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Original Article

Experimental Investigation on the Nonlinearity Effect on Large-Scale Fires: Propagation Characteristics and Observations

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Abstract *- Fire does not spread evenly. Natural resources, vital infrastructure, systems, and priceless human lives have all been irreparably lost as a result of the widespread uncertainty around large-scale fires. To address this critical issue, considerable research initiatives are steered every year aimed at preventing and alleviating such devastating occurrences to create novel tactics, advanced technology, and effective processes to proactively mitigate the danger of large-scale fires, thereby protecting lives and preserving valuable assets from significant damage. The present work aims to examine the non-linear characteristics of fire propagation. A setup was constructed to evaluate various non-linear layouts at many orientations. Various non-linear configurations for each direction were examined, and the pattern of fire propagation was recorded to collect critical information about fire propagation dynamics, Flame Spread Rate (FSR), and associated energy transfer. To gain true replication, experiments were conducted on dynamic models, Linear Time-Invariant (LTI), Linear Time-Variant (LTV), and the effect of spatial nonlinearity was studied on non-linear dynamic models, viz., Non-Linear Time-Invariant (NLTI) and Non-Linear Time Variant (NLTV), to determine spreading fire behavior and features. The data had been compared with the outcomes of an alternative linear configuration. Results largely state that the presence of nonlinearity significantly alters the thermal energy interaction between the pilot fuel and an array of external energy sources. It is reflected in the measurement of the spread rate. The study offers valuable insights into the complex mechanisms of fire spread, contributing to the enhancement of fire safety knowledge and improving our capacity to manage fire-related dangers. These findings may assist in the development of methods for forecasting and mitigating the harm caused by uncontrolled fires, which include wildfires, fires in aircraft, buildings, rockets, etc.*

Keywords *- Fire Spread Rate (FSR), External energy sources, Energy Transfer, Nonlinearity, Surface orientation.*

1. Introduction

The discovery of fire holds immense significance as it has profoundly shaped the trajectory of human civilisation. Fire is used in almost every aspect of life, from cooking food to steam engines to powerful rockets. The ignition sources can arise from natural phenomena such as lightning strikes or volcanic eruptions, as well as from man-made sources like electrical malfunctions, open flames, or combustible materials. This broad spectrum of ignition methods underscores the multifaceted nature of fire initiation, highlighting the importance of comprehensive fire prevention measures and the need for heightened awareness regarding potential fire hazards. Some natural causes of fires are extreme weather conditions, volcanic eruptions, and lightning in unburnt regions. The fires are classified as opposed flow fires and concurrent flow fires, based on the direction of air regarding the direction of spread. Opposed flow fires spread against the direction of air, whereas concurrent flow fires spread in the direction of air. Annually, the occurrence of extensive uncontrolled fires, including forest fires, industrial fires, and rocket explosions, leads to substantial losses in terms of natural resources, financial assets, and human lives.

As reported, it is impossible to remove all external energy sources in propagating fires. Some man-made causes of fires are chemical reactions, open flames, and explosives. Fires are generally encountered as Diffusion flames, Smouldering flames, Spontaneous combustion, and Premixed flames. The ongoing research pertains to the phenomenon of spontaneous combustion, which falls within the realm of fire initiation. The understanding and exploration of spontaneous combustion contribute to our knowledge of fire dynamics and prevention strategies. The scientific research on fires largely involves the measurement of Fire Spread Rate (FSR). Conventional forward heat transfer theory states that fire spreads owing to continuous heat transfer from the burning to the unburnt region. The nature of external energy sources as potential heat sources or heat sink and their impact, both singularly and coupled, specifies the heterogeneous nature of propagating fires, making it one of the significant issues to be resolved.

The present study is primarily stimulated by the recent LA fire in January 2025. The Los Angeles region and adjacent areas have been impacted by many severe wildfires since January 7, 2025. As of January 13, there were over 170 fire alerts in the region, which is more than 100 times the average so far for the first three weeks of 2012–2024. The wildfires had destroyed or damaged over 16,000 structures, displaced approximately tens of thousands of people, forced over 200,000 to evacuate, and killed at least 29 individuals up to January 28. The Palisades Fire, Eaton Fire, Hughes Fire, and Border 2 Fire are the four fires that were still burning as of January 29. In California's history, these fires are probably the third and second most destructive, respectively. Drought conditions, low humidity, a build-up of vegetation from the previous winter, along with hurricane-force Santa Ana winds that in some locations reached 100 miles per hour (160 km/h) all contributed to the fires. As noted by analysts at Peel Hunt, the insurance losses accounted for $32.5 billion, making the fires the worst in recent history, exceeding the $23 billion of insured losses from the peril in 2018, which was driven by the Camp Fire in Northern California's Butte County. The number of fire alerts rises as fires expand around Los Angeles County.

During the last 10 years (2013–2022), the United States has experienced an average of approximately 3,500 fire deaths annually, as estimated by the National Fire Protection Association (NFPA). Inhaling smoke from the toxic gases that fires release is one of the primary causes of fire-related fatalities. Moreover, the annual damages from fires in houses exceed $9 billion. Additionally, the U.S. Fire Administration reported that 2,840 civilians are killed by house fires annually on average. Annually, the U.S. experiences approximately 343,100 house fires, which include 86,000 apartment fires in the year 2020. Every year, a house fire occurs in about 1 in 413 homes. In the 1980s, there were 2.46 million fires annually on average. Over the past ten years, the average number of fires has declined to 1.34 million. The National Fire Incident Reporting System (NFIRS) reported that this amounts to a 45 per cent decline in fires.

Despite considerable research efforts dedicated to studying large-scale propagating fires over an extended period, a comprehensive theory that can fully elucidate the intricate behavior of such fires remains elusive. The complex nature of these events, coupled with a myriad of influential factors, poses a significant challenge in formulating a unified theory that can comprehensively explain their behavior. Therefore, continued research endeavors are essential to deepen our understanding of these large-scale fires and develop effective strategies for prevention, mitigation, and fire management. One such aspect is the nonlinear nature of propagating fires.

In physical problems, nonlinearity is natural, like fire propagation; however, the research has largely been simulated utilizing linearity. Because linear solutions are simpler to compute, have a lower computing cost, and may be superimposed on one another, linear approximations are essentially utilized, rather than because they are more accurate. Therefore, in circumstances that include developing high-performance components, determining the causes of failure, stimulating true material behavior, and attempting to understand physical phenomena better, for example, fires, nonlinear analysis is required, and linear analysis is insufficient.

As understood, nonlinearity happens when the rules of proportionality are violated. This indicates that small changes in the input may lead to significant changes in the output. Nonlinear systems like spreading fires often show chaotic behavior or necessitate more complex models than linear systems. Nonlinearity can lead to random, erratic outcomes. A linear relationship can be represented by a straight line when the dependent variable changes according to the independent variable because, in essence, it has a constant rate of change. When plotted, a nonlinear connection will not create a straight line since its rate of change is not constant. In a nonlinear connection, the value of the dependent variable is not altered in direct proportion to the independent variable since it is influenced by a range of inputs. There are three major types of nonlinearity, viz., material, geometric, and boundary. These may occur singly or in combination. The nonlinear curves can be broadly categorized as follows: gradually ascending and then rising more steeply; gradually declining and then dropping rapidly; rapidly climbing, then tapering off; and falling sharply and then gradually. The similar behavior conforms widely with the spread rate measurement for propagating fires.

Following the classical work on matchsticks as an array of fuels, Vogel and Williams (1970) executed experiments on flame propagation over uniform, linear, horizontal arrays of matchsticks oriented vertically. The investigation brought attention to differences in matchstick height and distance from one another. The matchstick array char angle, linear flame propagation rates, and required circumstances for flame propagation were all confirmed by the findings. Experimental research on flame propagation via linear, vertically oriented matchstick arrays on inclined base boards was conducted by Hwang and Xie (1984). The temperature distribution within the flame zone was assessed, revealing that the preheated area expanded with a rise in the baseboard angle. Convective effects are primarily crucial to flame propagation at matchstick-size scales, according to the theory and investigations. To examine the influence of the spacing among various fuel elements on the upward FSR, experiments were performed by Gollner et. al. (2012) employing vertical arrays of horizontal wood matchsticks arranged in groups of one to five. The findings prompted the notion that convective heating predominated the spreading process, and convective heat-transfer correlations were utilized to predict ignition timings. Equally, Viegas et. al. (2008) investigated one of the biggest firefighting accidents in the history of Croatia in 2007, with 12 dead and 1 badly injured firefighter. In order to understand the Kornati accident, a research team was formed, and an independent scientific investigation was performed. The accident was analyzed from meteorological, vegetation, thermodynamic, and aerodynamic points of view. The work described in detail one possible explanation connected with eruptive fire behavior. Based on the real Kornati accident data, the eruptive fire model was conceived, and appropriate results were derived.

In the realm of varying interspacing and surface inclination, the mechanism of flame propagation over thin solid fuel sheets was investigated experimentally by Hirano et. al. (1974), followed by Weber (1990), Miller and Gollner (2015). Meanwhile, on the front of employing distinct models, Ljung (2001) described the Linear Time Invariant (LTI) model under general conditions. A stochastic spreading model that is continuous in space and time and that makes use of georeferenced data and potent methodologies was proposed by Beneduci and Mascali in 2023.

In the framework of nonlinearity, Bishop et. al. (1993) studied the flashover phenomenon, representing a rapid rise in fire size, followed by Lattimer (2016) and Black et. al. (2021).

Appreciable scientific work had been done; however, selected aspects like the effect of nonlinearity in the form of placement, as well as accessibility of external energy sources on the fire spreading to obtain true replication, are yet to be investigated comprehensively. The urgency to undertake this research stems from the aim of minimizing extensive losses caused by fires. By developing a comprehensive understanding of the underlying physics behind large-scale fires, the goal is to effectively predict and manage these fires during their initial stages. The investigation focuses on discrete flame spread, and the specific objectives of this research attempt are to:

1) Measure the Fire Spread Rate (FSR) of the pilot fuel in the presence of external energy sources and identify crucial energy transfer that controls the propagation of fires in non-linear configurations resembling fires observed in real-world scenarios.
2) Gain insights into the role of key parameters that influence fire propagation under different conditions for effective prediction and resourceful utilization of thermal energy transfer.

By addressing these objectives, the research aims to contribute to the development of enhanced fire management strategies, thereby mitigating the devastating impacts of large-scale fires and safeguarding lives, resources, and infrastructure.

2. Experimental Setup and Solution Methodology

To evaluate several non-linear configurations at different surface orientations, a straightforward experimental setup (Figure 1) was designed and fabricated. The setup comprises a base plate, a main plate, and a protractor. The main plate includes 15 x 15 mm holes with a 5 mm diameter that are equally spaced 5 mm apart. The testbed was fixed at a specific orientation using the protractor. The primary plate can be maintained in seven orientations, ranging from 0° to 90°, with a 15° increment. Because aluminium is lightweight, it was selected for fabrication. As external energy sources and pilot fuel, homemade matchsticks were employed.

The matchsticks were marked as follows: 0.5 cm for flame stabilization, 1cm for spread rate measurement, three markings (1cm each), and 1 cm for clearance. The ignition source was a butane gas lighter. The split timings were measured using an optical shadowgraphy camera as well as a timer with a minimum count of 0.01 seconds and an accuracy of ± 0.1 seconds, for investigating the effect of nonlinearity and external energy sources to obtain an accurate replication of the natural phenomenon. The entire testbed was divided into 2 thermodynamic systems, consisting of pilot fuel (Primary system) and an array of external energy sources (Secondary system). To examine thermal energy interaction among them, the secondary system was classified into directional configurations, viz., Uni-lateral, Bi-lateral, Tri-lateral('Y'), Quad-lateral ('+'), defined according to ($2\pi/n_d$) with 'n_d' signifying the number of directions/branches. For all scenarios, the no. of external energy sources per direction 'n' was set at 3. Pilot fuel ignition was employed to start the experiment, and the impact of external heat sources on pilot fuel burning was observed for different configurations at various orientations.

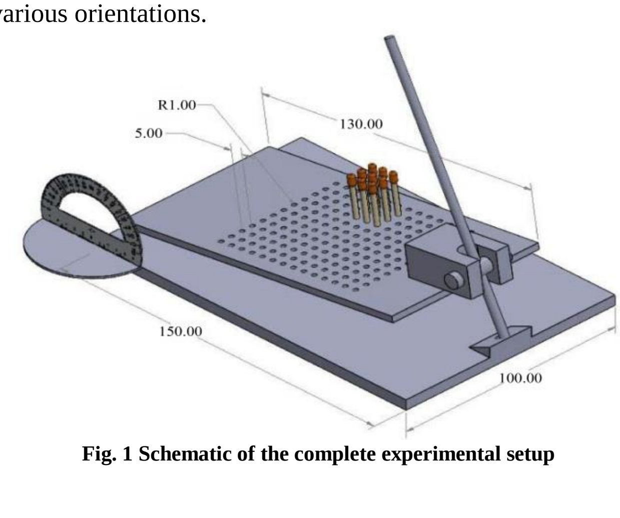


Fig. 1 Schematic of the complete experimental setup

Table 1. Sample specification and marking

Sample Specification	
Fuel-Material	Matchsticks
Test Bed	Wooden Table
Scale	Made using a black pen
Total Height	4.5cm
Total Width	0.2cm
Scale least count	0.01cm
Density	0.4g/cm³
Specific heat	1.76J/g°C
Thermal Conductivity	0.20W/m·K
Markings	
First 0.5cm	Flame Stabilization
Next 1 cm, three markings (1cm each)	Spread rate measurement
Last 1cm	For clearance

Fire Spread Rate (FSR) is known as the rate at which flame propagates on the solid fuel surface and is calculated linearly as:

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

The experiments were conducted in both spatial and temporal domains with definite nonlinearity. The spatial domain specified the placement of external energy sources as Linear (equidistant) and Non-linear (non-equidistant). The temporal domain indicated the availability of selected external energy sources as infinite as well as limited by selected time. Based on the methodology, four dynamic models designed as Linear Time Invariant (LTI), Linear Time Variant (LTV), Non-Linear Time Invariant (NLTI), and Non-Linear Time Variant (NLTV) were employed to understand better how nonlinearity affects the spread of fire in spatial (placement) and temporal (availability) arrangements.

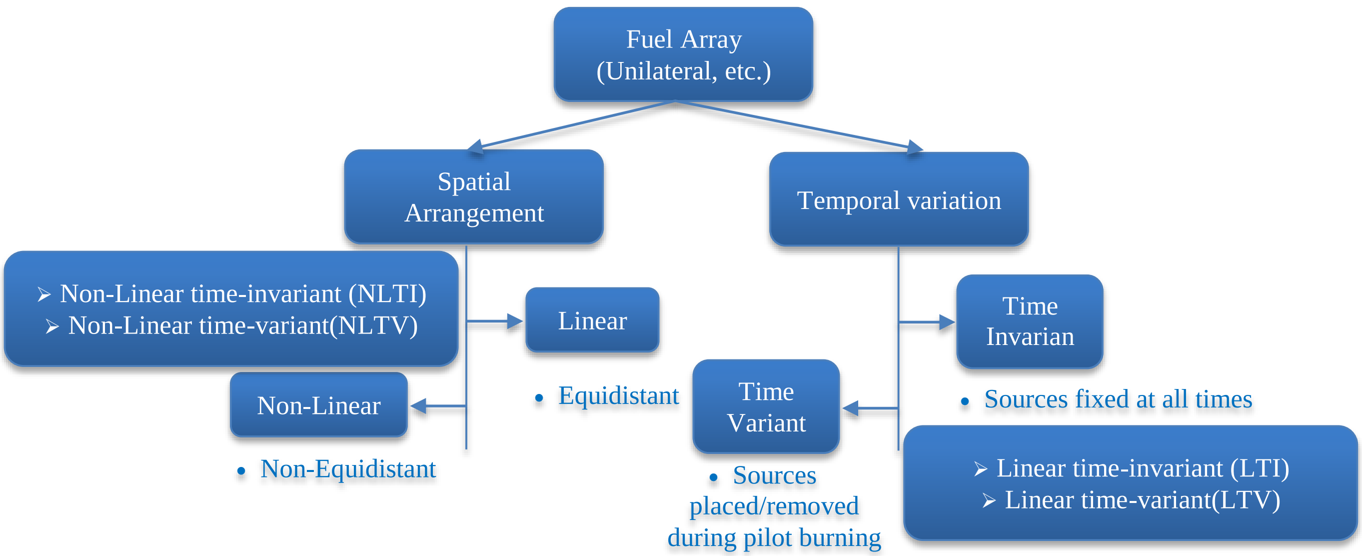


Fig. 2 Graphical representation of the classification of different dynamic models

The experimental simulations were conducted on several configurations with differing surface orientations, and significant instances of partially burnt, fully burnt, and extinguished external energy sources were examined. The experiment commenced with pilot fuel ignition and fire propagation, alongside the self-ignition effect for various configurations involving pilot fuel combustion, which was seen under different dynamic models. Crucial information was derived employing parameters that included fire spread rate, flame structure, and temporal variations in propagation patterns. As per Forward Heat Transfer Theory, the fire spread rate is determined as follows:

$$r = \frac{\int q(net)}{\rho.\tau.c.[T(surface) - T(\infty)]} \quad (2)$$

Here,

$\int q(net)$: Net integrated heat transfer
ρ : Solid fuel density
τ : Solid fuel thickness
c : Specific heat
T(surface): Fuel surface temperature
T (∞) : Ambient temperature
r : Fire spread rate

Formula (Equation (2)) provides the relationship between the spread rate along net heat transfer, suggesting that the spread rate is a useful measure of the energy exchanges taking place between two thermodynamic systems. Process comprises thermal interactions in the form of generated heat release rate and feedback in terms of heat losses (viz. conduction, convection, and radiation). Changes in the spread rate directly reflect the nature of thermal energy transfer. This understanding explains the importance of the Fire Spread Rate (FSR) as a quantifiable measure for evaluating the dynamics of heat transfer and energy exchange between the systems in question. As detailed by author's previous work, to facilitate the interpretation of forthcoming results, the non-dimensional parameter 'Spread Rate Coefficient (Ψ)' (Equation (3)) was employed. By quantifying the relative change in pilot fuel spread rate, the Spread Rate Coefficient (Ψ) enables a clearer understanding of the influence of external energy sources on the dynamics of fire propagation in the form of a heat source along with a heat sink effect.

$$Spread\ Rate\ Coefficient\ (\Psi) = \frac{Spread\ rate\ in\ the\ presence\ of\ external\ thermal\ energy\ sources}{flame\ spread\ rate\ of\ pilot\ fuel\ without\ any\ external\ sources} \quad (3)$$

The spread rate coefficient (Ψ) describes the nature of the secondary system as:

1) $\Psi < 1$ signifies the reduced FSR of pilot fuel because of the presence of the external energy sources. The thermal energy interaction between primary and secondary systems occurs such that heat is transferred from primary to secondary; thus, the secondary system acts as a heat sink. Possibly due to a decrease in pilot fuel surface temperature, owing to a reduction in the amount of oxygen to burn the pilot fuel.
2) $\Psi = 1$ indicates that the FSR of the pilot has not altered due to the existence of the external energy sources. The thermal energy interaction between primary and secondary systems occurs such that energy transfer balances and does not affect pilot fuel burning. In this case, the secondary system acts as a neutral system.
3) $\Psi > 1$ signifies that the increased FSR of the pilot has increased because of the presence of the external energy sources. Indicating that thermal energy is transferred from the Secondary to the primary system, and the secondary system serves as a heat source.

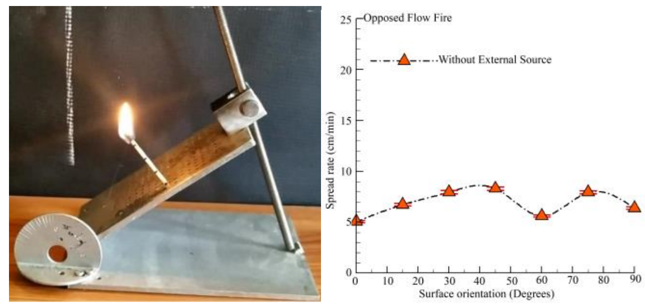
It is crucial to keep in mind that the experiments were carried out at room temperature with 21% oxygen concentration. Third-order repeatability and reproducibility were ensured, and the data presented carries a ±2% error margin and an uncertainty of < 1%, due to the measurement of the device.

3. Results and Discussions

3.1. Base Case Study

An initial pilot case experiment was carried out in order to evaluate the experimental setup predictions and set a baseline for the experiments. Seven distinct orientations, viz. 0, 15, 30, 45, 60, 75, and 90 degrees were used to test a single matchstick. The spread rate of the pilot stick was observed and recorded for each orientation (Figure 3(a)). Analysis of Figure 3(b) revealed that the maximum spread rate of 8.31 cm/min occurred at the 45° orientation. This finding aligns with the preceding research works of Tiwari et. al. (2017) and conventional heat transfer theory, providing additional confirmation of experimental results. Accuracy as well as dependability of the experimental setup are supported by agreement between observed maximum spread rate and the theoretical expectations, indicating that predictions of the experimental setup should offer practical physical insight into the propagating fire phenomenon.

The single fuel data was used as a reference for all subsequent experiments.



(a) (b)

Fig. 3 Base case results, (a) pictorial representation at 30º, (b) spread rate variation with surface orientation.

3.2. Effect of Uneven Energy Transfer on Non-Linear Time Invariant (NLTI) Dynamic Fire Spread System(s) on Pilot Fuel Spreading Rate

First, the case of spatial nonlinearity was tested for different configurations. To understand the relevance of placement, a comparison was made between the selected configurations of Uni-lateral, Bi-lateral, Tri-lateral, and Quad-lateral for LTI as well as NLTI dynamic models.

In LTI model, all configurations are defined with equidistant placement (5mm) of external energy sources whereas, the same was altered in NLTI model with non-equidistant placement with first external source placed at 5 mm, second at 1cm and third at 2cm away from the pilot fuel for different configurations (see Figure 4), to establish the geometric nonlinearity effect.

Looking at the spread rate variation for all cases, it may be inferred that the flame spread trend is non-monotonic and irregular for both non-linear and linear configurations. This confirms the heterogeneous nature of fire propagation. For Uni-lateral configuration, both LTI and NLTI models reported maximum rise at 90º reflecting the heat source effect, and maximum drop at 30º indicating the heat sink effect. The maximum rise for the linear configuration was 100.78% whereas it dropped to 64.86% for NLTI.

Likewise, owing to nonlinearity, the NLTI model reproduced an enhanced heat sink effect with a 53.18% drop in comparison to 33.46% by LTI. It is fascinating to observe that spread rate values congregate for both LTI and NLTI at 15° and 60º respectively. The NLTI model for the Bilateral configuration followed a similar non-monotonic trend as the Unilateral.

The maximum spread rate was observed at 75 °, reflecting the heat source effect with a 46.7% and the minimum spread rate was noted for horizontal (0º), highlighting the heat sink effect with a 32.03% drop. In comparison to the LTI model, values varied mostly; however, the spread rate values were found to converge with the heat sink effect at 30º with a 42% drop, and only the heat source effect with a 100% rise for vertical orientation (90°).

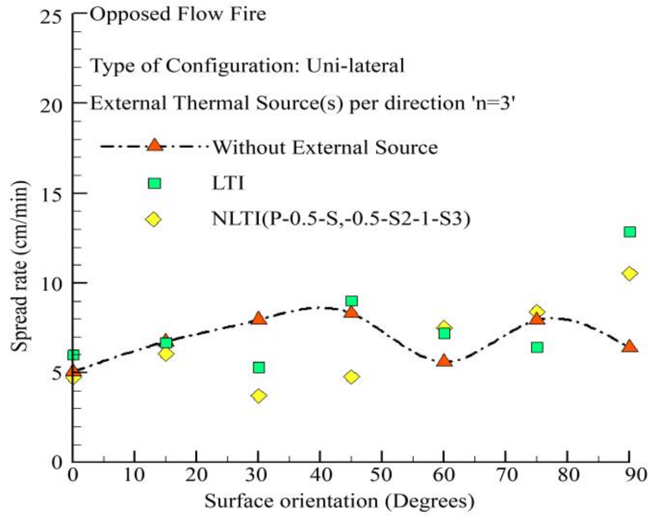
FSR exhibited a direct correlation with the net integrated heat transfer that takes place between the two thermodynamic systems. The temperature difference between the matchstick surface and flame front is what causes the flame to spread along the pilot fuel stick. This temperature difference drives the transfer of heat, leading to the advancement of flame as well as influencing the observed spread rate. Heat transfer takes place as conduction and convection in series with radiation in parallel.

Buoyant convection results from the temperature differential caused by conduction. The secondary system offers less energy than in the base scenario since the pilot fuel provides some of the generated energy to it. As a result, compared to the base case scenario, the temperature of the flame front reduces in proportion to the decrease in energy availability within the pilot fuel.

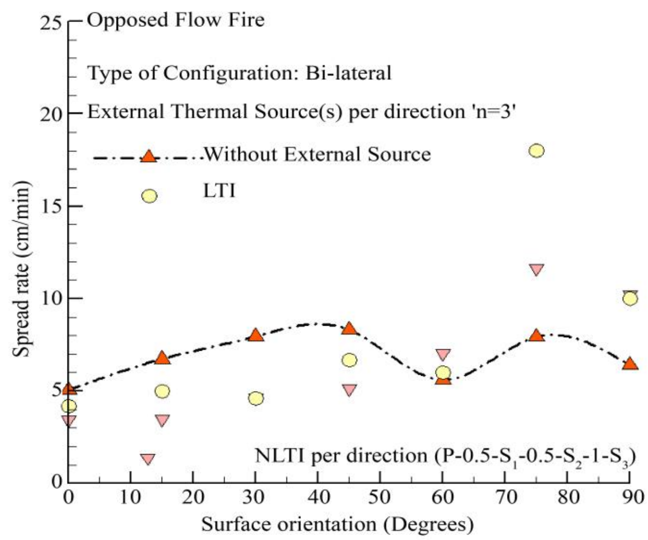
This finding emphasizes how energy distribution is interrelated and affects the flame front thermal dynamics. Consequently, the spread rate falls. Correspondingly, an increase in forward heat transfer, owing to enhanced thermal energy transfer from the secondary system, alters the pilot fuel surface temperature, resulting in an increased spread rate.

Nonlinearity was observed to cause maximum spread rate rise of 154.43% at 90º for the Tri-lateral configuration and minimum spread rate at horizontal orientation with maximum drop of 33.62% at 45º.

In comparison, LTI showed the disparity with a maximum drop of 44.34% at 30º and a maximum rise of 68.63% at 60 °. It is fascinating to note that the values converged at 45º for both models with the heat sink effect. Quad-lateral configuration highlighted nonlinearity effect in the form of a hybrid non-monotonic pattern with maximum spread rate rise of 66.92% at vertical orientation (90 °) and maximum heat sink effect with 40.5% drop at 45º. Comparison with LTI showed the convergence of both models, with only the heat sink effect at 30º and only the heat source effect at 60 ° and 75 °, respectively.



(a)



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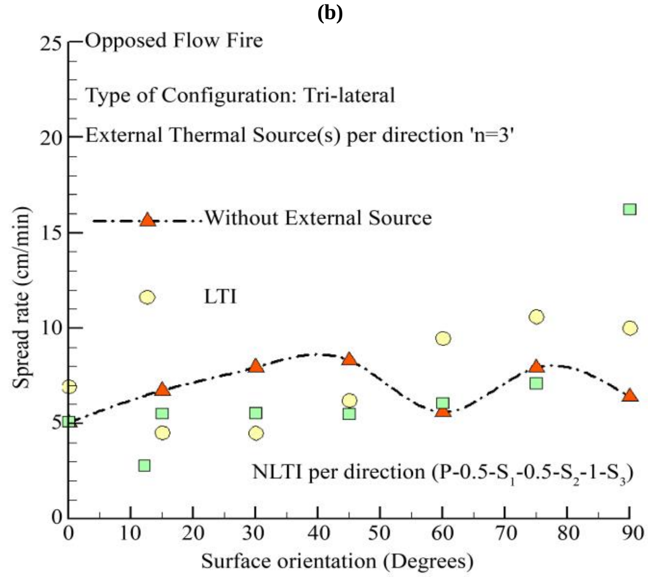

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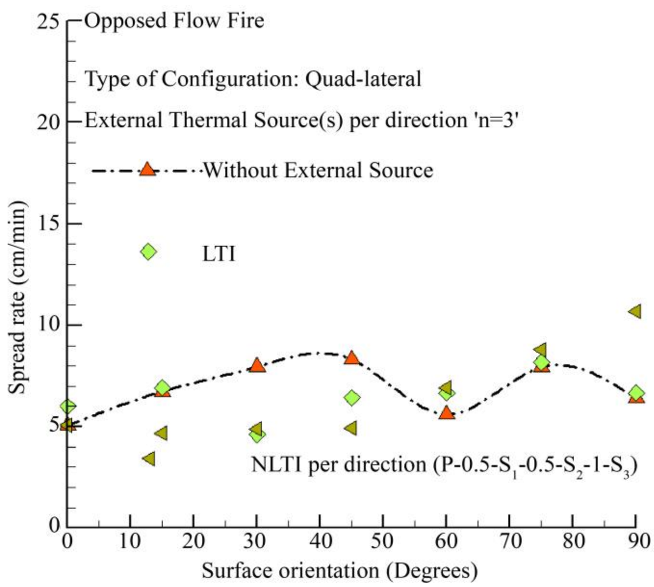


(d)

Fig. 4 Comparison of LTI and NLTI dynamic models for configurations: (a)Uni-lateral, (b)Bi-lateral, (c)Tri-lateral, and (d)Quad-lateral.

In the form of a spatial nonlinearity effect, an exaggerated variation in spread rate for different configurations at varying surface orientations was noticed, along with limited cases of unification. It can be noted that there is a significant transformation in the maximum rise and drop in spread rate values, along with the shift in surface orientations at which they occur.

Nonlinearity exhibited a drop in heat source effect for Uni-lateral, Bi-lateral, Tri-lateral configurations, and a drop in heat sink effect for Bi-lateral, Tri-lateral, Quad-lateral configurations. In contrast, it showed an increase in the heat sink effect for the Uni-lateral configuration and the heat source effect for the Quad-lateral configuration. Nonlinearity defines the heterogeneous nature of fires with surface orientation. Values at different orientations were noted to be altered, which indicated the irregular energy transfer and establishes the fact that uneven placement of external energy sources profoundly alters the energy transfer process, resulting in unpredictable variations. Reason may be ascribed to the transition of localized flame zones into merged flame, vice versa, thus distinctly affecting the associated energy transfer. It was noticed that the availability of external energy sources directly affects the pilot fuel burning process significantly.

In addition, the occurrence of the majority of heat sink effects from 0 ˚ to 45˚ and the heat source effect at higher orientations from 45˚ to 90˚ was established. For the corroboration of effect, the spread rate coefficient variation reflects coupled heat source as well as heat sink effect for different configurations under the LTV dynamic model. The maximum heat source effect for all configurations typically occurs at 90 ˚ and irregularly at 45º, 60 ˚, 75˚, similarly. The maximum heat sink effect was found to occur largely at 30º and infrequently at 15 ˚ and 45 ˚. The extent of the heat source effect was noted to rise close to 150%, whereas the heat sink effect incurs a maximum close to 45 ˚.

3.3. Effect of External Energy Source Deportation Time on Pilot Fuel Spreading for Varying Configurations in a Non-Linear Time Variant (NLTV) Dynamic System

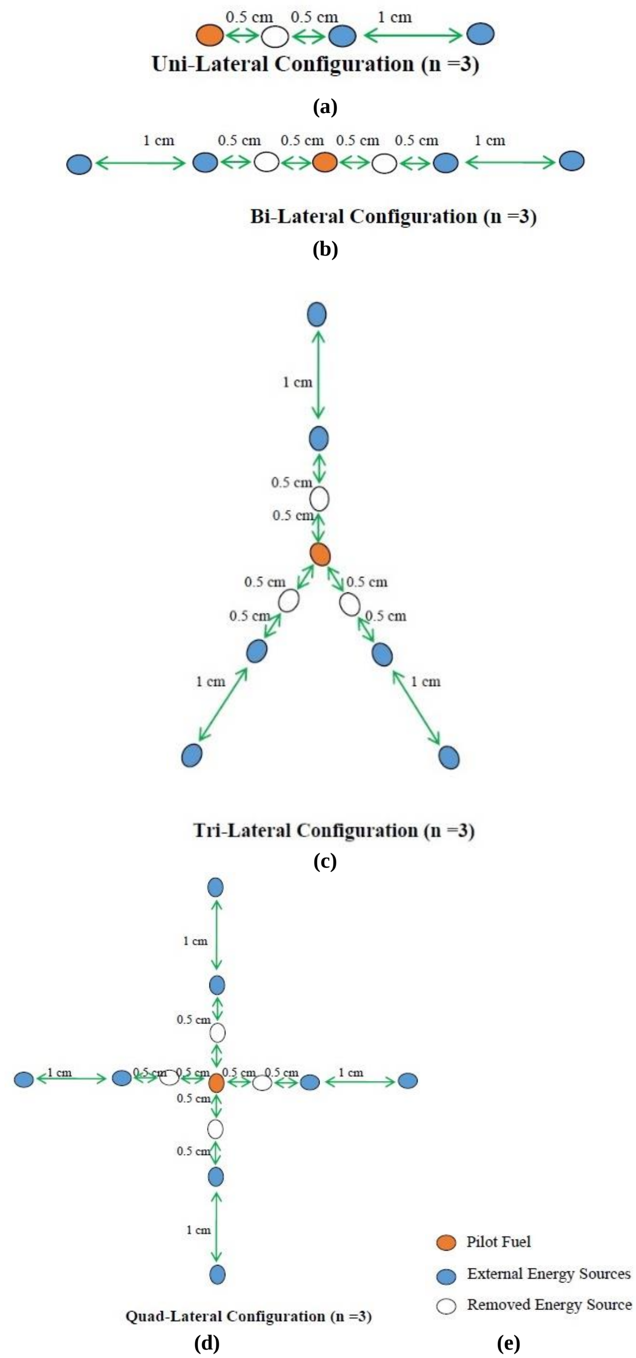
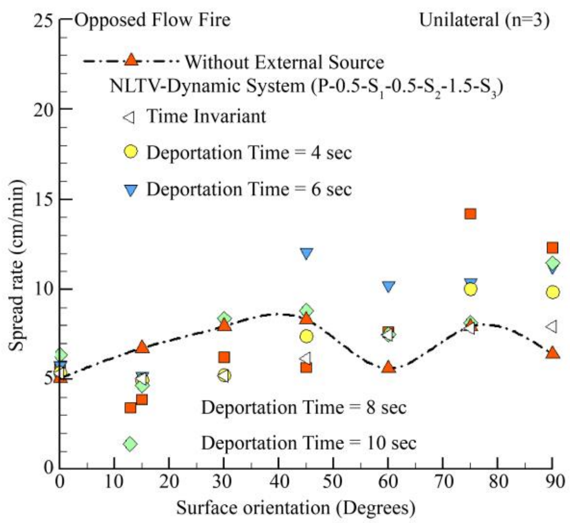
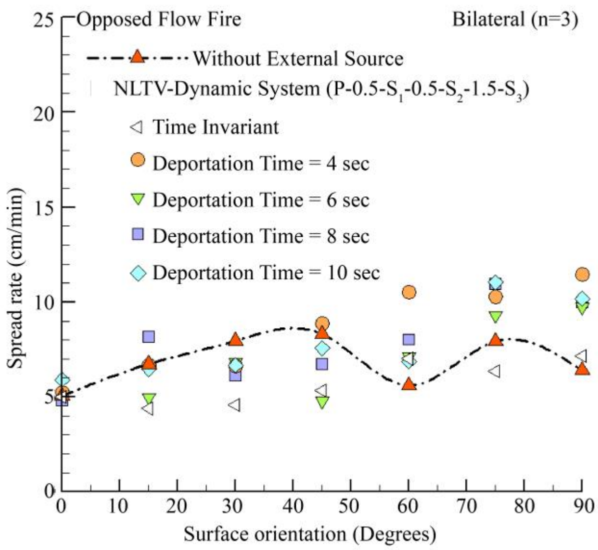


Fig. 5 Graphical representation of different configurations for the NLTV dynamic model: (a) Uni-lateral, (b) Bi-lateral, (c) Tri-lateral, (d) Quad-lateral, and (e) Energy sources.



(a)



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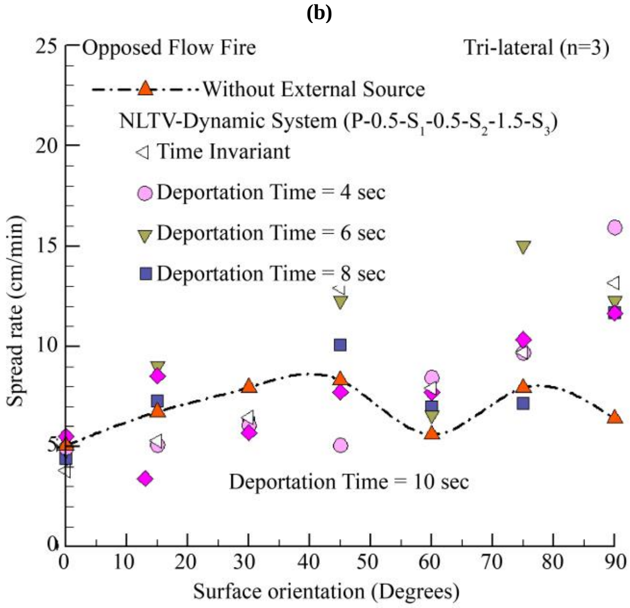

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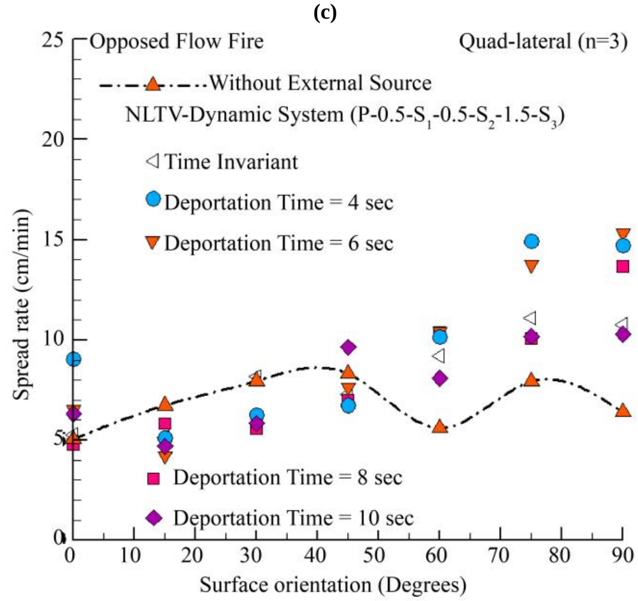


(d)

Fig. 6 Variation of spread rate with surface orientation in NLTV Dynamic System for selected configurations of: (a) Unilateral, (b) Bi-lateral, (c) Tri-lateral, and (d) Quad-lateral.

Next, the effect of nonlinearity on the spreading fires in the form of non-equidistant placement of external energy sources was assessed at distances of 5mm, 1mm, and 2mm away from the pilot fuel, as well as removal of external energy sources in the immediate vicinity at varying deportation time. Figure 6 shows the spread rate variation for different non-linear configurations with varying deportation times.

The plots also highlight a comparison with the Linear Time Invariant (LTI) dynamic model to deeply understand the significance of spatial and temporal nonlinearity. As external energy sources were placed non-linearly (non-equidistant) and one in the immediate vicinity was removed after a selected time, a mixed non-monotonic pattern was noticed in the spread rate variation with surface orientation. Unilateral configuration depicted massive heat source effect with 154% rise at 60˚ and heat sink effect of 34.34% drop at 30º for 4 sec. Whereas, for 6 sec, the maximum heat source effect was found to shift to 82.09% at 45˚. Similarly, the maximum heat sink effect increased by 26.24% drop at 15˚ surface orientations.

For the cases of late removal with 8 sec, the maximum heat source effect was noted as 92.34% rise at vertical orientation (90˚), followed by the maximum heat sink effect of 42.30% drop at 15˚. For 10 sec, the maximum heat source effect of 78.96% was followed by a 30.73% drop of heat sink effect at 15˚ surface orientation. The Bilateral configuration was found to follow a similar pattern as Unilateral, with a different rate of change. The cases of early removal, viz., 4 sec, 6 sec, resulted in an 87.25% rise at 60˚ for 4 sec, which drops to 52.10% at 90˚ for 6 sec.

In contrast, the maximum heat sink effect of 16.76% at 30° upshifted to 42.21% drop at 45 ° surface orientation. Similarly, for the cases of late removal, viz., 8 sec, 10 sec, the Bi-linear configuration depicted the maximum heat source effect of 56.32% at 90 °, which transformed to 58.97% at 10sec. However, the maximum heat sink effect of 22.78% at 30° for 8 sec dropped to 16.21% at 10 sec. Tri-lateral configuration for deportation time of 4 sec resulted in maximum heat source effect of 148.61% at 90° and maximum heat sink effect of 39.17% drop at 45°. For 6 sec, the maximum heat source effect remains at 90 °, but the rate of increase drops to 91.61%.

The maximum heat sink effect shifted to 27.35% at 30° surface orientation. Deportation time of 8 sec resulted in 82.71% heat source effect at 90 ° and 21.94% maximum heat sink effect at 30°. Deportation time of 10 sec, followed the prior pattern with maximum heat source effect of 82.09% at 90 ° and maximum heat sink effect of 28.35% at 30°. It is interesting to note that the Quad-lateral configuration in the NLTV dynamic model normalizes the same influence with maximum heat source effect at 90° for all deportation times. Whereas, the maximum heat sink effect falls in the realm of (15° - 45°).

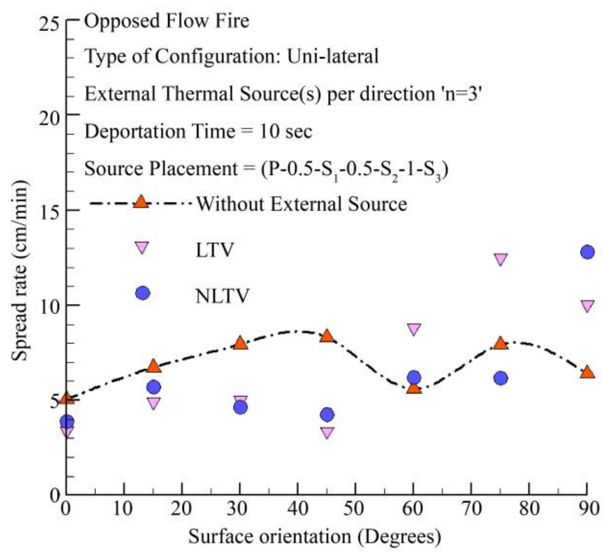
3.4. Role of External Energy Source Availability on Pilot fuel Spreading for Varying Configurations in a Non-Linear Time Variant (NLTV) Dynamic System

Next, the effect of nonlinearity on the spreading fires in the form of non-equidistant placement of external energy sources, such as 5mm, 1mm, and 2mm away from the pilot fuel, along with the removal of external energy sources in the immediate vicinity, was assessed. To evaluate the nonlinearity effect, the variation of fire spread rate with surface orientation for different configurations in LTV and NLTV dynamic models for a deportation time of 10 seconds each was compared (see Figure 7) to maintain simplicity, feasibility of experimentation, and gain useful physical insight. Looking at the plots, one can note a similar mixed hybrid non-monotonous pattern in the spread rate variation for both LTV and NLTV models. However, the nonlinear (non-equidistant) placement of external energy sources was found to result in altered thermal energy interaction among Primary and Secondary systems.

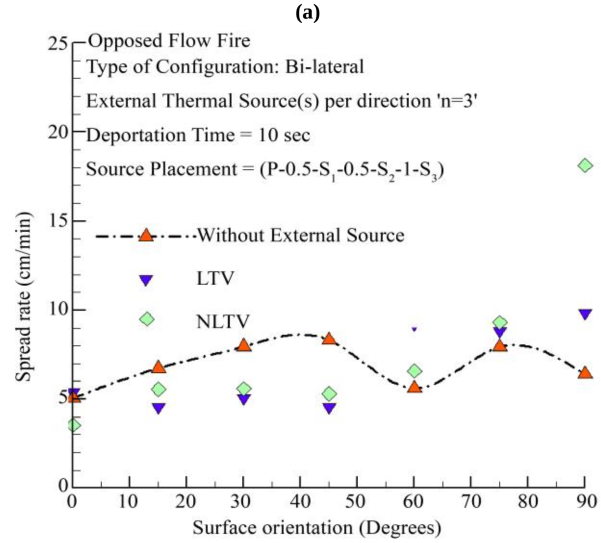
For the Unilateral configuration in the LTV model, maximum heat source effect was noted for vertical orientation (90°) with a 45.39% rise in spread rate, whereas maximum heat sink effect was noted with a 57.15% drop at 30°. However, owing to the effect of nonlinearity, the maximum heat source effect rises to 78.96% for vertical orientation (90°), and the maximum heat sink effect shifted to 30.73% drop at 15°.

Bilateral configuration in the LTV model recorded maximum heat source effect of 110.86% at 60° and maximum heat sink effect of 23.59% drop at 15° however, owing to the nonlinearity under similar conditions, maximum heat source effect was noted to drop to 58.97% at vertical orientation (90°) and maximum heat sink effect dropped to 16.21% at 30° surface orientation. Tri-lateral configuration in the LTV model showed maximum heat source effect of 78.46% at vertical orientation (90°) and maximum heat sink effect of 16.61% drop at 15°. Under similar conditions, nonlinearity was noted to cause a rise in the maximum heat source effect to 82.09% and a maximum heat sink effect to 28.35% drop at 30°.

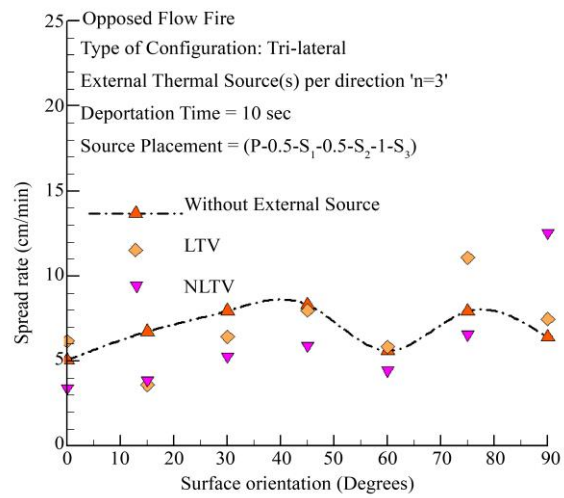
Similar changes were documented in the Quad-lateral configuration, with the presence of the nonlinearity (NLTV) model resulting in shifting of the maximum heat source effect to 60.69% for vertical orientation (90°) and uplifting the maximum heat sink effect to 30.36% drop at 30° surface orientation.



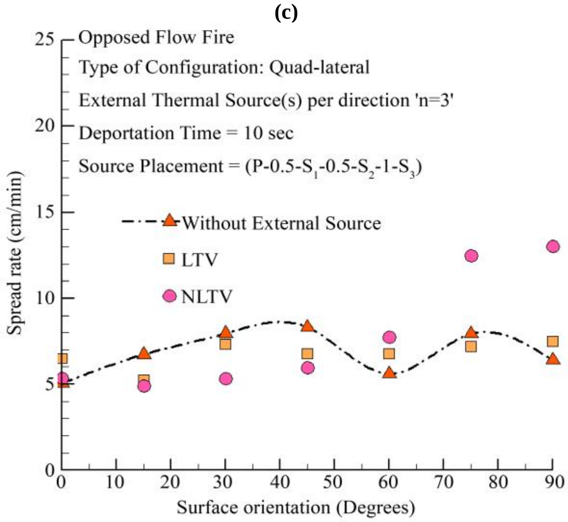
(a)



(b)



(c)



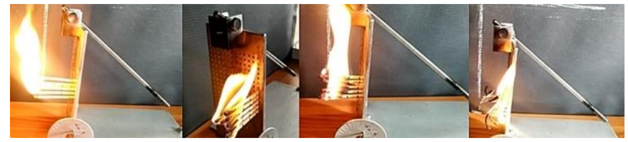
(d)

Fig. 7 Comparison of spread rate with surface orientation in LTV (Linear Time Variant) and NLTV (Non-Linear Time Variant) Dynamic System for selected configurations of (a) Uni-lateral, (b) Bi-lateral, (c) Tri-lateral, and (d) Quad-lateral.

To substantiate, Figure 8 shows the experimentation images for selected configurations at vertical orientation under the Non-Linear Time Variant (NLTV) dynamic model. The images are frames at 10-second intervals and represent fire behavior. Analysis of the images reveals altered fire behavior, resulting in instances of partial and complete combustion, as well as extinction, with varying configurations that support uneven energy transfer following pilot fuel ignition. The observation primarily reflects that instability as well as unsteadiness in flames grow with time, resulting in faster propagation and an increase in flame height.

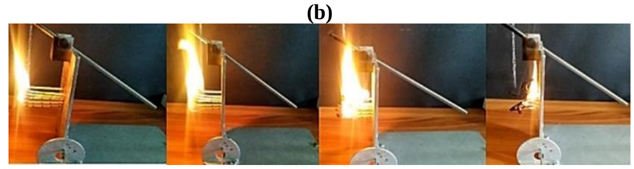
(i) (ii) (iii) (iv)

(a)



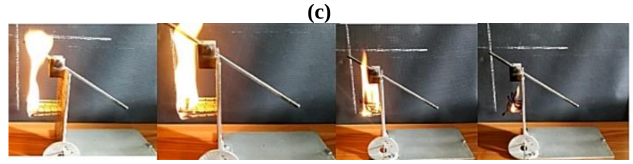
(i) (ii) (iii) (iv)

(b)



(i) (ii) (iii) (iv)

(c)



(i) (ii) (iii) (iv)

(d)

Fig. 8 Pictorial representation of experiments at vertical orientation in Non-Linear Time Variant (NLTV) Dynamic System for selected configurations of (a) Unilateral, (b) Bi-lateral, (c) Tri-lateral, and (d) Quad-lateral, for timestamps of (i) 10 seconds, (ii) 20 seconds, (iii) 30 seconds, and (iv) 40 seconds.

4. Conclusion

Systematic experiments to investigate nonlinearity in spreading fires were performed, and the data obtained were used to identify the key controlling parameters for flame propagation in a nonlinear array of external energy sources. As per the outcomes, subsequent conclusions can be drawn:

1) The presence of nonlinearity significantly alters the thermal energy interaction between the pilot fuel and an array of external energy sources. It is reflected in the measurement of the spread rate.
2) Results for non-linear configurations were compared with the linear configurations, and they confirmed the heterogeneous nature of fire propagation irrespective of the type of configuration of external energy sources.
3) The availability of external energy sources (time variant) directly affects the pilot fuel burning process significantly. The occurrence of the majority of the heat sink effect from (0˚- 45˚) and the heat source effect at higher orientations (45˚- 90˚) was established.
4) Non-Linear Time Variant (NLTV) dynamic model experimentation for different configurations highlights changed "fire behavior, resulting in cases of partial, complete burning, along with extinction. Observation largely reflects that instability and unsteadiness in flames grow with time, resulting in faster propagation and enhanced flame height.
5) Application of the Work: The findings and outcomes of this study have direct practical implications in mitigating resource losses caused by propagating fires through the prediction of fire propagation. This research contributes to the development of effective strategies for the early

detection, assessment, and management of fires. The predictive capabilities derived from this work can assist in proactive planning, resource allocation, and decision-making procedures, ultimately resulting in enhanced fire prevention, control, and mitigation measures. Future studies can be enthusiastically planned on the NLTV dynamic model to gain true replication at the lab scale with fire spread rate measurement.

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