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Postulation of the VRMAMIK Conjecture in fire spread over thin solid fuels

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Abstract

Severe issues related to the fire-spreading phenomenon have led researchers worldwide to try different approaches for simplification. The increase in fire-related accidents has escalated the need for better operating solutions. One of the significant ways is to enhance understanding of group fires / clustered fires involving continuous heat and mass transfer. The work presents, experimental simulations conducted on transitional fire spread to improve knowledge of the spread of heterogeneous fires in both space and time. Homemade matchsticks were used as pilot fuel and external energy sources. Different configurations were tested, at varying surface orientations with a fixed number of external energy sources per direction. The effect and spreading phenomenon were observed in pilot fuel ignition and change in spreading rate with insight into localized and global burning. To gain true replication, experiments were conducted on dynamic models linear time-invariant (LTI), linear time- variant (LTV), and effect of spatial non-linearity was studied on non-linear dynamic models viz., NLTI (Non- linear time-invariant) and NLTV (Non-linear time variant) to determine spreading fire behavior and features. Additionally, important probable like, effect of phosphate was examined. The results were compared with single fuel burning to get better insight into external heat source and heat sink effect in both singular and coupled modes. The results reflect turbulent nature of fire spread and disorderly burning process. The spread rate analysis highlights distinct heat source and sink effect, uncertainty involved with collective burning along with combustion instability in form of irregular energy transfer. The results can be utilized in designing effective fire suppressants and retardants within given fire safety norms.

Keywords: Fire Spread Rate (FSR), Energy Transfer, Configurations, Surface orientation, External energy source, Heat Source and Sink effect.

1. Introduction

Unquestionably, one of humanity's greatest discoveries is fire, which has continuously fueled human evolution. Engineering, real world, industrialization, and operational systems across a variety of sectors have all advanced magnificently as a result of the effective application of fire. However, as a consequence, fire has also been the biggest source of disasters in the forms of extensive propulsive fires in aircraft and rocket crashes, forest fires, industrial fires, and building fires, leading to an immeasurable decline in nature, resources, humanity, and large sums of money are invested annually on scientific study to halt them. (refer figure1). Fundamentally fire spread is diffusion flame propagating parallel to the surface and fires are widely classified as opposed flow fires and concurrent flow fires. This classification is based on the direction of the air concerning the direction of fire spread. In concurrent/upward flow fires, fire spreads in the direction of air whereas in opposed flow, the propagation is against the direction of air making it slow, steady, and easy to analyze. As per the heat transfer theory, fire spreads owing to continuous heat transfer from burning to the unburnt region, also known as forward heat transfer. Fire spread rate is the rate at which fire spreads over combustible surface and is one of the key measurable parameters. Fires are normally encountered as stationary (e.g. burners) and propagating. 60% of the fire accidents occur due to uneven energy transfer. There’s been a significant increase in structured fire losses up by 10.7 billion (USD) including 8.5 million acres of forest land burned with consistency in aircraft and rocket crashes, causing irreplaceable loss of mankind (Thousands) with an annual rise of 77% (*NFPA). The primary concerning fact about propagating fires is that there’s no closed-form solution available to detect, prevent, and suppress them, which is universally acceptable. As per fire research, it is impossible to remove all external energy sources in propagating fires. The presence of external energy sources in the form of heat sources and sinks is expected to significantly affect the energy transfer process by altering forward heat transfer and resulting in transformed spread behavior and flammability.

Heat sources are the primary reason for most of the sustaining fires and their presence is understood with an increase in maximum temperature, large temperature gradients, with shifting of maximum temperature zone. They are the potential source of the deadliest fires, causing severe loss of Mankind. Similarly, Heat sinks are widely understood to significantly affect pilot fuel combustion with a reduction in burning rate and suppression. They are the potential source of some of the biggest system failures, incomplete combustion resulting in heavy economic losses. Primarily, the heat source is identified to supply energy and a heat sink is expected to drain energy out of the system. Some of the selected reasons for the inability to resolve uneven energy transfer include difficulty in gaining true replication, challenges in designing a testing facility with structural integrity, inept safety provisions to protect against destructive unplanned accidents, and the influence of coupled external heat source and heat sink effect on burning rates is not studied comprehensively. As a result, simulations of fire effects are particularly sought after due to the hazardous nature of this occurrence. Simulating natural processes like fire is still challenging owing to instability and transitional nature. Virtual reality effects are also interested in fire simulations, for instance, to help educate firemen or to figure out where evacuation signs should be placed in smoke-filled rooms. Environmental geometry, fuel availability, and

(a)

(b)

(c)

(d)

Figure 1: Pictorial representation of (a) Aircraft fires, (b) Rocket fires, (c) Building fires, (d) Forest fires (**www.google.com*).

When discussing fire, ‘fuel’ refers to any flammable substance that is available for burning. Varied fuels have varied sizes, loads, and whether or not live tissues are present. Fire forecasting behavior is among the most crucial duties needed to run decision support systems for fuel and fire management. The main purpose of characterizing and modeling fuels for the majority of the 20th century was to forecast fire behavior, particularly the flame length, and rate of spread in surface fuels. Despite their continued value to fire managers, they fail to adequately capture the true unpredictability of the burning phenomenon. The rate of ignition and facility to burn, or combustibility rate, are both utilized to assess the possible impact of a fire. Systems that are frequently complex and extremely changeable can be viewed in simpler ways with fire models. A model is a database of crucial fuel characteristics utilized to evaluate the risk of fire and forecast its behavior. The models were conceived of as a set of consistent and formalized inputs for use in the spread model across the range of fire behavior. These fuel models comprise of initial 13 fuel models published by Anderson (1982). Similarly, a fuel bed is a group of physical fuel characteristics that describe specific fire settings and have been measured or averaged. The intrinsic physical properties of fuel that influence fire behavior and effects are referred to as a fuel bed by FCCS (Fuel Characteristic Classification System). Numerous qualitative and quantitative characteristics define fuel beds., with focus on traits that are essential for planning fire behavior as well as managing fuel. Resource managers can assess operations and management activities as well as fire hazards at both small and large spatial scales by employing fuel beds. Managers of air quality, ecologists, and carbon balance modelers have grown more and more interested in understanding attributes of fuel beds through investigation and description of spatial fuel property layers. Fuel classification is foundation of all fire behavior and consequences, its consistent and scientific application serves as essential for danger assessment evaluation, fuel mapping, and fire effects monitoring. Thus, structure and diversity of flames in and around fuel bed are essential to igniting and preheating process. Therefore, knowledge of transitional fire ignition and propagation phenomenon is essential to reducing fire-related problems. Based on Baldwin's (1968) seminal work on flame merging in many flames. According to laboratory experiments, size of flame front might have major impact on how rapidly fire spreads (Anderson, 1968). Flame fronts of different widths could be related through configuration factor of particular flame form. An analog method for finding down configuration factor of an unevenly shaped flame and impact of flame height and width on spread rate have been discussed in work. (Huffman et al.,1969) emphasized interplay and impact of several fires from nearby liquid pools on fuel's flame size, rate of combustion, and rate of heat transmission from flame to environment. The paper presented few experimental investigations of gaseous fuel-based interaction fire effects. (Rothermel, 1972) created mathematical model that can be employed to predict intensity and rate of fire spread for variety of wildland fuels. A theoretical and experimental investigation of variables affecting rate of combustion between two vertical parallel fuel surfaces facing each other was published (Kim et al.1974). Grashof number times channel aspect ratio (half-channel width divided by length) was discovered to regulate burning rate while equations were numerically solved. The work emphasized that Burning rate is unaffected by channel length in very long, narrow channels, and for wide channel separation, it's independent of channel separation distance. A positive agreement was found between experimental data and theoretical results. Anderson (1982) emphasized that when it involves mathematically modeling fire behavior and fire danger rating, choosing right fuel model is essential. The study reported photographic examples and tabulations when determining a fuel model for a given circumstance. The guide facilitated comparison with fire danger rating fuel models thereby making it easier to choose appropriate fire behavior fuel model. A similarity chart was employed for comparing 20 fuel models of NFDRS with thirteen fire behavior fuel models. (Weber, 1991) outlined necessary components for creating mathematical model of fire spreading across a fuel bed that were reviewed. According to main theoretical and experimental explanations in literature, buoyant convection which is extremely challenging to predict employing basic fluid dynamic equations is missing component for fire spread in still air. According to paper, turbulent transport via eddies could prove beneficial, leading to flame spread rates that are dependent on fuel bed's eddy diffusivity values. A multiphase method had been applied by (Porterie et al.,2000) to simulate spread of line fires fueled by wind through fuel beds. Mass, momentum, as well as energy exchange terms were employed to illustrate coupling between solid and gas phases, and set of time-dependent equations were derived for each phase. Discrete ordinates method (DOM) was implemented to solve radiative transfer problem. The processes for pyrolysis, water vaporization, and char burning were described via first-order kinetics. A high-order upwind convective scheme employing a finite-volume approach as well as projection method for pressure–velocity coupling was utilized to solve problem numerically. Induced hydrodynamics and wind-aided flames spreading throughout litter of dead pine needles were described by model's unstable behavior. Research on fire spread has been performed by (Nahmias et al.,2000) employing variety of full-scale and laboratory models with a range of flammable and nonflammable materials. It investigated how flame front and extinction behaved dynamically in randomly generated heterogeneous zones with and without wind. The analysis found that there are key thresholds for ratio of flammable to nonflammable components at point where fire moves from not spreading to spreading. In nonwind-driven studies, critical threshold values matched those predicted by percolation theory. The vectoring of slope and wind impacts on flame front was examined by (Viegas, 2004). The laboratory tests were contrasted with mathematical vectoring techniques. Multiple typical fire spread directions were introduced. A 30° slanted fuel bed has been employed in experimental laboratory study to examine how point source flame fronts were affected by changes in wind direction and velocity.

According to (Romme, 2005), frequency of fire effects varies greatly throughout a variety of temporal and spatial scales. From systems with regular, low-severity fires to systems with occasional yet stand-replacing fires, geographical features lead to a variety of fire regimes. Finer-grained, fire ignition under a moderate range of meteorological circumstances is influenced by spatial heterogeneity in fuel quantity and structure. According to reports, every fire event has different pattern of burning and produces range of fire intensities in burned region, thus leads to spatially varying energy and biogeochemical processes. The work suggested need to address pressing research concerns regarding spatial patterns in fire history, fire consequences, and reactions to geographical variability of fire, as well as to better integrate an understanding of spatial heterogeneity into fire management. (Ricardi *et. al.*, 2007) investigated fuel bed characteristics temporally and spatially. To capture the variability, Fuelbeds were created and categorized according to their ability to support fire and burn fuels utilizing FCCS Fuelbeds were considered homogeneous units, illustrating various combustion conditions that influence the behavior and consequences of fire. A number of qualitative and quantitative physical and biological factors had been employed to characterize fuel beds, with focus on traits that are valuable for managing fuel and planning fire behavior. At both small and large spatial scales, this system enables resource managers to assess fire threats, management efforts, wildland fuel operations, and effects on environment and air quality. According to (Finney and McAllister, 2011), existence of another fire nearby can significantly alter characteristics of a wildland fire. Although pertinent in many circumstances, study reviewed specific consequences of fire-fire interaction in terms of merging, pulsation, burning rates, temperature, indraft velocity, flame diameters, and convection column dynamics. Additionally, it was emphasized that spot fires that develop earlier main fire as well as convergence of distinct fire events in one area are examples of how fire-fire interactions naturally occur. Spatial ignition patterns can also be deployed to strategically create interactions during managed fires. To examine impact of distance between distinct fuel elements on upward flame spread rate, experiments were conducted on vertical arrays of horizontal wood matchsticks organized from one to five (Gollner et al., 2012).

To determine the impact of separation distance on upward flame spread rates which are determined by advancement of ignition front, time to burnout, and mass-loss rates vertical spacing between matchsticks in the array was varied.

For arrays closest to each other, the ignition front's advancement varied linearly with time, whereas for arrays farthest apart, it advanced with time. For spacings ranging from 0 to 0.8cm, upward flame spread rates were shown to rise significantly. These findings led to the hypothesis that convective heating dominated this spreading mechanism, and convective heat-transfer correlations have been employed to forecast igniting timings. Except for the zero-spacing example, which was over three times longer than in spaced arrays, individual matchstick burnout times were found to be almost constant for all cases at all heights. The droplet burning theory was used to model this behavior in spaced circumstances. The zero-spacing scenario was compared to vertical combustion over a wall u employing a similar computation. (Liu et. al., 2013) conducted experiments to examine, through analysis of burn-out time data, spatial distributions of burning rates in group fires of many fire sites. To identify the geographical locations of fire sites and investigate intricate spatial variations of burning rates under various situations, a novel concept known as the "fire layer" was established. Analysis revealed that there are several nonlinear modes in which the inner fire layer burns at a different rate than the outer. This suggested that different spatial fluctuations in fire arrays are involved in two fire interaction effects, heat feedback increase as well as air supply restriction.

Fire spacing and fire array size had been two main parameters that had a substantial impact on the spatial variations of 2 impacts of interaction. Spatial fluctuations and intense competitiveness of two interaction effects were identified as distinct spatial regions and parameter ranges. All fire layers' average burning rates were shown to exhibit regular fluctuations with respect to fire array size or fire spacing. It was discovered that average burning rates for each fire layer change linearly with fire area ratio when fire spacing gets changed. Furthermore, Analysis revealed that when fire merging occurs, it causes considerable impact on burning rates of all fire layers. Lastly, novel method for simulating spread of fire across distinct fuel sources was introduced, demonstrating beneficial impact of the nearby new fire sites on the initial ones' rates of combustion. External heat source orientation was tested on smoldering in both modes by (Tiwari et al.,2016). A physical understanding of phenomenon of heterogeneous heat transmission in smoldering combustion over thin solid fuels was evaluated. Main goal of study was to comprehend how smoldering combustion is affected by an external heat source. Sticks of incense were utilized as external heat sources while as possible fuel. The study shown that when an external heat source is positioned parallel to pilot fuel in both forward and reverse modes, heat transfer is significantly increased. With different surface orientations and external heat source distances from pilot fuel, results showed a considerable divergence of heat transfer. An external heat source significantly exacerbates combustion's transition from blazing to smoldering. Continuing discussion, (Tiwari et al.2017) examined relationship between thermal and acoustic energy and its consequences for smoldering combustion. Forward heat transfer is reportedly greatly enhanced by thermoacoustics interaction at different source separation distances. Whereas the closest placement of sound source had least amount of acoustic influence, intermediate location produced the most. Two separate zones were created according to location of external sound source, showing a sharp increase for upward and downward spread and no effect. According to (Aljerf and AlMasri, 2018), two independently generating heat components—one of which is inexhaustible and other is exhaustible through an autocatalytic reaction—are necessary for ignition in a self-heating solid system. The exhaustible component's ability to raise temperature determines ignition. A theoretical model for typical instances of ignition and self-heating was the aim of effort. The model's ignition criterion was demonstrated to have high degree of realism, and it was discovered that model could accurately forecast ignition based on primary kinetic and temperature data. Analysis of both adiabatic and non-adiabatic flame theories revealed that only in unique circumstance that a heat sink is present at the beginning temperature can a steady state be reached, and in typical situation of freely propagating, non-adiabatic flames, only a quasi-steady state can be reached. The forced flow-driven flame spread behavior along a range of wooden fuel elements was experimentally studied by (Giovanni et al., 2021) in order to comprehend flow-flame interactions that control fire spread. Five distinct fuel array spacings (0.75, 0.875,1.00,1.125, and1.25cm) were exposed to flow rates between 2.2 and 4.3m/s at intervals of 0.2m/s. In a flammability map, flame spread behavior was divided into three distinct regimes: discrete, continuous, and quenching. Evolving flame behavior and growing discretization of overall flame structure as flow speed rises were described visually from video data. The start of flame instabilities and quenching was shown to be correlated with Stanton number (St), Damkohler number (Da), and fluid mechanics and heat transport conditions. Following this (Hussain et. al., 2021) investigated Advanced combustion strategies for increasing fuel efficiency by focusing on one of the common industrial techniques for controlling combustion instabilities. The experiments were carried out on a laboratory-scale bluff-body combustor consisting of a centrally located conical bluff body. Three different secondary gases, ethylene, hydrogen, and nitrogen, were added locally to turbulent imperfectly premixed ethylene flames. The heat release fluctuations were determined, while the velocity perturbations were estimated from pressure measurements. The results showed that hydrogen was the most effective in reducing the magnitude of self-excited oscillations. Nitrogen had negligible effect, while ethylene only showed an effect at high secondary flow rates which resulted in sooty flames. (Nemitallah et. al., 2022) analyzed premixed oxy-methane flames for nine different cases in a Dual-Stage Lean Premixed (DLPM) combustor for gas turbine combustion applications. The combustor consisted of two streams, a primary central stream and a secondary annular one swirling in opposing directions.

For all cases, the oxygen fraction was fixed at 30%, and the equivalence ratios (φ) of the primary and secondary streams were varied to 0.9 and 0.55. Three different velocities were investigated for the primary central stream, and for each primary stream velocity, three different secondary velocities were considered to explore flow/flame interactions. The results showed that for all primary flow velocities, decreasing the secondary flow velocity led to the flame becoming thin and slightly elongated. The zone of peak local temperatures was concentrated in the flame core downstream of the center body near the primary flow inlet. Stable flames with reduced emissions were obtained over a wide range of inlet velocities indicating the effectiveness of the combustion approach for wider operability of gas turbine combustors. (Ribeiro et.al.2022) carried conducted a number of tests to examine how two parallel fire lines interact with a level, sloping fuel bed when wind is present. The fire spread that followed was detailed following the initial separation of two fire lines by 1.2meters. The findings demonstrated that rate of spread of approaching fire lines and their related properties were altered by the pyro-convective interaction between two fire lines and ambient wind. Using the dynamic interplay between two parallel fire lines in presence of wind, physical understanding of fire evolution was put forth. Considering impact of fuel structure on flame spread via porous fuel beds, experiments were conducted to assess effectiveness of Rothermel model (Campbell-Lochrie et al.,2023). Fuel structure's impact on physical processes underlying surface flame spread was considered when making this decision. To assess impact of fuel composition on predictions of the Rothermel model of spread rate and response intensity, study employed an existing dataset of flame spread tests in pine needle beds. Results showed that spread rate for compressed fuel beds was underestimated, primarily due to an underestimate of reaction intensity. It was determined that more knowledge was needed on the impact of fuel structure on energy release in the firefront area. Numerically, (Eftekharian et. al., 2023) investigated aerodynamic characteristics of wind enhanced by bushfires. The study reported the effects of fire source asymmetry on aerodynamic changes of wind by fire using a large eddy simulation analysis based on the fireFoam solver of the OpenFOAM platform. The results revealed that deviation from fire source symmetry resulted in asymmetric behavior of counter-rotating vortices where the maximum cross-sectional wind enhancement occurs. (Li et. al. 2023) devised a simple and effective method to construct a discrete flame spread model. This work was driven by the research of 2-D horizontal discrete flame spread behavior with different spacings and rows. The burning characteristics of the discrete flame spread were experimentally studied with six different row numbers (1–11 with an interval of 2) of cylindrical dowels (birch wood, 3 mm diameter × 50 mm height) under three selected spacings (6, 7, and 8 mm). Based on the heat transfer model developed, the correlation between dimensionless flame height and dimensionless heat release rate for the horizontal discrete flame spread scenario was established.

(Hamdan et. al., 2024) contributed to flame inhibition by focusing on the role of nanomaterials, like aluminum oxide (Al_2O_3). The study provided insight that nanoparticles merge two flame inhibition techniques: cooling and physical barriers and offer unique properties due to their small size and high surface area, which enhance their usefulness in disrupting the combustion process. It was highlighted that nanoparticles can act as heat sinks and can also catalyze the formation of noncombustible gases on the material's surface. Experiments were carried out within a pressure range between 3.2 and 5.3 cm of Hg, corresponding to a fuel-oxygen ratio of 9.3 % to 14.8 %, respectively. The results revealed that Al_2O_3 as a fire inhibitor provided a more enhanced impact of fire retardance compared with conventional retardation materials, and less adverse environmental effects. The study concluded that adjusting nanoparticle concentrations can significantly alter inhibitory effectiveness. In recently, In recently, (Wu et. al. 2024) addressed the significant fire hazards associated with using thermoplastic materials by employing a methodology that combines small-scale experiments and theoretical analysis. The study investigated the impact of material width on the behavior of discrete flames in open spaces, using specimens ranging from 5 to 10 cm in width. The findings showed that an increase in specimen width affects the burning area, while the dimensionless flame height and heat release rate per unit width display a negative power law decay with increasing width. This suggests that beyond a critical width, further increases in width have little influence on flame propagation. Although the aforementioned scientific contributions have led to the formation of a remarkable arrangement for tackling the challenges at hand, a thorough comprehension of issues has been hindered by the presence of heterogeneous heat and mass transmission. Current work increases critical understanding of large-scale propagating fires for safety and resourceful utilization under varying conditions to achieve effective applications by introducing beneficial bodily awareness. The goal of project is to advance safer, more advanced fire-resisting technologies and to improve fire safety. Alongside work are certain significant goals, such as:

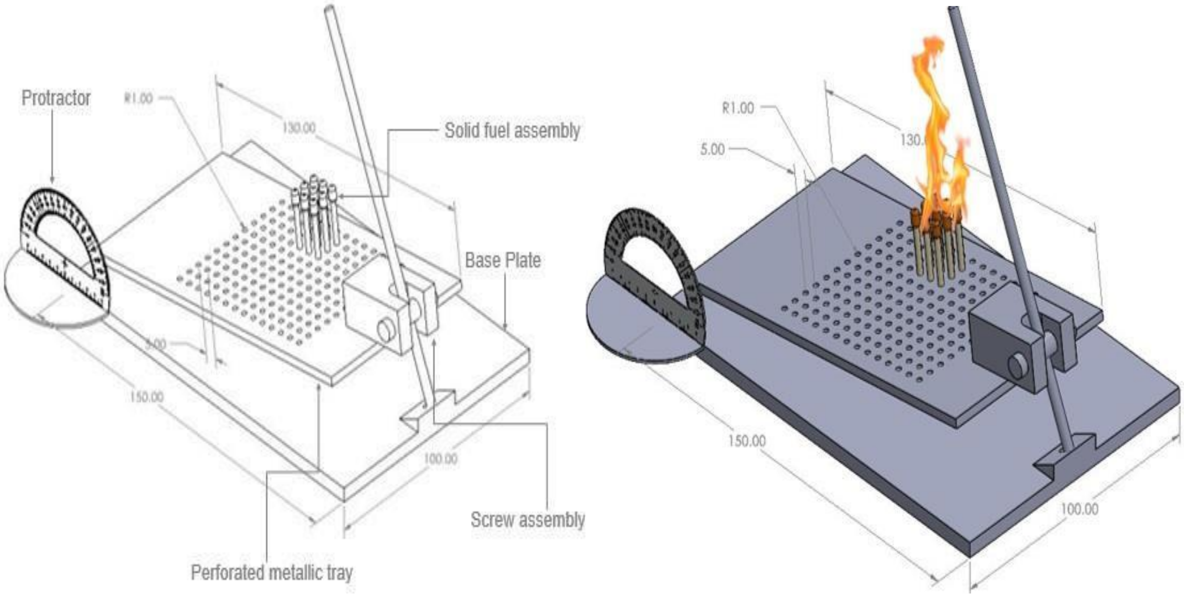
I. To explore fundamentally effect of external energy sources on the burning of pilot fuel and make appropriate application-related deductions.

II. To predict the energy transfer for both linear and non-linear spatiotemporal design configurations in pilot fuel ignition and external heat sources.

III. To understand the role of key controlling parameters and establish appropriate co-relations between them.

2. Experimental Setup and Solution Methodology

For investigation, a straightforward experimental setup (figure2(a and b)) was designed. The experimental setup consisted of a) a metallic base plate, b) a perforated metallic tray, c) a protractor, d) a screw assembly, e) a solid fuel to comprehend the function of important controlling factors and create suitable correlations between them, assembly as pilot fuel, and an array of external energy sources (labeled homemade match stick), f) stopwatch with least count of 0.01 sec and accuracy of ± 0.1 sec (used to measure the split times) and g) camera (for optical shadowgraphy) (refer figure 3).



(a) **(b)**

Figure 2: Schematic of the complete experimental setup (a) component-wise description, (b) graphical representation.

(a) (b) (c) (d) (e)

Figure3: Pictorial representation showing(a) experimental setup (b) labeled pilot fuel and external energy source,
(b) butane-gas lighter as ignition source, (d) camera, (e) stopwatch.

The design comprises a metallic base plate attached to a movable perforated metallic tray with provisions for testing at different surface orientations. The surface plate of setup has a [15 x 15] matrix of equidistant holes placed 0.5cm from each other. The setup was so designed that the burning of matchsticks facilitates transitional fire spreading with fast ignition owing to phosphate at the start and retardation in spreading due to plate surface at the end. All matchsticks including external energy sources and pilot fuel were labelled 4 sections of 1cm and an initial 0.5 cm post ignition was reserved for flame to regain stability.

Table1. Sample specification and marking.

Sample Specification	
Fuel-Material	Matchsticks
Test Bed	Wooden Table
Scale	Made by using black pen
Total Height	4.5 cm
Total Width	0.2 cm
Scale least count	0.01 cm
Markings	
First 0.5 cm	Flame Stabilization
Next 1 cm Three markings (1 cm each)	Spread rate measurement
Last 1 cm	For clearance

The measurement was carried out on the remaining 3 sections with a spread distance of 3 cm (table 1). The experimental setup provides provision for thoroughly investigating heterogeneous fires in appearance of external heat sources along with measurement of initial, average, and instantaneous spread rate variation with propagation in spatial and temporal domains.

The external energy sources (matchsticks) could be arranged in various configurations and kept at different orientations ranging from 0 to 90 degrees.

The rate at which the surface burns is called the Flame spread rate which is linearly calculated as:

$$\text{Spread rate}, r = \frac{Distance\ burnt\ along\ the\ matchstick\ surface\ (3\ cm)}{Time\ taken\ (to\ burn\ 3\ cm\ of\ matchstick)} \quad (1)$$

Forward Heat Transfer Theory

From Energy Equation 2nd form

Net Energy = Energy Generated – Energy Lost.

Flame spread rate (r), as determined by Classical Forward Heat Transfer Theory, "is

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

(2)

where,

q_{net} :Total Energy (difference between the energy generated and the energy lost) ρ_s :Density of the solid fuel
τ_s :Thickness of the solid fuel $T_{Surface}$:Temperature of the surface
T_∞ :Temperature of the surroundings cs :Specific heat
r :Flame spread rate.

Conventional theory of heat transfer over solid fuels states that the propagating front moves upstream from burning solid fuel to unburned solid fuel via heat feedback, or forward heat transfer. Spread rates rise or drop as a consequence of this (refer to equation 2). Across fuel surface, localized velocity, temperature fields and convective buoyant movement evolve. High-temperature smoke contributes extra energy and preheating by carrying heat parallel to fuel surface. Thermodynamically, experiments were performed with a Primary system (Pilot Fuel) and a Secondary System (external energy sources), and the effect was understood in form of Primary system ignition and spread rate. To get a better understanding of data, a non-dimensional number Spread Rate Coefficient(Ψ) was defined and its variation was investigated to understand the related energy transfer.

$$\psi = \frac{Spread\ rate\ in\ presence\ of\ external\ thermal\ energy\ sources}{Flame\ spread\ rate\ of\ pilot\ fuel\ without\ any\ external\ sources}$$

The Spread rate coefficient (Ψ) signifies the nature of the Secondary System (set of external energy sources) and details the thermal energy transfer as:

'Ψ'>1: Heat Source Effect 'Ψ'=1: Neutralizing Effect 'Ψ'<1: Heat Sink Effect

The outcomes were grouped into three zones.

1) Heat Sink Zone: indicates that existence of other energy sources has reduced pilot fuel's flame spread rate; as a result, we can say that secondary system functions as heat sink. Owing to reduction in concentrated temperature around pilot fuel, heat transfer in this regime decreases. The explanation for this is that there isn't enough oxygen to burn the pilot's fuel. Spread rate in this instance is therefore lower.

2) Neutralizing Zone: signifies that pilot fuel's rate of flame spread has not changed because of presence of external energy sources. In this situation, secondary system functions as neutral system. The single pilot fuel has the same heat transfer in this zone. The spread rate is same in this instance as it was in pilot fuel base example.

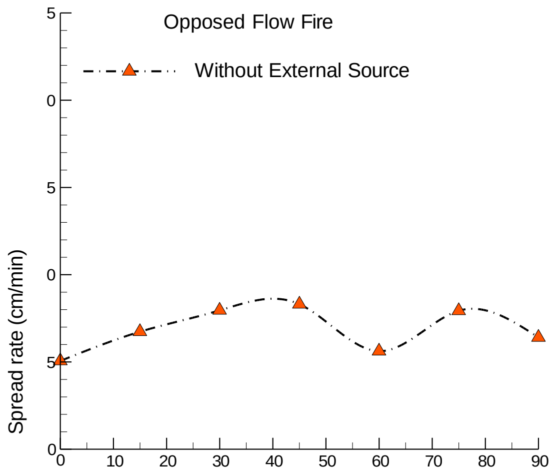
3) Heat source zone: This zone is dominated by accumulated heat transfer due to buoyancy, that transports heat from secondary system to primary. Consequently, in this case, primary system has a greater spread rate. This signifies that flame spread rate has increased due to presence of external energy sources. The secondary system acts as a heat source within case.

It is significant to remember that experiments were conducted at standard room temperature. The third order repeatability and reproducibility are ensured and the data presented carry a ±2% error margin.

3. Result and Discussions

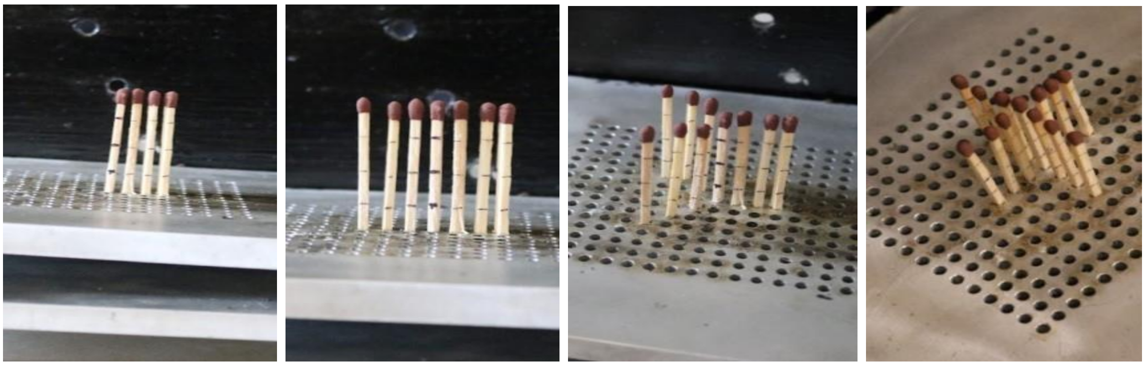
3.1 Base Case

Initial experimentations for a single fuel spread rate with variation in surface orientation were carried out. Figure 4 exhibits a comprehensive variation of spread rate to surface orientation. A non-monotonic trend with a maximum of **8.3 cm/min** at **45°** and a minimum of **5.0 cm/min** at **0°** was observed. This validates experimental setup predictions reasonably well with the conventional heat transfer theory and preceding research work(s) [17,18]. Indicating that experimental setup predictions are likely to offer good physical insight into the propagating fire propagation phenomenon. The single fuel values were used as reference for comparison.



Surface orientation (Degrees)

Figure 4: Variation of downward flame spread with surface orientation for pilot fuel without an external source.



(a) (b) (c) (d)

Figure 5: Pictorial representation of different “configurations for n=3 - (a)Unilateral, (b)Bilateral, (c)Trilateral, (d)Quad-lateral

3.2 Classification of array arrangement / Dynamic models

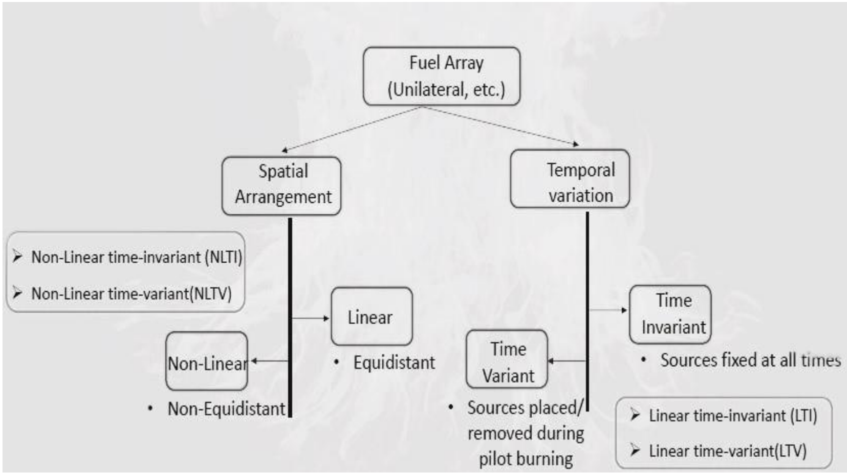


Figure 6: Graphical representation of classification of different dynamic models.

In an attempt to gain the true replication of the natural phenomenon, one approach that is yet to be applied is experimenting with the placement and availability of the external energy sources. In the methodology devised, the entire testbed was divided into two thermodynamic systems comprising of the pilot fuel (Primary system) and array of external energy sources (Secondary system) to understand the thermal energy interaction between them. The secondary system was divided into different directional configuration(s) viz., Uni-lateral, Bi-lateral, Tri-lateral('Y'), Quad- lateral ('+'), classified as per (2π/nd) with 'nd' referring to the number of directions for configurations and number of external energy sources per direction 'n' as 3 for all cases (refer figure 5). Experimentation was initiated with pilot fuel ignition and the collective effect on pilot fuel burning was noted with a detailed analysis of self-ignition, and propagation effects due to the presence of external heat sources at varying configurations. The experiments were conducted in both spatial and temporal domains. The spatial domain indicates placement of external energy sources as Linear (equidistant) and Non-linear (non-equidistant). The temporal domain indicates availability of external energy sources as infinite and limited by selected time. Four unique dynamic models were designed as LTI (linear time invariant), LTV (linear time variant), NLTI (non-linear time invariant) and NLTV (non-linear time variant) for investigation to provide better insight into the spatial (placement) and temporal (availability) effect of external energy sources on fire spreading (figure 6). The experimental simulations were carried out on different configurations at varying surface orientations and notable cases of partially burnt, completely burnt, and extinguished external energy sources were analyzed.

3.3 Effect of Phosphate on irregular energy transfer

The matchsticks carry phosphate in the beginning for ignition, which is likely to affect the spreading process. To assess phosphate's impact on pilot fuel combustion and external energy sources, a distinct study was carried out on Quad-lateral configuration on Linear Time-Invariant (LTI) Dynamic system and results were compared with without phosphate and single burning fuel.

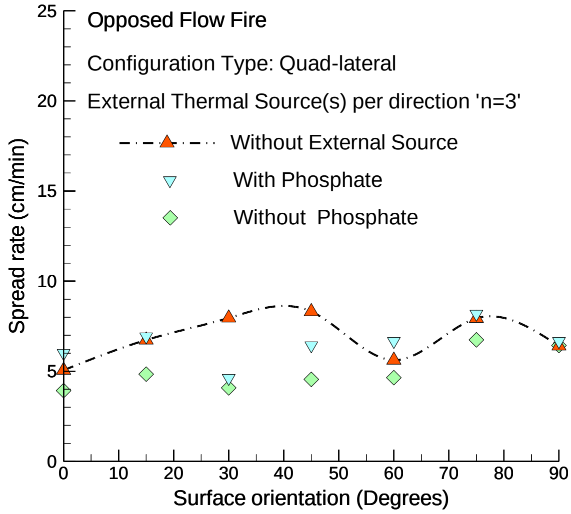
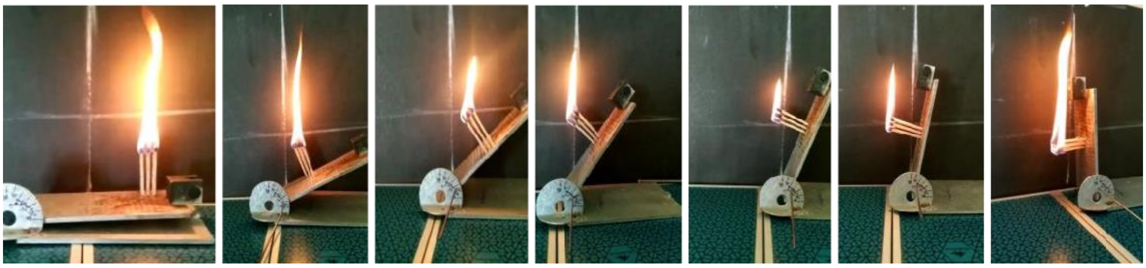
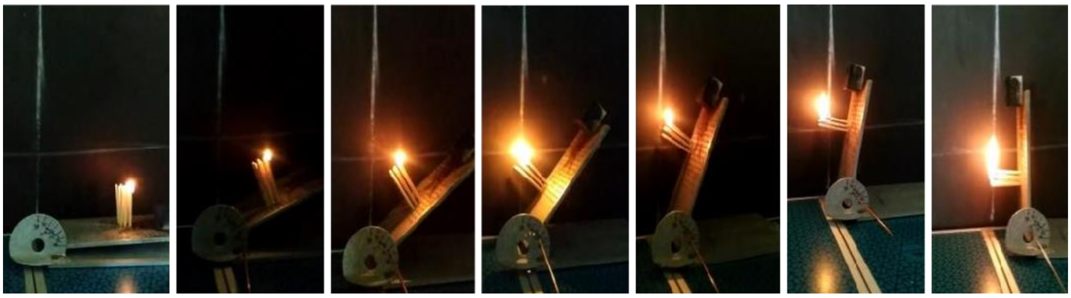


Figure 7: Variation of spread rate with surface orientation on Quad-Lateral Linear Time-Invariant (LTI) for the effect of Phosphate in the burning of experimental samples.



(i) (ii) (iii) (iv) (v) (vi) (vii)



(i) (ii) (iii) (iv) (v) (vi) (vii)

Figure 8: Pictorial comparison of the effect of phosphate in fire spreading phenomenon for the case of Quad- Lateral Linear Time Invariant (LTI) for (a) with phosphate, and (b) without phosphate at different orientations after 10 seconds at surface orientation of (i)0^o (ii)15^o (iii)30^o (iv)45^o (v)60^o (vi)75^o (vii)90^o.

Figure 7 shows the difference in fire spreading owing to the presence of phosphate. One can note the visible alteration in the spreading of single pilot fuel and with configuration. However, it is interesting to note that, when the investigation was expanded without phosphate, the variation in spread rate was observed to be reasonably close eventually matching at 90°. Ignition of the sample through phosphate instantly sets the fire, gradually regaining stability. Similar to the one with phosphate, without phosphate samples reflect the maximum drop of **48.7%** at **30°** and a marginal rise of **0.39%** at **90°** compared to the single pilot fuel. While comparing at different orientations, we can observe large fully developed fires with phosphate cases reflecting progressive ignition and energy transfer to the Primary system and small evolving steady flames without phosphate (refer to figure 8(a and b)). This leads to the understanding that phosphate is primarily meant for ignition and does not necessarily affect the spreading phenomenon.

3.4 Variation of Spread rate coefficient (Ψ) for different dynamic models

Table2. Variation of 'Spread rate coefficient 'Ψ' with surface orientation for different models. (a) Uni-lateral configuration, (b) Bi-lateral configuration, (c) Tri-lateral configuration, (d) Quad-lateral configuration, (e) Matrix-lateral configuration.

Surface Orientation (Degrees)	LTI	NLTI	LTV	NLTV
0	1.1	0.9	0.6	0.7
15	0.9	0.9	0.7	0.8
30	0.6	0.4	0.6	0.5
45	1.0	0.5	0.4	0.5
60	1.2	1.3	1.5	1.1
75	0.8	1.0	1.5	0.7
90	2.0	1.6	1.5	1.9

(a)

Surface Orientation (Degrees)	LTI	NLTI	LTV	NLTV
0	0.8	0.6	1.0	0.7
15	0.7	0.5	0.6	0.8
30	0.5	0.5	0.6	0.7
45	0.8	0.6	0.5	0.6
60	1.0	1.2	1.6	1.1
75	2.2	1.4	1.1	1.1
90	1.5	1.5	1.5	2.8

(b)

Surface Orientation (Degrees)	LTI	NLTI	LTV	NLTV
0	1.3	1.0	1.2	0.6
15	0.6	0.8	0.5	0.5
30	0.5	0.6	0.8	0.6
45	0.7	0.6	0.9	0.7
60	1.6	1.0	1.0	0.7
75	1.3	0.8	1.3	0.8
90	1.5	2.5	1.1	0.3

(c)

Surface Orientation (Degrees)	LTI	NLTI	LTV	NLTV
0	1.1	1.0	1.2	1.0
15	1.0	0.6	0.7	0.7
30	0.5	0.6	0.9	0.6
45	0.7	0.5	0.8	0.7
60	1.1	1.2	1.2	1.3
75	1.0	1.1	0.9	1.5
90	1.0	1.6	1.1	2.0

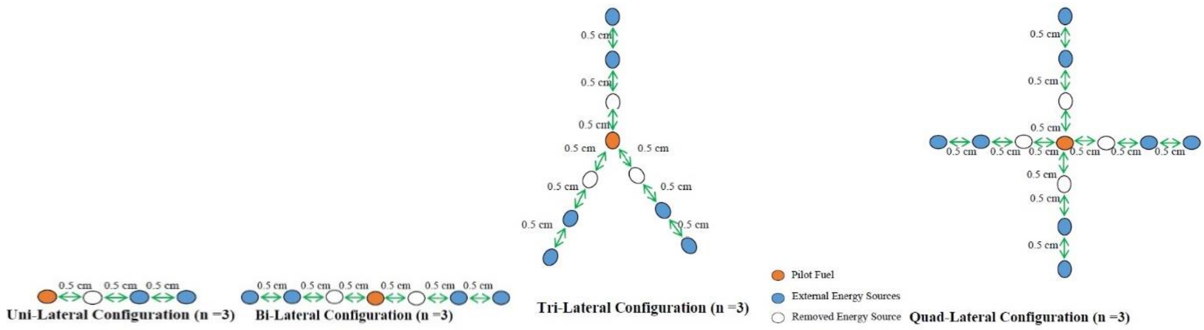
(d)

Surface Orientation (Degrees)	LTI	NLTI	LTV
0	1.8	1.1	1.1
15	0.7	0.6	0.5
30	0.4	0.7	0.7
45	0.6	0.6	0.3
60	1.0	1.1	0.9
75	1.0	1.3	1.6
90	1.4	1.5	2.1

(e)

Referring to the Spread Rate Coefficient Ψ, Table 2(a-e) highlights the observed coupled heat source and heat sink effect owing to the thermal energy interaction among Primary and Secondary systems. One can note that the secondary system (external energy sources) exhibits both heat source and sink effect for all the dynamic models at all orientations. At higher orientations of 60°, 75°, and 90° acts largely as a potential heat source whereas at lower orientations of 0°, 15°, and 30° inclines mostly to heat sink behavior. The reason for this may be attributed to the merging of localized fires to upsurge into a large fire and affect the forward heat transfer to the primary system, reflected in the spread rate. Contrary to the predefined convention of providing energy to the pilot fuel, the secondary system post-ignition reflects irregular energy transfer in spatial and temporal domains. Based on the observations with significant variations, a distinct counter behavior from heat sources in the form of the potential heat sinks leads to a new notable distinction entitled **'VRMAMIK Conjecture'**, which signifies the counter-behavior by the same articulate under similar conditions concerning time. The conjecture is important to understand from providing resolution to the heterogeneous fire behavior. In most cases, the behavior comprised of 'Upsurging-steady fluctuations-downgrade' flames owing to irregular energy transfer. This could be attributed to the shift of localized flame zones into a merged large flame, which affects the energy transfer associated with the system. Subsequently, the secondary system adopts the roles of heat sink and source. Next, the temporal dynamic systems were experimented with selected configurations.

3.5 Effect on Uneven Energy Transfer on Linear Time Variant (LTV) Dynamic model



(a) (b) (c) (d) (e)

Figure 9: Graphical representation of different configurations for LTV dynamic model (a) Uni-lateral, (b) Bi-lateral, (c) Tri-lateral, (d) Quad-lateral, (e) energy sources.

Figure 10 exhibits the effect surface orientation has on spread rate in a unilateral configuration of the Linear Time Variant model. In this case, 3 external energy source(s) at an interspatial distance of 0.5,1, and 1.5 cm respectively from the virgin fuel were fixed linearly (refer figure 9). A deportation time of 10 seconds was utilized to remove the nearest external energy source to pilot fuel. The impact of limited availability of external energy source was then observed on the pilot fuel spread rate. A non-monotonic trend depicting uneven energy transfer was carefully analyzed. Compared to single fuel burning, a maximum spread rate of 12.4 cm/min was observed at an orientation of 75°. A minimum spread rate of 3.3 cm/min was observed at 45°. A maximum percentage drop of **59.3%** was obtained at a surface orientation of **45°** while a maximum percentage rise of **57.2%** was achieved at **75°**. The secondary system (external energy sources) behaves as a heat sink from orientations of 0° to 45° forming the heat sink zone. However, owing to the VRMAMIK Conjecture, we observe that the same external energy source(s) behave as heat sources from 60-90°. The spread rate coefficient Ψ showed variation of 0.4 to 1.57, hence showing a transition from heat sink effect up to heat source effect. One can note controlled self-ignition and fire propagation effect. With time, gradual transition of unsteadiness in energy interaction occurs and flame becomes single, merged and departs from being steady and developed towards extinction with decrease in flame height possibly as the energy associated with the forward heat transfer to the pilot fuel diminishes.

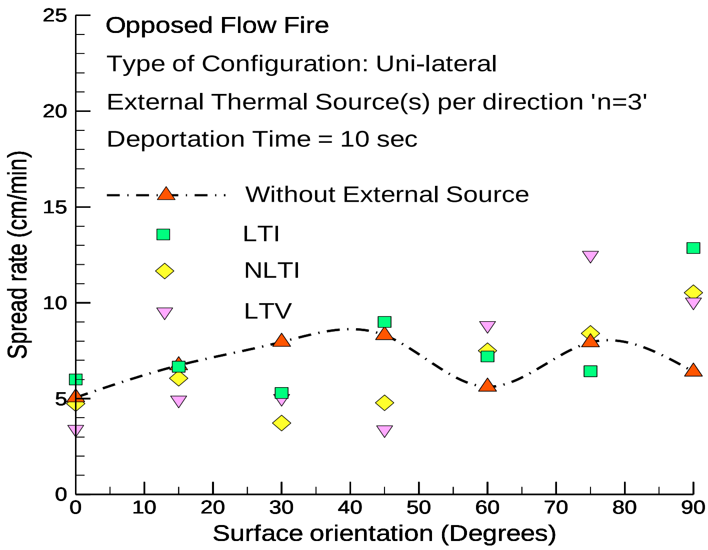


Figure 10: Variation of Spread rate with Surface orientation on Linear Time variant (LTV) Dynamic Fire Spread System on Pilot fuel spreading rate in unilateral configuration.

Thus, reflecting heat sink effect of the secondary system. In comparison with LTI model for same configuration, the values of spread rate were found to converge at 30° reflecting heat sink effect and diverge at 45° with heat sink effect for LTV model and heat source effect for LTI model.

Figure 11 shows the effect surface orientation has on the spread rate in a Bilateral configuration of the Linear Time Variant model. A total of 6 external energy sources, 3 on each side of the pilot fuel were fixed. 3 external energy sources at an interspatial distance of 0.5,1 and 1.5 cm respectively from the virgin fuel were fixed linearly on both sides of the virgin fuel (refer figure 9). The availability of the nearest energy sources was limited to 10 seconds. Hence, within 10 seconds they were removed. The spread rate of pilot fuel is affected by limited availability of nearest energy sources as was observed. Following the Uni-lateral configuration, a non-monotonic trend depicting uneven energy transfer was carefully observed. This validates the heterogeneous energy transfer involved in the propagation of fire. The spread rates analyzed from orientations of 0° to 45° showed values within same range of 4.5 cm/min to 5.5 cm/min. However, a surge in spread rate of 9.2 cm/min was noticed at

60° orientation.The highest spread rate of 9.8 cm/min was observed at 90 degrees orientation while the lowest is 4.5 cm/min at 15° orientation. The sudden upsurge in spread rate at **60°** shows the highest percentage rise of **64.1%**. A maximum percentage drop of **45.1%** was observed at **45°**. A neutralizing effect was seen at 0°. However, a heat sink effect stretches from 0-45°. It was observed that a counter behavior is portrayed by the secondary system (external energy sources). They start behaving like heat sources from orientations of 0°, 60° to 90°, and heat sink for surface orientations of 15°,30°,45°. Thus, spread coefficient displays values in the range of 0.5 to 1.3. A careful transition from a neutralizing effect to a heat sink and then a heat source effect was observed in experimental simulations carried out in the Bilateral configuration of the Linear Time Variant model.

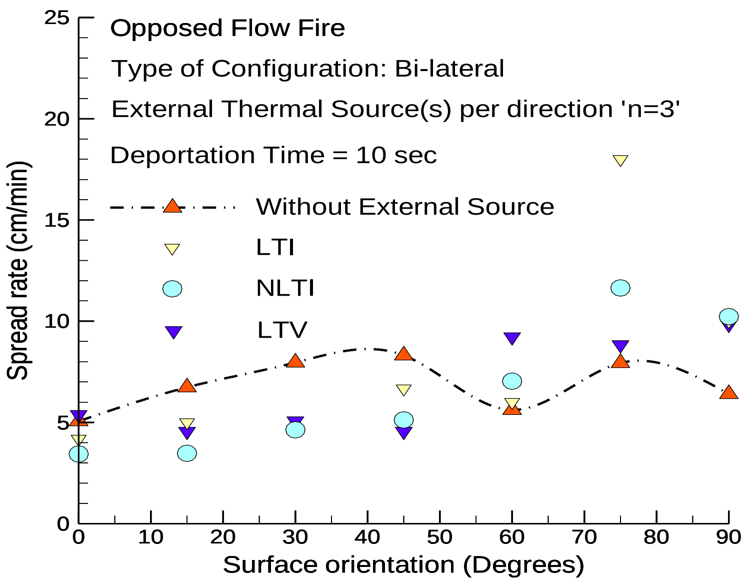


Figure 11. Variation of Spread rate with Surface orientation on Linear Time variant (LTV) Dynamic Fire Spread System on Pilot fuel spreading rate in Bi-lateral configuration.

Figure 12 shows the effect surface orientation has on the spread rate in the Trilateral configuration of the Linear Time Variant model. 3 external energy sources were fixed in a linear arrangement of 0.5, 1, and 1.5 cm respectively from Pilot fuel in 3 directions that were 120° angled from each other (refer figure 9). In this case, the deportation time of 10 seconds was utilized to remove the 3 nearest external energy sources to the virgin fuel, each angled 120° to one other. Here, availability of 3 nearest external energy sources is altered concerning time. The trend followed by the spread rate curve is a non-monotonic hybrid one. The lowest drop-in spread rate of 3.6 cm/min was seen for 15° orientation. However, the highest value observed was 11.09 cm/min for 75° orientation. Consequently, a maximum percentage drop of **46.4%** for **15°** orientation and a maximum percentage rise of **39.7%** for **75°** orientation was observed. The heat sink effect stretches from 15° to 45° with the values of spread rate coefficient ranging from 0.5 to 0.9. At 60° orientation a neutralizing effect is displayed by the secondary system (external energy sources), the spread rate coefficient being 1. However, a strong heat source effect was observed at 75°, 90°, and at 0° orientation

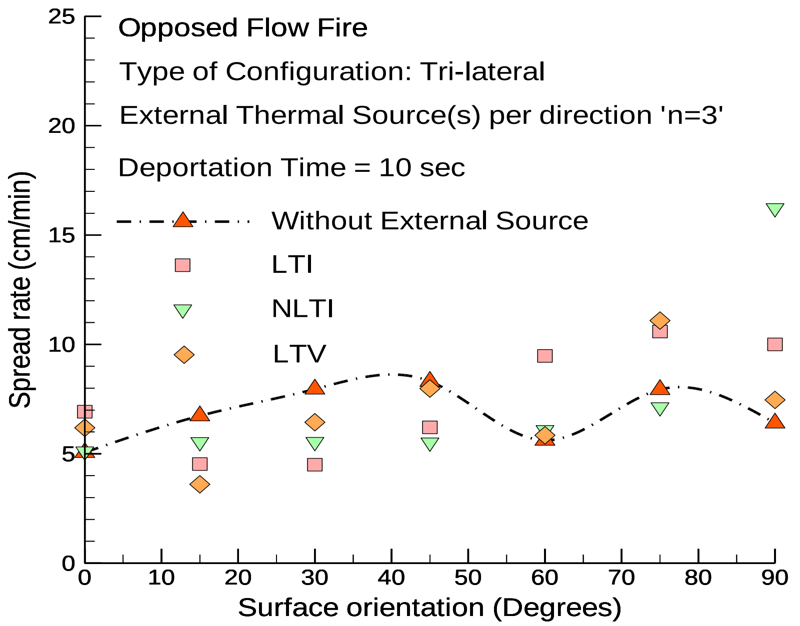


Figure 12. Variation of Spread rate with Surface orientation on Linear Time variant (LTV) Dynamic Fire Spread System on Pilot fuel spreading rate in Tri-lateral configuration.

Figure 13 shows effect surface orientation has on the spread rate in the Quad lateral configuration of the Linear Time Variant model. In this case, 12 external energy sources surround the pilot fuel. 3 external sources are arranged linearly at distances of 0.5, 1, and 1.5 cm from pilot fuel and are diametrically opposite to the other 3 external energy sources arranged similarly. The 6 external energy sources were fixed linearly at the other diametric ends (refer figure 9). The spread rates at all orientations were enumerated to be within the range of 6.5 cm/min to 7.5 cm/min except for orientation of 15°. The 15° orientation resulted in the lowest drop of 5.2 cm/min. Consequently, the highest percentage drop-in spread rate of **21.6%** was observed at 15° orientation giving a maximum value of 7.5 cm/min at 90°. The maximum percentage rise of **28.7%** was analyzed at **0°** orientation. The limited availability of external energy sources led to observing a heat sink behavior of external energy sources at orientations of 15°, 30°, 45°, and 75°. However, a heat source effect was critically analyzed at 0°, 60°, and 90°. It is important to note that in all plots present, the spread rate variation of the pilot fuel is measured when subjected to different conditions of specific surface orientations, approaches, and configurations. This proves the presence of the VRMAMIK Conjecture.

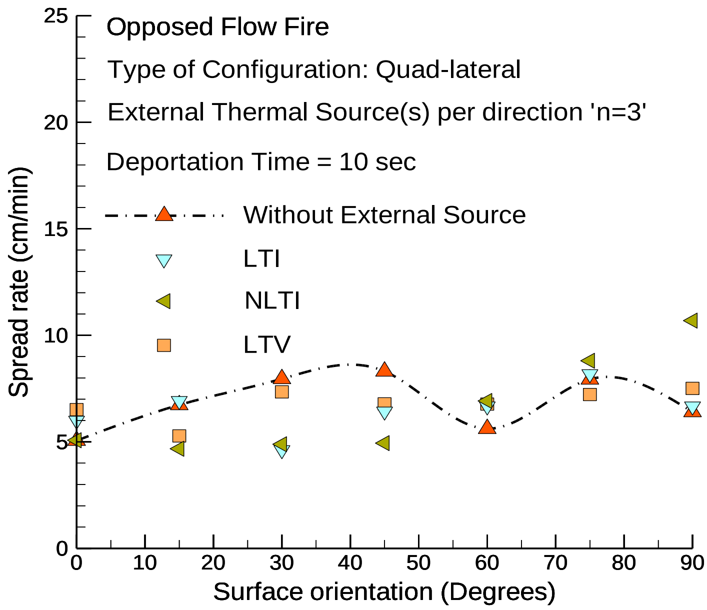


Figure 13. Variation of Spread rate with Surface orientation on Linear Time variant (LTV) Dynamic Fire Spread System on Pilot fuel spreading rate in Quad-lateral configuration.

(a) (b) (c) (d) (e)

Figure 14: Pictorial comparison of fire spreading phenomenon for the case of Quad-Lateral Linear Time variant (LTV) experimentation after 10 seconds at surface orientation of (a) 0^o (b) 30^o (c) 45^o (d) 60^o (e) 90^o. It is interesting to note fully developed flame in the initial stages of experimentation for all cases assisted by the secondary system to constitute a single large flame (refer figure 14). Similarly, the same secondary system (external energy sources) was noted to alter the role of heat sink and heat source uncertainly. One fascinating observation is the energy interactions between the Primary and Secondary systems such that at lower orientations up to 45°, a heat sink effect can be expected in most of the cases, whereas, at higher orientations from 45°-90°, a heat source effect can be expected mostly under different dynamic systems.

3.6 Effect on Uneven Energy Transfer on Non-Linear Time Variant (NLTV) Dynamic model

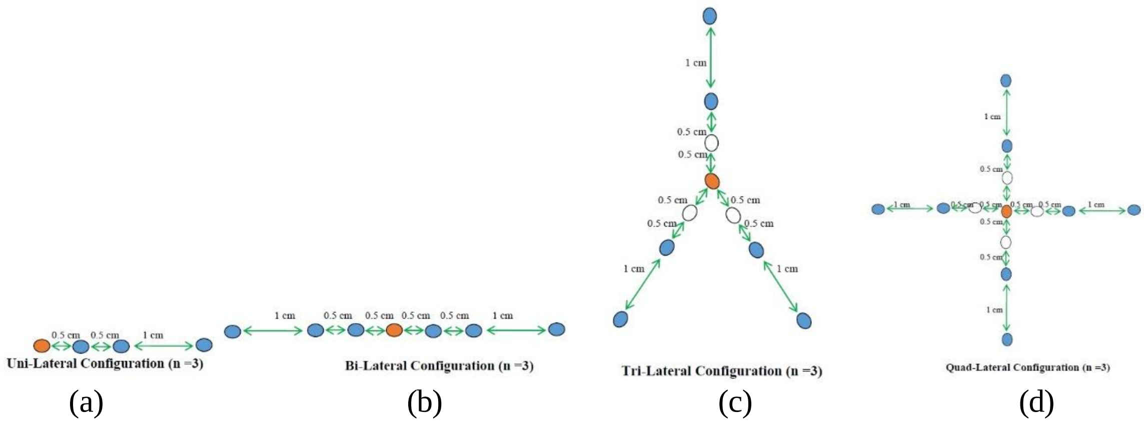


Figure 15: Graphical representation of different configurations for NLTV dynamic model (a) Uni-lateral, (b) Bi-lateral, (c) Tri-lateral, (d) Quad-lateral.

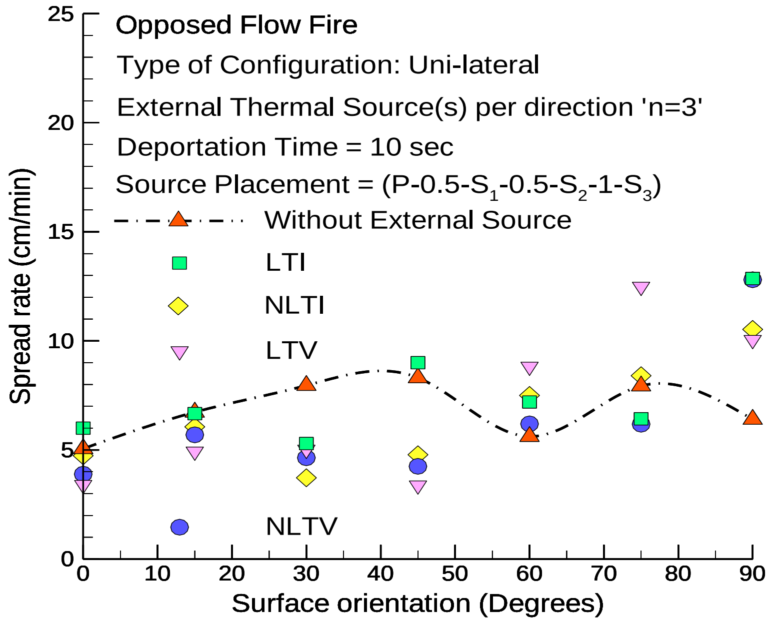


Figure 16. Variation of Spread rate with Surface orientation on Non-Linear Time variant (NLTV) Dynamic Fire Spread System on Pilot fuel spreading rate in Uni-lateral configuration.

Figure 16 shows the effect of related uneven energy transfer in the Non-Linear Time variant (NLTV) Dynamic Fire Spread System on the Pilot fuel spreading rate. This case utilized a unilateral configuration. 3 external energy sources at an interspatial distance of 0.5,1 and 2 cm respectively from the virgin fuel were fixed in non-linearity (figure 15). The availability of the nearest external energy source to the pilot fuel was limited to 10 seconds. The limited availability of external energy sources produced a modulated effect on spread behavior. The non-monotonic trend in spread rate stretched from 0°-45°. However, a monotonic rise in spread rate then followed from a 45° orientation. The limiting presence of the nearest external energy source led to an upsurge in spread rate values. This marked a distinct heat source effect. The highest upsurge of 12.8 cm/min was at 90 degrees. Consequently, this orientation adds to the highest rate of change of rise of **99.9%**. The lowest spread rate of 3.8 cm/min was noted at 0 degrees. The lowest percentage drop-in spread rate of **48.8% was** at **45°**.

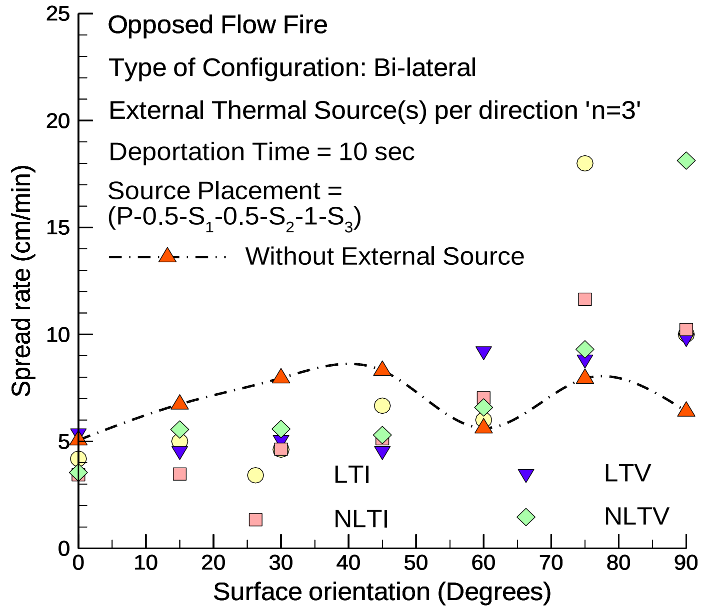


Figure 17. Variation of Spread rate with Surface orientation on Non-Linear Time variant (NLTV) Dynamic Fire Spread System on Pilot fuel spreading rate in Bi-lateral configuration.

Figure 17 shows the effect of related uneven energy transfer in the Non-Linear Time variant (NLTV) Dynamic Fire Spread System on the Pilot fuel spreading rate. In this case, a Bilateral configuration was employed to carry out spread rate analysis. 3 external energy sources at an interspatial distance of 0.5,1 and 2 cm respectively from the virgin fuel were fixed in non-linearity with another set of energy sources arranged diametrically opposite in a similar way. The nearest external energy sources from both sides were available only for 10 seconds (figure 15). This resulted in a non-monotonic trend in spread rate up to 45°. From 45°, there was a monotonic increase in flame spread rate. The highest spread rate of 18.1 cm/min was noticed at 90° while the lowest of 3.5 cm/min was achieved at 0°. The rate of change in spread rate was non-monotonic. Highest percentage rise was **183.08** noted at **90°** while the lowest percentage drop of **36.2** was at **45°**. A heat sink effect was analyzed from 0 to 45° and 45° onward, and a heat source effect was observed, consolidating the existence of the VRMAMIK Conjecture.

Figure 18 shows the effect of related uneven energy transfer in the Non-Linear Time variant (NLTV) Dynamic Fire Spread System on the Pilot fuel spread rate in the trilateral configuration. In this case, 3 external energy sources were fixed in a linear arrangement of 0.5, 1, and 2 cm respectively from Pilot fuel in 3 directions that were angled 120° from each other (figure 15). The parameters exploited were non-linearity in interspace distance along with the availability of nearest external energy sources. Therefore, the nearest 3 external energy sources to virgin fuel when removed in 10 seconds, affected the spread rate of pilot fuel in a non-monotonic hybrid pattern. 90° orientation results in a maximum spread rate of 12.5 cm/min. The novelty of trilateral configuration in the NLTV model was observed at 90° orientation. Contrary, to scientific predictions regarding spread rate behavior at 90° orientation we observe a peculiarity. The former produces the lowest spread rate of 3.4 cm/min at 0°. Moreover, the experimental simulations carried out in this case capture a heat sink effect solely except 90°. The highest percentage drop is **42.24%** at **15°**

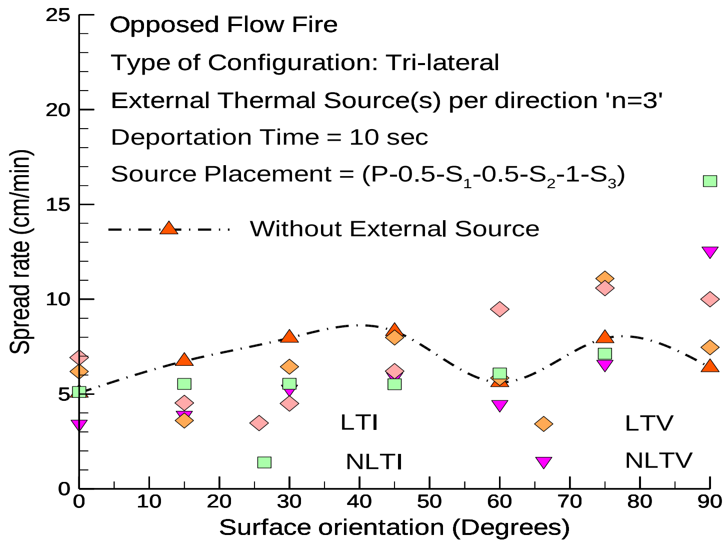


Figure 18. Variation of Spread rate with Surface orientation on Linear Time variant (NLTV) Dynamic Fire Spread System on Pilot fuel spreading rate in Tri-lateral configuration.

Figure 19 shows the effect of related uneven energy transfer in the Non-Linear Time variant (NLTV) Dynamic Fire Spread System on the Pilot fuel spread rate in the Quad-lateral configuration. 12 external energy sources surround the pilot fuel. 3 external sources are arranged non-linearly at distances of 0.5, 1, and 2cm from pilot fuel and are diametrically opposite to the other 3 external energy sources arranged similarly. The 6 external energy sources were fixed non-linearly at the other diametric ends in a similar way (figure 15). Overall, we observe a monotonic rise in the Spread rate from 15° to 90°. 13 cm/min was the maximum spread rate observed at 90° while 4.8 cm/min was the minimum spread rate at 15°. The highest percentage rise of **103.1%** was also observed at **90°**. However, the highest percentage drop of **33.1%** was keenly noticed at **30°**. A coupled heat source and heat sink effect were analyzed through flame behavior.

The spread rate coefficient Ψ values corroborate the analysis. The flame portrayed a neutralizing effect at 0°. Subsequently, a smooth transition from a heat sink zone was observed from 15°-45° took place leading to a heat source zone from 60°-90°. While comparing with NLTI model for same configuration. It is interesting to note the converging values reflecting heat sink effect at 30° and diverging values showing heat source effect at 90°. The experiments reflect that instability and unsteadiness grows with time resulting in faster propagation and increase in flame height.

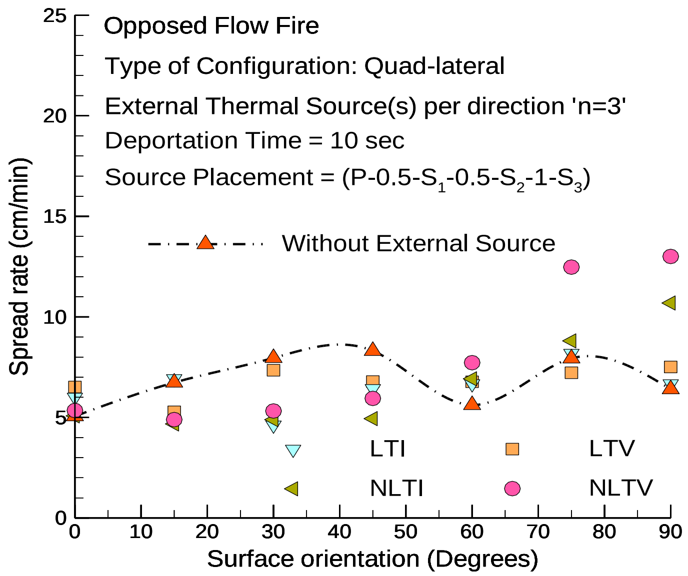


Figure 19. Variation of Spread rate with Surface orientation on Linear Time variant (NLTV) Dynamic Fire Spread System on Pilot fuel spreading rate in Quad-lateral configuration.

4. Conclusions

An experimental investigation had been carried out to explore transitional fire spreading. The study comprised of an original experimental approach to investigate fire spread based on reduced scale experiments. 4 unique dynamic models, LTI, NLTI, LTV, and NLTV were devised to replicate real fire spread situations. Every model had a set of configurations viz., unilateral, bilateral, trilateral, and quadrilateral to help critically analyze spread rate of pilot fuel in the presence of a coupled heat source and heat sink effect. Analysis was done on impact of external energy sources in form of heat sources and sinks considering space and time variation. A new non-dimensional number namely, spread rate coefficient (Ψ) was devised to define nature of secondary system. We observe an irregular energy interaction subsequently dictating phenomenon of heterogenous spread of fire. A new Conjecture was observed and named the **'VRMAMIK Conjecture'**. It is a reflection of the counter-behavior by the same articulate under similar conditions concerning time. The spread rate variation, spread rate coefficient (Ψ), and values validated the VRMAMIK

Conjecture defining the diverse nature of fires singularly with surface orientation. From the research carried out, the following inferences can be made:

1) Spread of fire does not have a specific pattern. Its heterogeneous behavior was observed during experimentation in the form of measurements on spread rate of pilot fuel. The pilot fuel had been in presence of an array of fuels in 5 configurations utilized in 4 models considering space and time variation.

2) Different configurations corroborate uneven energy transfer as a result of self-ignition and propagation. Experiments highlighted Irregular thermal energy interaction.

3) Heterogeneity/Instability in fires is reflected in rapid self-ignition, drop in flame intensity with time, flame merging and segregation, formation of localized flame zones, unsteadiness, and re-emergence of steady fire.

4) Varying surface orientation significantly altered fire behavior, resulting in partial, complete burning, and extinction cases reflecting irregular and uneven energy transfer.

5) The Non-Linear Time variant model in the Bilateral configuration shows an unpredicted high heat source effect of 18.1 cm/min at 90° orientation.

6) Applications of the work***:*** The physical insight from the present study can be very useful in understanding the nature of large-scale fires viz., compartment fires, forest fires, building fires, and propulsive fires. This knowledge can be utilized to increase the control time, devise new fire safety equipment, in test, validate, and design existing systems and engineering structures. Present Work may be employed efficiently for the detection, prevention, and possibly suppression of fires resulting in preventing a lot of monetary and human loss. Furthermore, a novel device can be invented for requirements of spread rate control in the form of termination, augmentation.

5. Authors' contributions

Vinayak Malhotra: Conception, Methodology, Design, Data collection, Interpretation, Data analysis, Paper writing

The author have read and approved the manuscript.

6. Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

7. Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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