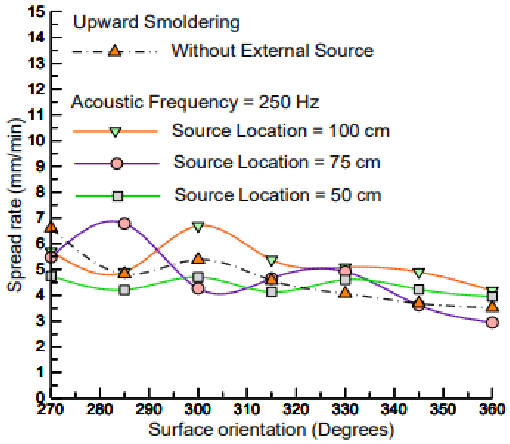


Fig. 18: Effect of acoustics source variation on upward smoldering for acoustic frequency of 250 Hz.

Conclusion:

An experimental study was carried out to investigate the governing physics of regression rates variation with surface orientation. Based on the results obtained it has been concluded that external forced flow has a significant effect on upward smoldering. The speed of the external forced flow, the distance between the forced flow source and the smoldering front, and the surface orientation are all key controlling parameters in this phenomenon. The presence of an external heat source alters the reaction zone and further disrupts the interaction zone. The synergy of these have combined momentum and thermal effect which is noticed on the regression rate. Applications of the work: In real case, there is varying forced flow and there is sound in the nearby environment. All these affect the smoldering phenomenon. Hence by understanding the physics behind the phenomenon, certain necessary measures can be taken to avoid forest fires. Findings from present work can be taken advantage of various engineering systems. Based on this new framework and guidelines for fire-safety can be formed. The knowledge gained might lead to some solution and application in predicting large scale fires in buildings, industries, forests, airplanes and rockets and that would give us sufficient control and rescue time to minimize the damage. To ensure fire safety for all kinds of practical and scientific work and to ensure better combustion for various engineering systems. The work carries wide range of applications including engineering.

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