EXPERIMENTAL STUDY OF EFFECT OF ANGULAR ORIENTATION ON FLAME SPREAD OVER THIN SOLID FUELS

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ABSTRACT

Understanding the spread rate of a combustible surface is vital in estimating the fire hazards involved while handling that material. The spread rate is a function of several physical parameters, one of which is the inclination of the surface with respect to the gravity vector. Further, flame spread direction plays a significant role. For instance, upward flame spread is gravity assisted since the flame spread direction is same as the buoyancy induced flow direction and it takes place at a much faster rate when compared to the downward flame spread where gravity induced flow opposes the flame spread. Hence, there is a need to study the effect of inclination of the fuel surface with respect to gravity vector in both upward (concurrent) and downward (opposed) flame spread situations. This paper is an attempt to experimentally study the effect of angular orientation of a thin paper surface on flame spread rates. Spread rate of diffusion flame established over a thin paper having dimensions 20 mm by 300 mm, has been measured by orienting the fuel surface at various angles from -90⁰ to 90⁰ measured with respect to the horizontal, (0⁰ corresponds to horizontal orientation).

INTRODUCTION

Flame spread over inclined fuel surfaces is a common fire hazard scenario. However, it has received less attention in the literature than vertical or horizontal flame spread processes. Assessment of the fire hazard of a material often entails estimation of the flame spread rate over the surface of the material. The maximum spread rate determines the worst case scenario used in design of fire detection and fire suppression systems. The effect of gravity induced flow field on flame spread rate is significant. The angle that the gravity vector makes with flame spread direction either accelerates or decelerates the flame. Spread across inclined surfaces of thatched roof tops is an example. In case of a natural environment, wild land fires often spread over sloped surfaces. Of special interest is flame attachment, the transitions where flames lie closer to the fuel surface and where the flame accelerates rapidly. Knowledge of flame geometry can be useful to model fire spread in practical situations, as radiation-dominated flame spread will be influenced by the view factor between the flame and unburned fuel. The rate of the convective-dominated flame spread will be greatly increased when flames are attached closer to the fuel surface.

Spalding [1] was one of the first to present a theoretical analysis of the vertical burning problem when he obtained a Pohlhausen solution based on several approximations. Kosdon et al. [2] investigated burning of vertical cellulose cylinders by means of a boundary layer type two-dimensional similarity solution. Ahmad [6] studied the flame characteristics in vertically oriented methanol wicks in both laminar and turbulent regimes. Tamanini [7] has presented a numerical model for obtaining flame structure and mass burning rates for radiation controlled, turbulent, single vertical wall fires. An analysis of laminar, free convective burning of a thermally thick, vertical PMMA surface has also been described by Sibulkin et al. [8]. Kumar et al. [10] investigated the flame spread phenomena over thin solids by comparing the flammability limits and spread rates for purely opposed and concurrent flows.

Literature related to inclined flame spread was initially presented by Hirano et al.[3] who experimentally examined the heat transfer to the unburnt surface in front of the pyrolysis zone along downward flame spread over thin sheets using Schlieren photography. Another work of Hirano et al.[4] described the gas velocity and temperature profiles of spreading flames over paper at three different angles using particle tracer techniques and fine wire thermocouples. Takashi et al. [5] employed α-cellulose sheets to measure downward flame spread velocity from vertical to horizontal configurations under varying external radiant fluxes. Quentiere [9] showed the critical transition angles while burning metalized polyethylene terephthalate and paper on glass fiber insulation from upward to downward flame spread configuration. Akihiko et al. [11] experimentally investigated the propagation and extinction mechanisms of opposed flow flame spread along a thick slab of PMMA at four different orientation angles in several air flow rates. Numerical results were presented by Seik et al. [12] on laminar, quasi-steady burning characteristics of a thin film under atmospheric pressure and normal gravity conditions. The

entire orientation range of -90° ≤ θ ≤ +90° was considered and the mathematical model accounted for normal as well as cross flow buoyancy components, so as to differentiate between upward and downward burning rates. Later, Seik et al. [13] extended the studies of Ahmad [6] by estimating the variation of heat flux parameter along the fuel and downstream wall surface. Recently, Gollner et al. [14] used a thermally thick slab of polymethyl methacrylate to study the effects of the inclination angle of a fuel surface on upward flame spread. It was shown that maximum spread rate doesn't correspond to maximum fuel mass loss rate.

Most of the previous works mentioned above have considered only vertical and horizontal configurations or have described the characteristics of single side burning for thick fuels at certain orientation angles. The present work focuses on experimentally evaluating the spread rates of diffusion flame established over thin paper with the flame advancing on both sides of the fuel sheet. The critical angles, where transition in spread rates occur, are also captured. The tests were carried out for configurations ranging from 90º to -90º , in steps of 10º measured with respect to the horizontal (0º corresponding to horizontal) as shown in Fig. 1.
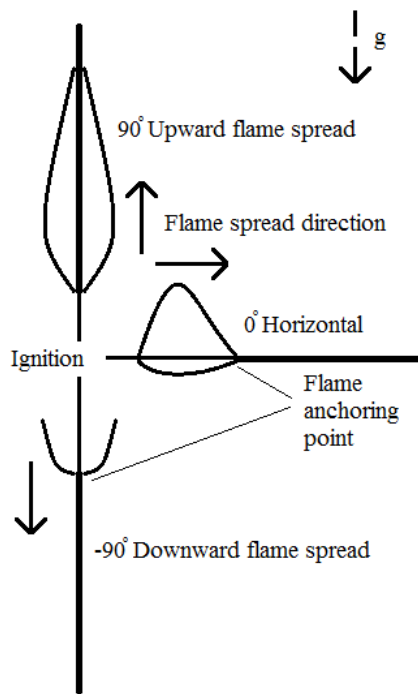

Figure 1: Schematic of flame spread directions

EXPERIMENTAL SETUP

An experimental set up has been fabricated to hold the thin solid fuel sheets such that they can be inclined at any desired orientation angle. The set up consists of two sections. The lower base is made of mild steel, which clutches and enables the upper arrangement to be held at a specific orientation angle. The upper aluminium section holds the fuel sheets to be ignited. The lower base consists of two L-shaped mild steel plates of 0.5 cm thickness. They are firmly fixed 30 cm apart by welding

2 arms at the bottom of the plates. Two arc shaped slots are provided on both the plates to permit the rotation of the upper casing up to an angle of 90º. A common lift rod passing through these slots are clasped at a desired location by a knob fixed into the rod through a wing nut mechanism. The lift rod is connected to the upper casing by a link arm.

The upper casing is made of aluminium. The photograph of the upper casing of the experimental setup exhibiting its front and side view is shown in Fig. 2. It consists of a base plate of thickness 0.5 cm and has 6 holes drilled through it. The holes are separated by 15 cm in the height wise direction and by 20 cm in the width wise direction. Rods are fastened in the holes. The rods hold 0.1 cm thick aluminium frames, which are 23 cm wide and 33 cm long with holes to pass through the rods. The fuel sheets are sandwiched between two such frames. The frames have a 2 cm by 30 cm slot in the middle where the thin fuel sheet burns. Once the fuel sheet is clamped between the frames, it is tightened by screws. The fuel sheets are cut such that they fit into the slots of the frames to burn completely with no discontinuity. The fuel used is thin paper which produces almost no ash on burning. As the burning of fuel sheets gets affected by moisture, it is heated in an oven for about 1 hour at 105ºC. This was arrived at by noting the weight loss history for the release of the moisture. The paper is then cooled to room temperature in a desiccator. In order to prevent subsequent absorption of moisture from ambient by the fuel sheets, it is ignited within 90 seconds after its removal from the desiccator. Samples were ignited at the bottom using a butane diffusion flame of 0.5 cm diameter. In order to ensure no preheating takes place, uniform ignition is maintained. A conical extension is formed at the end of each sample to preserve consistent flame growth. Once ignited, it spreads uniformly to finally move into the region at the slot. Once a particular orientation is complete, the knob of the lift rod is loosened and the rod is lifted to a desired orientation before tightening it to hold it rigidly in that position. The burnt sheet is removed and the frames are cleaned to make sure no residue is left behind. A new fuel sample is then fitted between the frames for the next experiment. It is important to note that all the tests were repeated 3 to 5 times to ensure repeatability of the results.
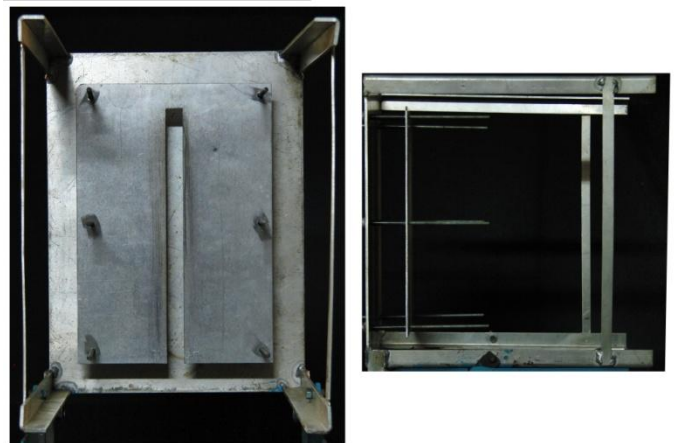

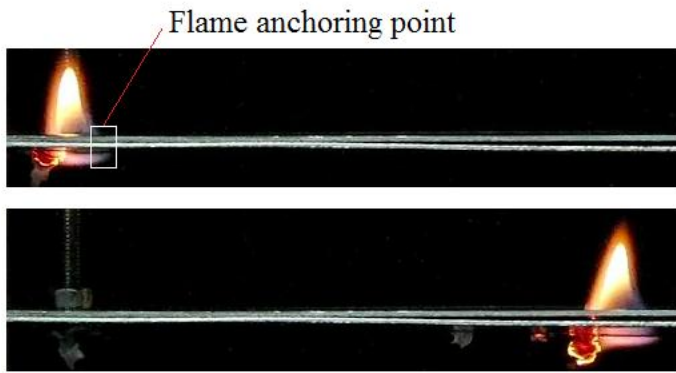**Figure 2**: Front and side view of the Experimental setup

Figure 3: Instantaneous images of flame at 2 different time instants for horizontal configuration (0^0)

Videos of all the trials in each configuration have been recorded. All the videos were recorded at a speed of 29 frames per second. The videos were disintegrated into individual frames/images and were processed using MATLAB to assess the movement of the flame. The flame anchoring point was taken as the reference point to track the growth of the flame. The position of the flame anchoring point at the end of every 29 frames gives the distance moved for one second. Adequate frames are chosen such that it either covers the entire distance or attains steady state flame spread . The flame anchoring point of the first frame is chosen as a template and it is tracked for each subsequent frame. The anchoring point shifts as the flame progresses and thus gives the movement with each frame. Typical instantaneous flame locations for 0^0 inclination at a time gap of 35 seconds depicting the details of anchoring point is shown in Fig. 3. Movement of the flame anchoring point with each frame is measured in terms of pixels. The distance moved in terms of pixels is then converted to dimensions of length. By knowing the distance moved with each frame and the frames per second value of the video, the spread rates are calculated.

RESULTS AND DISCUSSION

The instantaneous flame images at various inclinations is shown in Fig. 4. It is observed that the flame extent decreases as the inclination changes from 90^0 to 0^0. As a result, the pyrolysis length also reduces as it approaches horizontal. This is due to the resulting natural convective flow field associated with the orientation angle. For downward flame spread, the size of the flame is very small compared to the upward flame spread as the flame has to propagate against the buoyancy induced flow for these cases. For all negative angles, the flame shape and extent remain almost same. The variation in the flame spread rates as a function of orientation angle for opposed/downward flame spread and assisted/upward flame spread are shown in Figs. 5 and 6, respectively.

Upward flame spread is called gravity assisted spread as the high temperature burnt gases move upward due to buoyancy. This increases the distance between the flame anchoring point and the flame tip, and therefore convectively heats up the unburnt fuel ahead of the flame. The pyrolysis length is comparable to the flame length in these cases. As a

result, the time required to pyrolyze the unburnt surface is lesser and this causes the fire to spread at a much faster rate.
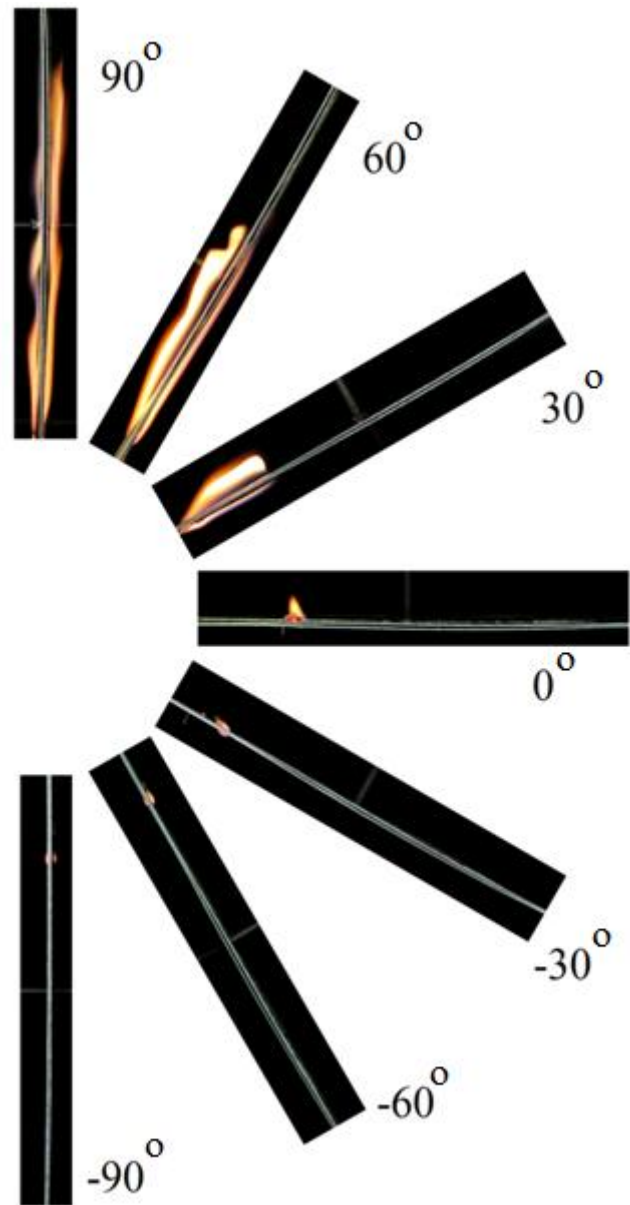

Figure 4: Photographs of flame shapes at different angular orientations

In downward flame spread, the movement of flame is against gravity induced flow and hence the burnt gases do not transfer any heat to the unburnt fuel surface by convection. The propagation of heat is restricted to conduction alone unlike upward flame spread. From Fig. 5, it is clear that the spread rates remain fairly constant for the range of angular orientations between -90^0 to -20^0. The opposed flame spread is almost steady and occurs at a low rate. An increasing trend in the flame spread rate is observed at inclination angles of -10^0 and 0^0. As the orientation angle tends to zero, opposing effects of

buoyancy driven flow reduces and therefore, the flame spread rate shows an increasing trend.
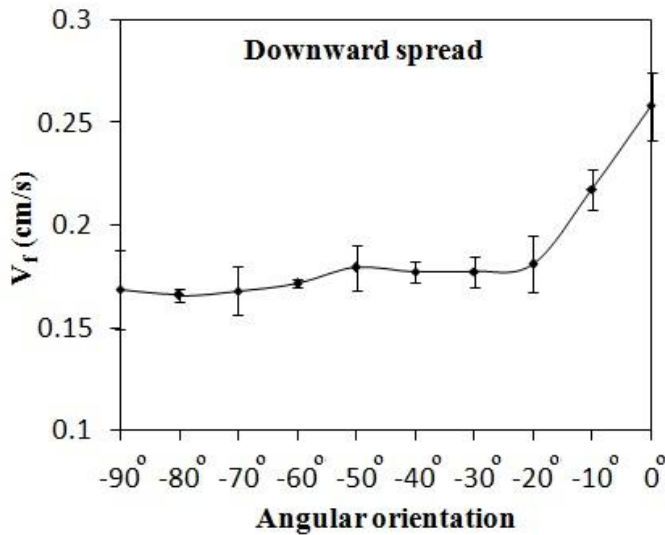

Figure 5: Variation in spread rate with angular orientation for downward spread. The error bars indicate the standard deviation of variation between tests
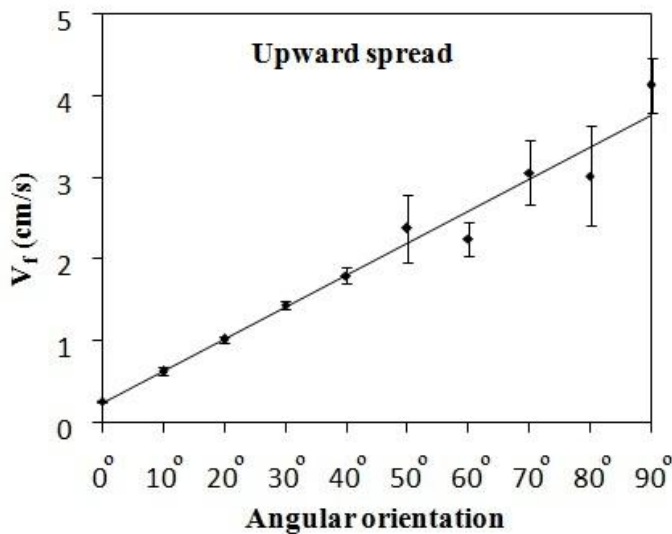

Figure 6: Variation in spread rate with angular orientation for upward spread at the end of 30cm. The error bars indicate the standard deviation of variation between tests

For the upward flame spread, as depicted in Fig. 6, the spread rate shows an increasing trend with the orientation angle. The spread rates mentioned are the values obtained when the flame is at the end of 30cm slot. The spread rate is higher compared to the corresponding positive angular orientations. Buoyancy induced flow contributes to the increase of flame length and convective preheating of the fuel. Therefore, the flame spread rate is increased.

Temporal variations of flame spread rates have been plotted in Figs. 7 and 8, for opposed flame spread cases. In the range of angles between -90° to -50°, initially there is a notable difference in the spread rates, however, the rates approach steady, constant values with time eventually (Fig. 7).

From Fig. 8, it is observed that the spread rate increases with increasing orientation angle and the horizontal case 0° has the maximum spread rate as indicated in Fig. 5.
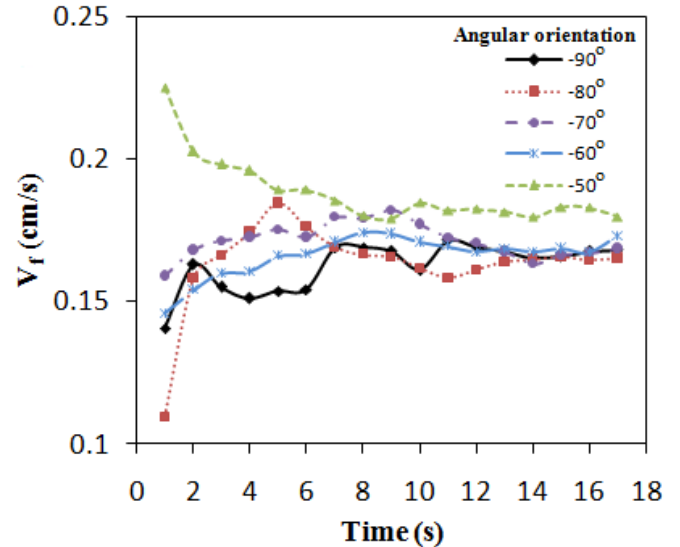

Figure 7: Variation in spread rate with time for downward spread for angles -90° to -50°
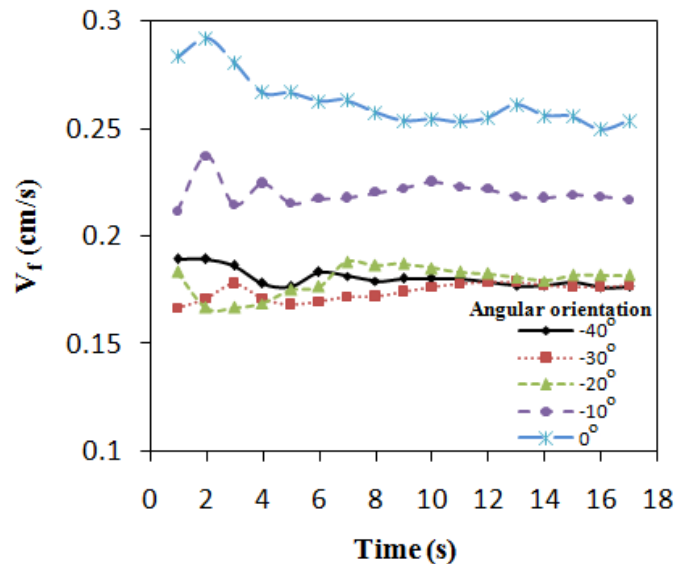

Figure 8: Variation in spread rate with time for downward spread for angles -40° to 0°

For upward flame spread, it can be seen that spread rates accelerate with time for all the inclinations. From Fig. 9, it can be deduced that the spread rates start to increase from the inclination of 10⁰. However, the acceleration or rate of change of spread rate of each curve inflates as the orientation approaches vertical. A sharp jump in the spread rate is observed at 30⁰ after which it accelerates similarly for all inclinations without reaching a steady state. Initial fluctuations and crossovers in spread rates in Fig. 10 can be neglected.
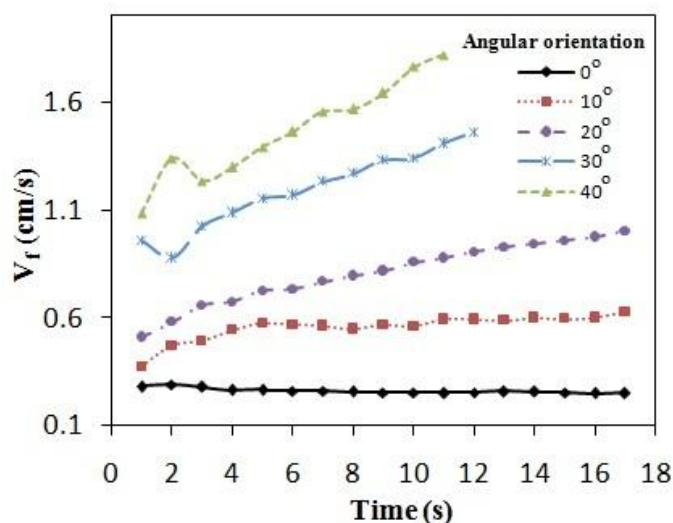
Figure 9: Variation in spread rate with time for upward spread for angles 0° to 40°
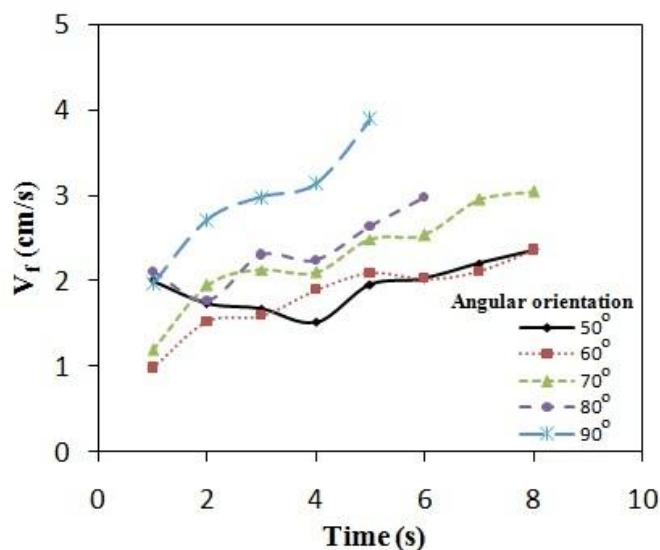

Figure 10: Variation in spread rate with time for upward spread for angles 50° to 90°

The principle observation to be made from the present work is that the maximum spread rate occurs for vertical upward flame spread configuration (90⁰) with the value being nearly 4 cm/s at its peak. The lowest spread rate occurring at vertical downward flame spread configuration (-90⁰) with a value of about 0.16 cm/s. It would be noteworthy to point out that the results obtained here is much different from the results presented by Gollner et al. [14] owing to the change in fuel which primarily exhibited single side burning.

CONCLUSIONS

In this study, an experimental setup was designed to investigate the effects of surface orientation on burning rates over thin films. Spread rates were measured for orientations from the range of -90⁰ (vertical downward spread) to 90⁰ (vertical upward spread) with respect to horizontal in steps of 10⁰. It was concluded that highest spread rates were achieved in upward flame spread when the angle of inclination was 90⁰ and the lowest being same at most of the downward flame spread configurations (-90⁰ to -20⁰). The role of gravity was hence found to have played a big role in the growth of fire. Graphs and figures developed indicate that spread rates remain steady for all the downward spread cases and steep acceleration was found to have started in the upward inclination of 30⁰.

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