

On The Role of Configuration Types and Surface Orientation on Ignition and Fire Spread in Array of Thin Solid Fuels

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Abstract

With systematic experimentation, the fire propagation and self-ignition effect is explored. With the increasing number of fire disasters in recent years and from the accompanying scientific development. It is imperative to test distinct approaches to develop enhance understanding of this heterogenous phenomenon to prevent future incidents and to minimize losses. The study presents a macroscopic qualitative approach to the assessment using central investigation parameters. Varying linear configuration(s) incorporated with the slope effect is investigated and useful physical understanding is drawn to gain the true replication. Quintessential parameters like, nature of flame, classification of propagation effect, the flame height, assisting heat source and heat sink effect in view of self-ignition effect are observed. The results clearly show the large-scale fire propagation phenomenon to be highly heterogenous in nature. Unique singularities were observed with different cases which proposes better probability-based solution.

Introduction

Combustion is the source of energy for about 80% of all processes in the world. Combustion can be defined as a chemical reaction between a fuel and an oxidizing agent that produces energy, usually in the form of heat and light. Basically, there are three major requirements for combustion to take place: (a) enough oxygen to sustain combustion (b) some fuel or combustible material (c) enough heat to reach the ignition temperature. When all these three interact in a particular ratio, combustion

occurs. Fire have been a continuous source of enthused human progress. Competent application of fire has resulted in splendid advancement in the fields of engineering, industrialization, practical, functional and operational systems. However, fire has had also been the biggest source of adversities that occurred in the forms of large-scale fires in industries, forest(s), building(s), Aircraft and Rocket crashes, leading to immeasurable loss of human lives, nature, properties and every year enormous efforts are being taken on scientific research to achieve fire safety. National Fire Prevention Association (NFPA) data reports 8.5 million acres loss of land due to forest fire(s), structured fire loss of 10.7 billion dollars (USD), residential, industrial, educational institutions, wildlife states loss of 10,700 million dollars (USD) and the rate of rise of 77% every year. One of the primary reasons is the marginal understanding of the scientific community about the fire ignition and propagation phenomenon. To mitigate the fire related problems, it is important to first understand the fire ignition and propagation phenomenon. Present work highlights primarily on the in-depth understanding of fire propagation phenomenon and based on the physical insight, new guidelines in fire safety on normal and extra-territorial atmosphere can be framed. The work carries wide range of applications including storage, easy handling, stability, cost effectiveness and could be extensively used in wide range of engineering viz., combustion and propulsion, defence systems validation, testing and upgradation like missile systems, industrial with power generation systems, practical, functional, scientific applications (refer figure 1).

Following the classical work of Egerton and Thabet [1] on the propagation phenomenon with burning speed measurement of slow flames and limits of combustion. The study detailed development of a technique to calculate burning velocities of combustible gas/air mixtures near the limits of combustion using a burner providing a flat disk-shaped flame. The method was applied to methane, propane, n-pentane, n-heptane, ethylene, acetylene and benzene flames of velocities 5 to 10 cm/s and flame characteristics were discussed. The results stated that the time during which unburnt gas can be heated by conduction from the flame is inadequate and the reactions are therefore initiated by diffusion of radicals from the flame front. This leads to the fact that burning velocities of the slow flames are mainly dependent on reaction heat which determines the temperature of the flame and the rate of the reactions.



(a)

(b)

(c)



Figure 1: Pictorial representation of (a) forest fires, (b) building fires, (c) industrial fires, (d) aircraft fires, (e) rocket fires, (f) compartment fires.

Rothermel and Anderson [2] carried out a study on the mechanisms of fire spread to enhance knowledge of forest fires. Material viz., pine needles, leaves, and rotten wood were documented as the fuels. The laboratory research primarily aimed to understand the effect of moisture extent of the fuel and air velocity over it. The result produced useful physical insight into its cause and effects leading a better awareness of the basic science of fire spread. The work also highlighted that for future experiments the geometric pattern-oriented experimentation would lead to easy replication and will not be able to produce true replication of the phenomenon. Vogel and Williams [3] carried out experimental investigation of flame propagation along matchstick arrays along uniform, linear, horizontal arrays of vertically oriented matchsticks. Matchstick height and spacing between matchsticks were varied. Results indicated the necessary conditions for flame propagation and linear rates of flame propagation on the face of the matchstick array. The study offered, theoretical explanations for the experimental observations on the basis of a model which employed an ignition temperature and previously determined flame shapes for individually burning cellulosic cylinders. The remarkably good agreement between theory and experiment supported the argument that convective effects are of primary importance in flame propagation at matchstick size scales. Rothermel [4] developed a mathematical model for predicting rate of fire spread and intensity applicable to a wide range of wildland fuels. The model was developed and being used as one of the imperative aspects for appraising fire spread and intensity in the NFDR (National Fire Danger Rating) system. The preliminary work was done using fuel arrays comprising of uniform size particles. Three different fuel sizes were tested over a wide range of bulk densities. It was stated that the model does not require prior knowledge of a fuel's burning characteristics but only inputs relating the physical and chemical makeup of the fuel and the environmental conditions in which it was expected to burn. Inputs included fuel loading, fuel depth, fuel particle surface-area-to-volume ratio, fuel particle heat content, fuel particle moisture and mineral content, and the moisture content at which extinction can be expected. Environmental inputs were mean wind velocity and slope of terrain. The results of the work were found to be useful for fuels ranging from pine needle litter to heavy logging slash and introduced the concept of fuel models, wherein parameters of wildland fuels necessary for inputs to the model were categorized and tabulated. These were used to predict fire spread and intensity. Fernandez-Pello and Hirano [5] summarized the experimental studies

on the mechanisms controlling the spread of flames over the surface of combustible solids. The work advocated that in most practical situations, the spread of fire in opposed gas flows occurs at near extinction or non-propagating conditions and thus, gas phase chemical kinetics plays a critical role and it must be considered. However, in the concurrent mode, forward heat transfer is the primary controlling mechanism. The study further detailed that, gas phase chemical kinetics is important in the establishment and extension of the diffusion flame that generates the spread process. Jones [6] evaluated the various fire models constructed over the years for defining a general outline for further research in fire modeling. The work attempted to formulate each model in terms of similar variables. The one-room model with related physics and chemistry had been developed was discoursed. The model was assumed to be rooted in a world of uniform temperature and reference pressure with the basic conservation equations, the source and sink terms and contact of various objects in a single compartment fire. The governing equations were divided in to facilitate the development of a model which will be modular in scope as well as general in application. The work aimed that with such a model distinct testing of various fires, fire spread, and entrainment models will be possible.

Baines [7] worked on the different physical progressions which affect the fire spread rate on surface fuel beds including conduction, radiation from the flame and fuel bed, and convective heating influenced by wind. With results, a new understanding of laboratory experiment(s) was given, and balance between radiative heating from the flame and convective cooling of the fuel bed was recognized. The ratio between these two effects was expressed as a new dimensionless number, P with conditions that, If $P < 1$, radiation from the flame of the fire alone is not capable of causing the fire to spread, whereas if $P > 1$ moderate to large fires in the field. The study also stated that, the most significant factor affecting fire propagation is wind, as it increases both radiative and convective heating and bigger part of fire propagation is turbulent and involves large eddies in the boundary layer and their interaction with fires is poorly understood. Weise and Biging [8] investigated the effects of wind velocity and slope on fire spread rate and flame length. Experiments were carried out with fuel beds of vertical sticks and coarse excelsior with mean fuel moisture content of 11% and 12%, respectively. The study combined varying slopes viz., negative, positive, none with varying wind velocities viz., heading, backing, none. The spread rate was measured with thermocouples and the flame length was estimated from video imagery. The results stated that spread rate of downslope heading fires exceeded spread rate of no-wind/no-slope fires and increased fuel moisture reduces spread rate and flame length. Viegas [9] presented the different phases in the development of forest fires and characterized the propagation regimes, together with the main factors affecting them. The laboratory experiments on the propagation of a linear fire front on an inclined surface was carried out and, the linkage between convection and radiation in the fire propagation process was verified. Further, the result was generalized for wind-driven fires and an interpretation for the global movement of the fire front under slope or wind conditions was configured. The work highlighted problems of modelling the various fire behaviour regimes, with specific significance to surface fire propagation. The role of convection and radiation processes on fire propagation was considered.

Further, Viegas [10] explored the fire propagation phenomenon with modulation of wind and slope effects on a flame front. The work presented the perception of multiple standard fire spread directions and comprised effects of varying wind velocity and direction on point source flame fronts on a 30° inclined fuel bed. Mathematical methods for vectoring were presented and the results were compared with experiments. Sullivan [11] carried out a case study of advances in computational power in effort to model the behaviour of wildland fires and to simulate fire spread across the landscape. The study presented survey of all types of surface fire spread models developed during the period 1990–2007 of a physical or quasi-physical nature and considered models based on the fundamental chemistry and physics, of combustion and fire spread besides review models of an empirical or quasi-empirical nature, and mathematical analogues. The work directed that many models were extensions of models developed before 1990. Gollner et. al., [12] investigated the fire propagation phenomenon in view of vertical matchstick array burning. Experimentation was done for vertical arrays of horizontally matchsticks, arranged from one to five to investigate the influence of the inter-spacing on rates of upward flame spread. The results showed that the advancement of the ignition front varies linearly with time. Rates of upward flame spread were found to increase intensely for low-spacings. Based on the observations, the influence of convective heating was offered to dominate the propagation mechanism. Alkhatib [13] evaluated machineries that have been used for forest fire detection with in-depth surveys of their techniques used. The work provided quintessential review of all the methods and deliberated examples of experiment results and some market product approaches for better understanding. With thorough comparison, the study stated that each technique has its own advantages and disadvantages which entails the four methods. Sharples [14] explored the issue of bushfire risk assessment by considering the risk implications arising from state-of-the-art developments in the bushfire propagation and extreme fire development. The study provided an assessment of the current standards and practices employed in bushfire risk assessment. The review precisely focused on the fire behavioural aspects of the current guidelines for construction in bushfire prone areas. The results of the review showed that the best practice in the development of bushfire management strategies, significantly under-estimate the risk of bushfire under extreme fire danger conditions when applied to regions with steep slopes. In recently, Yuan et. al., [15] investigated the self-heating phenomenon in porous fuels as a smouldering fire. In the study, a numerical model was built that connects the simulation of self-heating ignition and smouldering spread by adopting a two-step kinetic scheme. The model predictions were confirmed with hot plate experiments of coal in both flat and wedge configurations. The simulation results established that the hot spot instigated at the hot plate and then spreads towards the free surface due to oxygen utilization. The height of maximum temperature point decrease with wedge angle, and that the effect of wedge angle can be explained by the heat transfer. Appreciable scientific work had been carried out to deepen the understanding the fire propagation and self- heating effect as applicable to the large-scale fires. One aspect which is yet to be comprehensively investigated is to gain the true replication. Present work attempts an experimental lab scale study to establish the uniformity and outline

of fire propagation phenomenon.

Present work is primarily inspired by the need to enhance understanding of fire propagation phenomenon under varying conditions for better safety, reliability and suitable applications. The specific objectives of the study are:

- a) To understand the qualitative nature of fire propagation and self-ignition effect for varying configuration(s) and orientation(s).
- b) To draw useful interrelations for large scale heterogenous fire spreading.
- c) To understand the role of key controlling parameters.

Experimental Setup and Solution Methodology

A simple experimental setup (figure 2 (a & b)) was upraised for the study. The experimental setup consisted of a) metallic base plate, b) perforated metallic tray, c) protractor, d) screw assembly, e) solid fuel assembly as pilot fuel and an array of external energy source (labelled homemade match stick), f) stopwatch and g) shadowgraph (for optical visualisation). The design comprises of a metallic base plate attached to a movable perforated metallic tray with provisions for testing at different surface orientations.

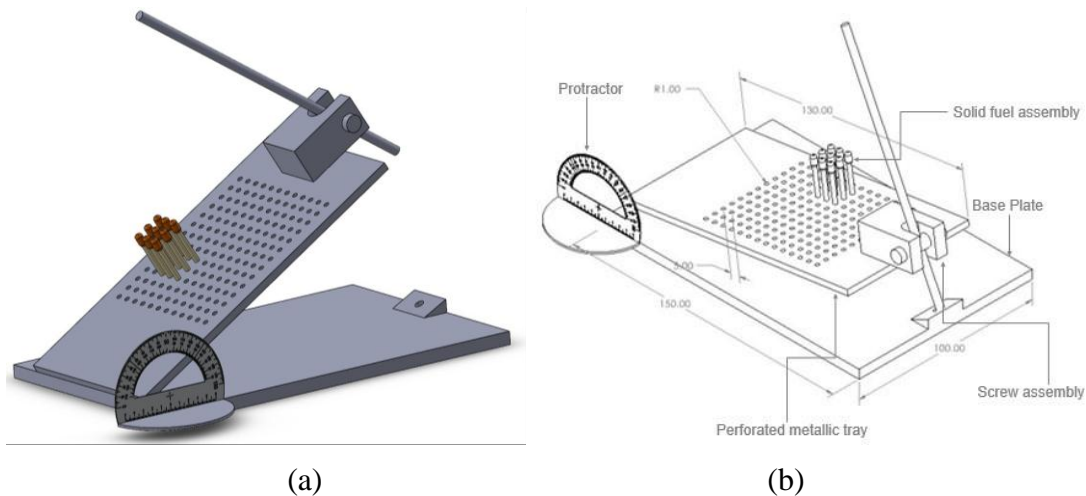


Figure 2: Schematic of (a) experimental setup representation, (b) component-wise characterization.

In an attempt to gain the true replication of the natural phenomenon, detailed analysis of pilot fuel ignition, self-ignition and propagation effect due to and on the external heat sources for varying configuration(s) was carried out. The experimental setup provides the provision for thoroughly investigating heterogeneous fires in presence of external heat source(s) and sink(s) along with the measurement of initial, average and instantaneous spread rate variation with sectional propagation in spatial and temporal domains. The predictions were corroborated with the conventional heat transfer theory besides the preceding research data and matches reasonably well. Different

configuration(s) viz., unilateral, 'Y', 'T', '+' for spatial (linear configuration(s)) with interspace distance of 0.5 cm and external energy source(s) as 2 for all directions were tested. Experimentation is initiated with pilot fuel ignition and effect on external energy source(s) in the neighbourhood was observed. Entire experimentation was properly video graphed for maximum of 60 seconds and useful specifics were extracted. Noteworthy cases of completely burnt, partially burnt and extinguished external energy sources, for different configuration were detected.

It is important to note that entire experimentation was carried out in normal and controlled conditions with oxygen concentration of 21% and the data presented represents repeatability and reproducibility of Third Order.

Result and Discussions

In practical scenario, the ignition source is always surrounded by the external heat sources (provides energy, enhances maximum temperature) and external heat sinks (takes energy of ignition source and results in suppression). Thus, in order to gain the true replication, systematic experimentation was carried out to observe the occurrence and variation of flame propagation behavior and the self-ignition effect in form of heterogeneous energy transition. The fire behaviour was observed in terms of parameters viz., modulation in ignition, flame shape and size, sustenance with time and the surface orientation. The role of surface orientation was tested on propagation and self-ignition effect with variation in surface orientation for cases of 0°, 30°, 45°, 60°, 90° respectively for different linear configurations.

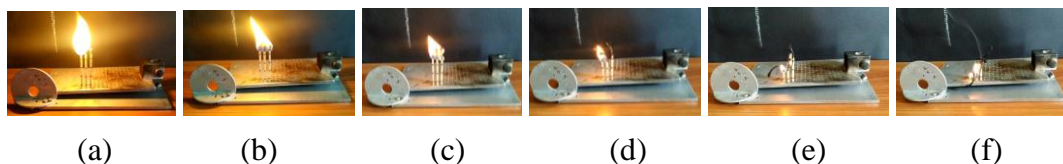


Figure 3: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for unilateral configuration (0°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec, (f) 50 sec.

Figure 3(a-f) shows the fire propagation and self-ignition effect for unilateral configuration at 0°. Looking at the images one can note the abrupt propagation with self-ignition of external energy source(s) resulting in a single large merged flame (figure 3(a)). With respect to time, the intensity of flame suddenly drops which directly reflects on the propagation phenomenon (refer figure 3(b)). Furthermore, the coupled flame dissociates and gradually converts into weaker singular flame with time (figure 3(d-e-f)). The case represents partially burning where propagation and self-ignition effect and was observed however, it was not strong enough to burn the entire configuration.

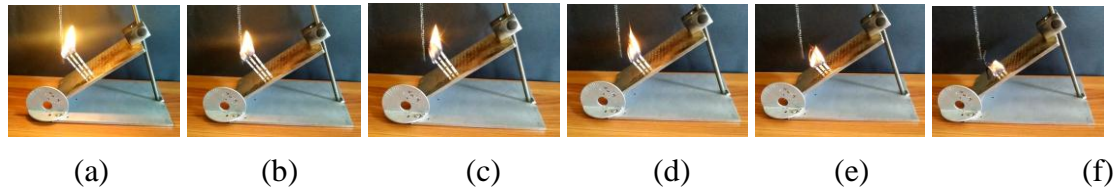


Figure 4: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for unilateral configuration (30°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec, (f) 50 sec.

Next, the effect of surface orientation was investigated as change in surface orientation brings severe difference. Figure 4(a-f) highlights the propagation and self-ignition effect at 30° . Strong propagation and self-ignition effect were noted with buoyant convection in the form of abrupt fire spread of external energy source(s) resulting in a single merged flame (figure 4(a)). With respect to time, marginal drop in flame intensity was observed which indicates weak propagation effects (refer figure 4(b-c)). It is fascinating to note that, the flame remains single, merged and results in well patterned propagation (figure 4(d-e-f)). One can note that, the merged flame for 30° is smaller than that of 0° . The case of 30° surface orientation characterizes total burning where propagation and self-ignition effect and were strongly observed and charred the entire configuration.

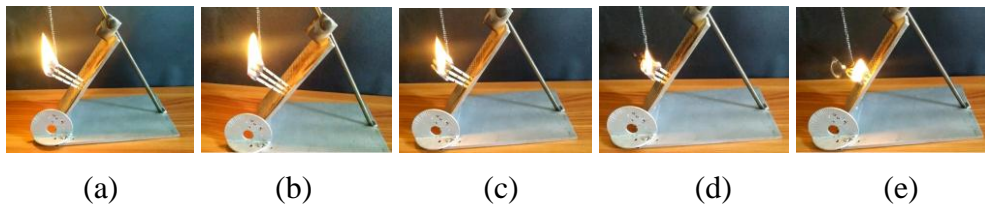


Figure 5: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for unilateral configuration (45°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec.

Significant changes were observed with further variation in surface orientation to 45° (figure 5(a-f)). Rapid propagation and self-ignition effect resulting in a single merged flame (figure 5(a)) was noted. With respect to time, marginal increase in flame intensity was observed which indicates cohesive propagation effects (refer figure 5(b-c)). It was exciting to note that, the flame remains single, merged and resulted in well patterned propagation (figure 5(d-e-f)) than 30° . One can note that, the merged flame at 0° represents the strongest of all merged flames. The case of 45° surface orientation characterizes total burning where propagation and self-ignition effect and were strongly observed and burnt the entire configuration thoroughly. Surface orientation of 60° represents modified case of 45° surface orientation (figure 6(a-e)). Looking at the images, one can clearly note the abrupt propagation and self-ignition effect ensuing a single merged flame (figure 6(a)). It is interesting to note that with time, marginal drop in flame intensity was observed which indicates condensed propagation effects (figure 6(b-c)). The flame remains single, merged and well patterned (figure 6(d-e)) and suddenly re-emerges as bigger flame after 30 seconds. The case of 60° surface orientation also symbolizes total burning case.

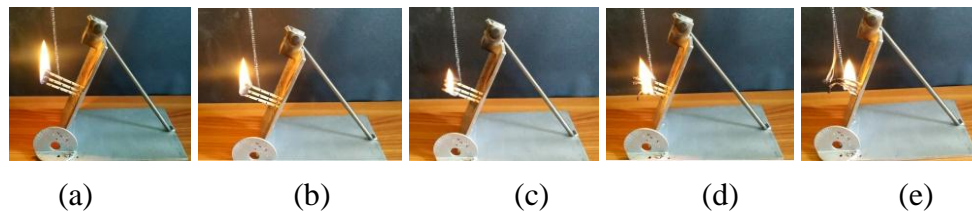


Figure 6: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for unilateral configuration (60°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec.

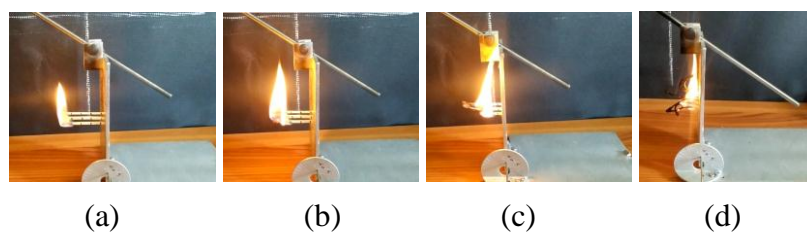


Figure 7: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for unilateral configuration (90°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec.

Surface orientation of 90° represents extreme case of abrupt fire propagation and self-ignition effect merging into a single, large flame (figure 7(a)). The vertical surface orientation represents highest flame height and strongest coupled flame. With time, increase in flame intensity was observed which indicates dominating propagation effects (figure 7(b-c)). The flame remains single, merged and well patterned propagation (figure 7(d)). The case of 90° surface orientation also represents total burning case. It is interesting to note that, the surface orientation strikes an important role in providing stability to the external energy sources with self-ignition and propagation effect which grows till vertical.

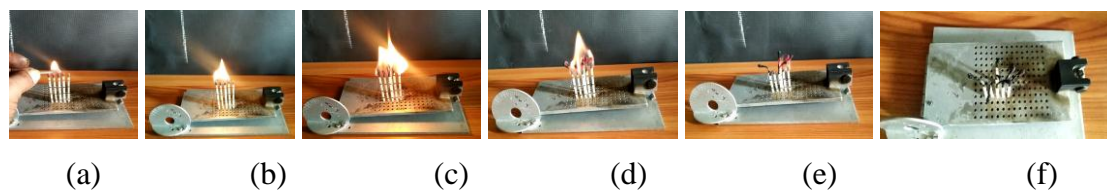


Figure 8: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for 'T' configuration (0°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec, (f) 50 sec.

Next, the behavior of fire propagation was observed upon 'T' configuration. The behavior of self-ignition and propagation effect is investigated with varying surface orientation and duly compared with 'Unilateral' configuration under similar conditions. Figure 8(a-f) highlights the self-ignition and fire propagation effect for 'T' configuration at 0° (horizontal). With ignition of pilot fuel (figure 8(a)), rapid self-ignition of external energy source(s) occurs resulting in a single merged flame (figure

8(c)). With time, the coupled flame intensity drops (figure 8(d)) leading to flame extinction and emerging as a flame extinction case (figure 8(e-f)). Similar to the 'Unilateral' configuration, 'T' configuration reports rapid self-ignition and consequently drop in flame intensity with time. However, the flame extinction effect is more adverse in 'T' configuration than in the 'Unilateral' configuration which reports partially burnt case.

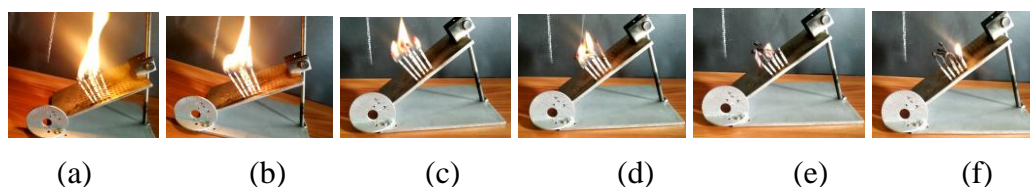


Figure 9: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for 'T' configuration (30°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec, (f) 50 sec.

Prominent effect of surface orientation was noted in 'Unilateral' configuration. However, in 'T' configuration as surface orientation was varied to 30° , distinct case of intermittent flame merging and de-merging was observed (figure 9(a-f)). Pilot fuel ignition results in abrupt self-ignition and flame propagation resulting in higher merged flame (figure 9(a)). With time, the coupled effect and flame intensity drops (figure 9(b)) and gradually shifting to local singular flame(s) (figure 9(c-d)). Furthermore, with increase in time the propagation slows down with fire extinction on most of the external energy source(s) (figure 9(e-f)). At 30° , 'T' configuration reports partially burnt case in comparison to the totally burnt case in 'Unilateral' configuration.

In addition, flame remains merged, single and drop in intensity is low in 'Unilateral' configuration whereas, 'T' configuration offers a completely diverse case with dual nature of flame merging and segregation. To understand the heterogenous behavior, the surface orientation was further varied to 45° , and figure (10(a-e)) shows the self-ignition and fire propagation nature with time. In comparison to the single, merged, well patterned flame with gradual drop in flame intensity representing totally burnt case, 'T' configuration signifies sudden emergence of single, merged flame with steady drop in flame intensity till significant time (figure 10(a-c)). After selected time (here, 30 sec), the drop in flame intensity rises however flame remains single and merged (figure (10(d))). It is interesting to note that, phenomenon of sudden re-emergence of large singular flames was observed with flame height higher than initial steady cases. The re-emergence leads to abrupt propagation and total burning of entire configuration (figure 10(e)). The case of 45° 'T' configuration details the fastest fire propagation effect noted.

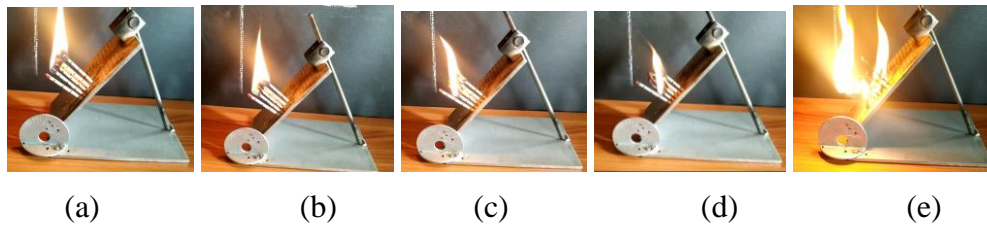


Figure 10: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for 'T' configuration (45°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec.

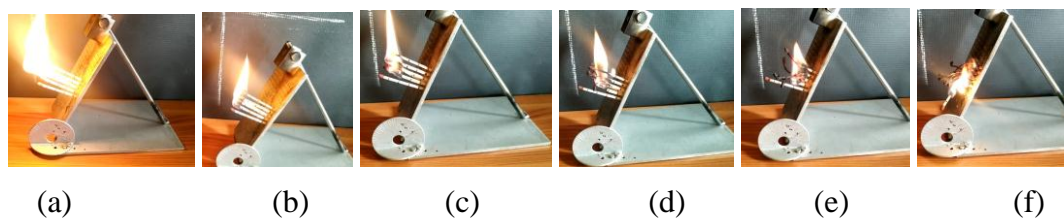


Figure 11: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for 'T' configuration (60°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec, (f) 50 sec.

'T' configuration at 60° (figure 11(a-e)) shows the case of potentially rapid self-ignition with acute drop in propagation effect with time. Pilot fuel ignition results in abrupt self-ignition of external energy source(s) resulting in a single, merged, larger flame (figure 11(a)). With increase in time, one can note sudden drop in flame intensity (figure 11(b)) which starts redirecting leading to re-emerging stronger flame and gradual drop in flame intensity with time (figure 11(c-d)). With further increase in time, the flame intensity drop rises however the flame remains single, merged and resulting in total burning case (figure 11(e-f)). In comparison to 45° case, both shows strong and abrupt self-ignition, sudden drop in flame intensity, and gradual propagation with time except the strong singular re-emergence. In comparison to the 'U' configuration, which represents steady self-ignition, propagation of a single, merged flame with gradual drop in flame intensity and finally resulting in a totally burnt case, 'T' configuration dictates distinct changes in fire behavior with abrupt self-ignition, sudden drop in flame intensity with is inconsistent.

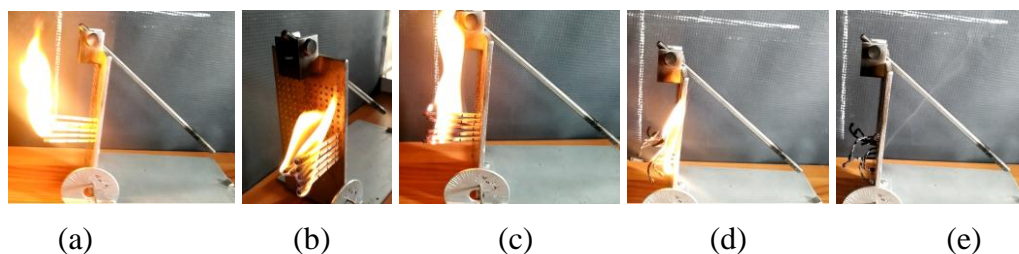


Figure 12: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for 'T' configuration (90°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec.

Vertical orientation case often represents concurrent flame spread resulting in stronger self-ignition and propagation effects. ‘Unilateral’ configuration detailed sudden merging, bigger flame and fast propagation and ‘T’ configuration matches the process (figure 12(a-e)). The pilot fuel ignition results in immensely stronger self-ignition effect with a single, merged, larger flame (figure 12(a)). The flame intensity drops with time (figure 12(b)) but, results in strong re-emergence of merged, coupled flame with greater flame height than other configuration and orientation (figure 12(c)). It is interesting to note that, with time the flame intensity drops again slightly without significantly affecting the flame structure and finally completely burns the entire configuration (figure 12(d-e)). In comparison to other surface orientations, 90° dictates strong buoyant convection effect resulting in a strong, merged flame without any sudden re-emergence or extinction. In comparison to ‘Unilateral’ configuration, the ‘T’ configuration dictates stronger propagation characteristics. It is important to note that, the noted changes in fire behavior do not adhere to surface orientation and configuration. Different configurations at same surface orientation may respond to similar behavior and similar configuration at varying orientation may result in distinct fire behavior cases which details the coupled role of both configurations and surface orientation.

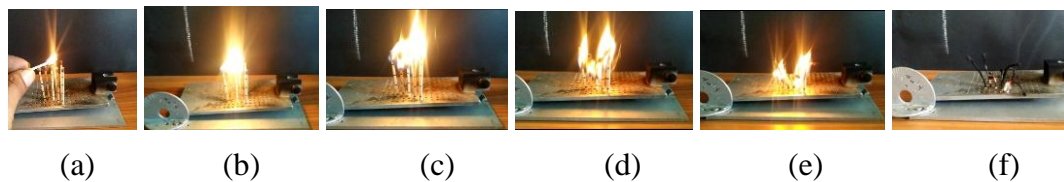


Figure 13: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for ‘Y’ configuration (0°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec, (f) 50 sec.

Trilateral or ‘Y’ configuration responds similar to the unilateral and ‘T’ highlighting the heterogenous fire spread behavior. Figure 13(a-f) shows the pictorial representations of ‘Y’ configuration for horizontal surface orientation (0°) with time. Looking at the images one can note that, the self-ignition and fire propagation effect responds in a distinct pattern. Post pilot fuel ignition, self-ignition effect results in a single merged flame (figure 13(a-b)). With time, the flame starts to disintegrate into localized singular flames (figure 13(c-e)). Under similar surface orientation conditions, ‘unilateral’ configuration results in well patterned single merged flame with slow propagation and partial burning whereas ‘T’ configuration shows enhanced fire propagation with single merged flame resulting in fire extinction. The flame intensity is modulated with sudden increase and decrease resulting in formation of localized flame zones which sustains till complete burning.

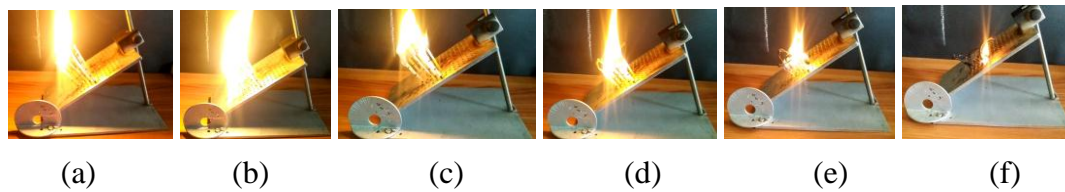


Figure 14: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for ‘Y’ configuration (30°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec, (f) 50 sec.

To understand the surface orientation effect, at 30° the self-ignition and propagation effect varies with higher flame intensity. Pilot fuel ignition results in abrupt self-ignition and propagation effect with formation of a larger merged flame (figure 14(a)). With time, the flame intensity rises initially as reflected in the flame height (figure 14(b)) and then drops gradually (figure 14(c-e)), eventually leading to the case of complete burning (figure 14(f)). It can be noted that, the surface orientation variation outcomes in larger coupled flame and faster propagation. Under similar surface orientation conditions, ‘unilateral’ configuration highlights single merged flame with low height, slow propagation resulting in a complete burning case however ‘T’ configuration indicates abrupt self-ignition, sudden dissociation of larger merged flame in localized flames and ending with partial burning. The flame intensity picks strongly and sustains consistently with marginal drop highlighting dominating buoyant convection.

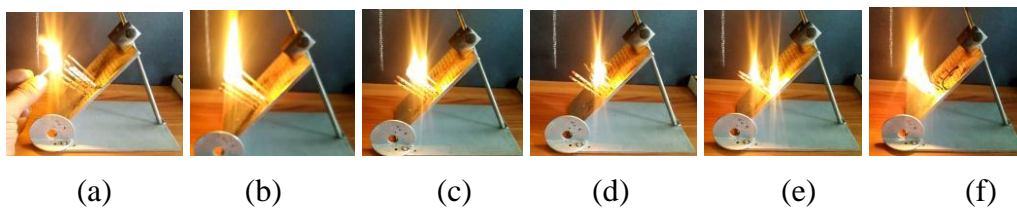


Figure 15: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for ‘Y’ configuration (45°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec, (f) 50 sec.

Further, at 45° surface orientation, partial self-ignition effect was noted with formation of single merged flame (figure 15(a)) and converges in a confined zone. With time, flame intensity first rises resulting in larger flame height (figure 15(b)) followed by the sudden drop (figure 15(c)) which drops suddenly (figure 15(d)). The energy transfer undergoes transition with formation of localized singular flames within the confined zone (figure 15(e)). It is interesting to note that, post zonal burning, the flame extends to the unburnt regions with final resulting in a complete burning case (figure 15(f)).

Under similar surface orientation conditions, ‘unilateral’ configuration results in a well patterned single merged flame with slow propagation resulting in a complete burning case however ‘T’ configuration shows abrupt self-ignition with larger merged flame and faster flame propagation and sudden dissociation in magnified localized flames ending with partial burning.

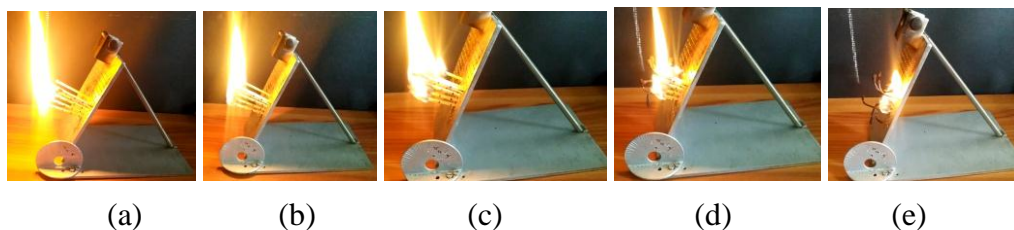


Figure 16: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for 'Y' configuration (60°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec.

The 45° case shows diverse nature of flame propagation with distinct changes in flame intensity within a localized zone and picking up in remaining unburnt zone in the end. 60° surface orientation marks the beginning of upward spreading effect with abrupt self-ignition and propagation which grows with time resulting in faster complete burning phenomenon (figure 16(a-e)) than at other orientations. It was detected that the higher flame intensity of the single merged flame sustains with time without any dissociation into localized flame zones. Under similar surface orientation conditions, 'unilateral' configuration shows similar abrupt self-ignition and propagation with sustained single merged flame with lower flame intensity however 'T' configuration responds with rapid self-ignition with modulated flame intensity resulting in rise and drop of flame height and ending with complete burning case. The 60° case shows the uneven pattern of most of natural phenomenon with sudden rise towards peak and consistent sustenance till the end.

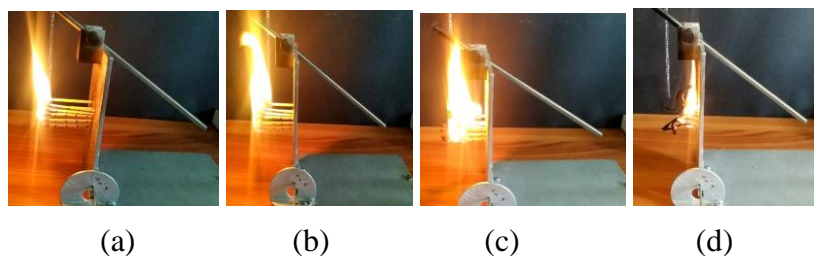


Figure 17: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for 'Y' configuration (90°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec.

Next, we look at special vertical surface orientation (90°). Figure 17(a-d) highlights the self-ignition and flame propagation behavior. Looking at the images one can note that, post pilot fuel ignition the upward spread intensifies in a larger merged flame (figure 17(a)). With time, the flame intensity rises and gains consistency resulting in faster complete burning case (figure 17(b-d)). Under similar surface orientation conditions, 'unilateral' configuration displays slow start of self-ignition and propagation effect which suddenly rises resulting in abrupt complete burning case with lower flame height however 'T' configuration retorts with rapid self-ignition in form of maximum single merged flame height with instable flame intensity. The 90° case shows the controlled upward spread effect with sudden rise to larger single flame which sustains with time with minimum fluctuations.

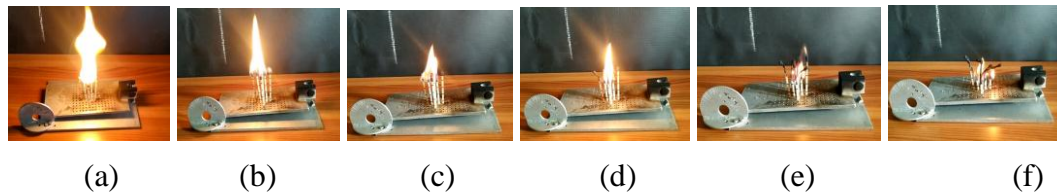


Figure 18: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for ‘+’ configuration (0°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec, (f) 50 sec.

To corroborate the heterogenous nature of self-ignition and fire propagation effect, systematic observation of ‘+’ configuration under similar conditions was carried out. Figure 18(a-f) shows the fire behaviour with time for horizontal surface orientation (0°). ‘+’ configuration represents rapid self-ignition and fire propagation with uneven energy interaction resulting in maximum flame height (figure 18(a)). With time, the single merged flame regains stability and flame intensity drops with height (figure 18(b-c)). Furthermore, the flame starts shrinking keeping outermost external energy source(s) unburnt (figure 18(d)) with rapid drop in intensity leading to

extinction (figure 18(e-f)) thus making it a case of partial burning. In comparison with other configurations under similar conditions, ‘unilateral’ configuration shows higher stability post pilot fuel ignition with formation of single merged flame in which flame intensity drops with time leading to partial burning case. ‘T’ configuration responds with lower energy interaction in the form of single merged flame which gains intensity with time and ending similar to ‘unilateral’ in partial burning case. ‘Y’ configuration represents the dissociation of single merged flame into localized flames however resulting in complete burning case. The horizontal surface orientation case details instability in self-ignition and propagation effect with turbulent rise and sudden drop in flame intensity.

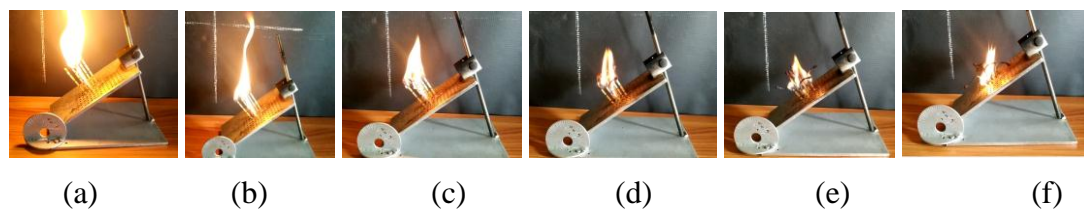


Figure 19: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for ‘+’ configuration (30°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec, (f) 50 sec.

Figure 19(a-f) shows the fire behaviour with time at 30° surface orientation. Looking at the images one can note, rapid self-ignition and fire propagation effect while covering confined region (figure 19(a)). With time, the flame intensity drops however, the flame extends to unburnt external energy source(s) and forming a stable single merged flame (figure 19(b-c)). The intensity of flame drops further though the flame remains single and merged eventually ending up as complete burning case (figure 19(d-f)). In comparison with other configurations under similar conditions, ‘unilateral’ configuration displays a slow, steady and single merged flame with

relatively lower height but burns completely. ‘T’ configuration retorts with rapid self-ignition and propagation effect along with formation of localized flames which drops with time leading to partial burning. ‘Y’ configuration represents the abrupt self-ignition and propagation effect with large single merged flame which remains consistent with time resulting in complete burning case. The 30° surface orientation case specifies the limitation of fire propagation effect in presence of external energy source(s) in terms of confined self-ignition. With time, the energy interaction leads to merged flame covering unburnt external energy source(s) however, the flame intensity drops.

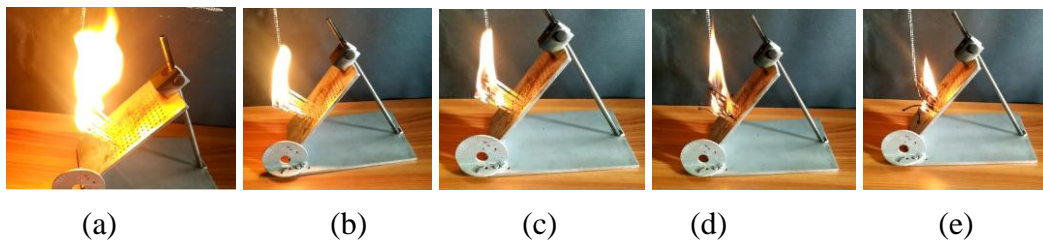


Figure 20: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for ‘+’ configuration (45°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec.

At 45° surface orientation, unlike other surface orientation cases, ‘+’ configuration results in abrupt self-ignition and propagation effect with single merged flame of maximum height (figure 20(a)). With time, the flame intensity fluctuates with sudden drop and rise as noted with flame height resulting in complete burning case (figure 20(b-d)). It was stimulating to note that the flame remains single and merged with no signs of dissociation. In comparison with other configurations under similar conditions, ‘unilateral’ configuration shows a slow, steady and single merged flame with complete burning whereas ‘T’ configuration presents intermittent self-ignition and propagation effect besides re-emergence of strong localized flames ending in complete burning however ‘Y’ configuration specifies the confined self-ignition and propagation effect with large single merged flame resulting in complete burning case. The 45° surface orientation case indicates strong self-ignition effect with gradual drop in flame intensity to a critical limit.

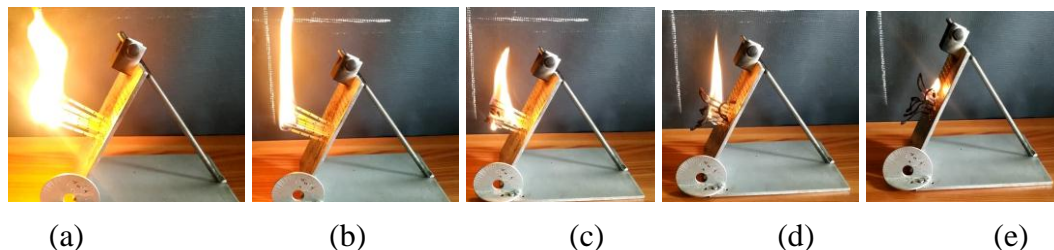


Figure 21: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for ‘+’ configuration (60°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec, (e) 40 sec.

60° surface orientation follows 45° but with gradual transition. Figure 21(a-e) shows pictorial representations of temporal variation of self-ignition and fire propagation behavior at 60° surface orientation. One can note rapid self-ignition and propagation effect highlighting unsteadiness in energy interaction (figure 21(a)). With time, the unsteadiness drops and flame becomes a single, merged, and longer (figure 21(b)) however, sudden drop in flame intensity follows (figure 21(c)) with drop in flame height. Further, the flame regains stability finally resulting in complete burning case (figure 21(d-e)). In comparison with other configurations under similar conditions, ‘unilateral’ configuration shows steady self-ignition, slow propagation with single merged flame resulting in complete burning. ‘T’ configuration represents rapid and confined self-ignition with steady fire propagation leading to complete burning however ‘Y’ configuration details usual upward spread effect with rapid self-ignition and fire propagation leading to faster complete burning. The 60° surface orientation case indicates the essence of instability with unsteadiness and re-emergence of steady fire behavior with time.

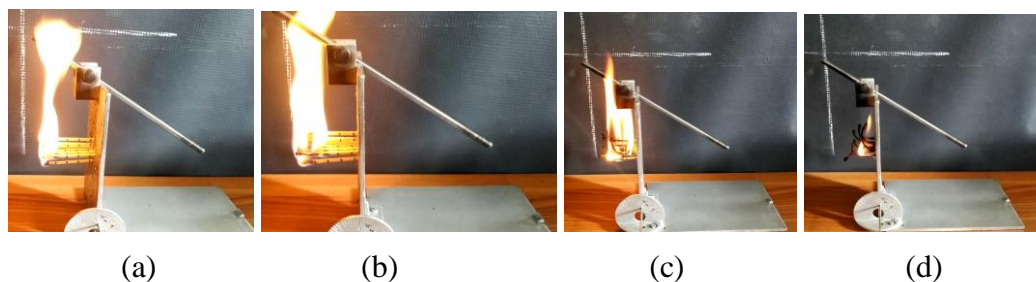


Figure 22: Pictorial representation of temporal variation of self-induced ignition and propagation phenomenon for ‘+’ configuration (90°) (a) 5 sec, (b) 10 sec, (c) 20 sec, (d) 30 sec.

For the case of vertical surface orientation (90°), ‘+’ configuration qualitatively corroborates with other configuration(s) in rapid self-ignition, fire propagation and faster burning leading to complete burning phenomenon. Figure 22(a-d) shows the behavior of fire propagation along with self-ignition effect. With pilot fuel ignition, upward fire spread depicts rapid self-ignition as a single merged flame which is uninhabited (figure 22(a)). With time, the unsteadiness in flame grows which results in faster propagation and increase in flame height (figure 22(b)). Gradually flame intensity drops reasonably however flame remains single and merged (figure 22(c)) thus leading to complete burning case (figure 23(d)). In comparison with other configurations under similar conditions, ‘unilateral’ configuration shows rapid self-ignition, and propagation which sustains. ‘T’ configuration represents abrupt unsteadiness in fire behavior which modulates with time. ‘Y’ configuration specifies usual rapid, consistent upward spread with rapid self-ignition and fire propagation leading to faster complete burning. The 90° surface orientation case details the instability and stability phenomenon interrelation in fire propagation with time. The effect highlights the instability with uneven energy transfer however the fire regains stability which further leads to instability. It is interesting to note that, instability in a natural phenomenon leads to stability and vice versa.

Conclusions

Systematic experimental investigation and qualitative analysis of the fire spread singularity was carried to understand the heterogenous behavior of fires in presence of external heat source(s). The study was motivated to gain true replication of the natural phenomenon, in different linear configuration(s). The primary aspect(s) observed was the self-ignition and fire propagation effect for different linear configuration(s) viz., unilateral, 'T', 'Y', '+' with pilot fuel ignition. Important information was drawn with parameters like flame structure, propagation pattern, changes with time. Based on the results obtained through experimentation and graphical analysis, following major conclusions can be drawn:

1. The investigation validates that in large scale fires, presence of external energy source(s) always exists in the form of heat source and heat sink effects observed with increased flame size and subsequent extinction.
2. Surface orientation plays a quintessential role in altering the fire behavior under different conditions resulting in cases of partial, complete burning and extinction. The effect can be noted in form of providing stability to the external energy source(s), rapid self-ignition and subsequently drop in flame intensity with time, dual nature of flame merging and segregation, modulated flame intensity with sudden increase and decrease resulting in formation of localized flame zones, instability with unsteadiness and re-emergence of steady fire behavior with time.
3. The horizontal surface orientation largely depicts cases with controlled self-ignition and fire propagation effect whereas, the vertical surface orientation case details the instability and stability phenomenon interrelation in fire propagation with time.
4. The reason for heterogenous nature may be attributed to the uneven energy transfer that is a result of self-ignition and propagation effect post pilot fuel ignition. As a uniformity, this outcomes in a single, merged flame for all configuration(s). The effect details the flame instability and mode of regaining stability with uneven energy transfer which further leads to instability marking that, instability in a natural phenomenon leads to stability and vice versa.
5. **Applications of the work:** To provide closed form solution to the fire safety related issues, it is imperative to understand the behavior and governing mechanism of the phenomenon. The physical insight from the present study can be very useful in understanding the nature of large-scale fires viz., forest fires, compartment fires, building fires, propulsive fires. This knowledge can be utilized to increase the control time, devise new fire safety equipments, in testing, validation and designing of existing system and engineering structures.

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