Experimental Investigation of the heterogeneous fire propagation in real time scale

Jayesh Sharma[1], Mir Raza Ali Naqvi[2], Saurabh Randive[3], Vinayak Malhotra[4 *]

[1]Department of Aerospace Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai, India, 603203

Abstract: Forest fire, building fire and explosion of rockets are some examples of uncontrolled self-igniting and propagating fires. The uncertainty around such large-scale fires has led to irreplaceable loss of precious lives, natural resources, systems, facilities and every year huge amount of money is spent on research efforts to prevent it. Researchers have been studying the phenomenon for a long time but are yet to replicate something that is close to reality. The study investigated the effects of external energy sources placed in different configurations under varying conditions in uncontrolled self-igniting and propagating fires. Systematic experiments were performed with a setup with matchsticks arranged in varying configurations as external sources and their effect was noted by the change in flame spread rate of the pilot fuel. Optical shadowgraphy was used to collect data which helped in rendering an insight about the heterogeneous behaviour of fire propagation, flame spread rate and associated energy transfer. It was observed that flame spread rate varies non-monotonically with orientation and number of external energy sources. The key controlling parameters were identified their effects on fire propagation was understood. A new non-dimensional number was introduced for easier understanding of results. The results obtained can be used to design state of the art fire prediction systems which would give us extra control time to minimize the losses.

1.Introduction:

Fire is an uncontrolled exothermic chemical reaction. Lightning, extreme weather, earthquake and volcanic eruption are some natural causes of fire. Open flames, explosive environments, inattention and chemical reactions are some man-made causes of fire. Fire can majorly be classified into four types: Diffusion flames, Smoldering, Spontaneous combustion and Premixed flames. Current work falls in the spontaneous combustion category. Since its discovery fire has permeated every walk of human life, from cooking food to industrial boilers to powerful rocket engines! Fire if used sensibly can give magical results. But this coin has a flip side too which is the fact that fire is unpredictable and non-linear in nature. Every year large scale uncontrolled fires such as forest fire, industrial fire, aircraft crash fire, rocket explosion causes huge loss of natural resources, infrastructure, facilities, money and precious human lives. Researchers of the domain have been studying large scale propagating fires for a long time still there is no one theory that can explain behaviour of such fires completely. Kim and DeRis [1] worked on Laminar Burning Between Parallel Fuel Surfaces and found out that burning two solid-fuel surfaces is considerably more intense than a single. Burning rate was found to be controlled by the product of Grashof number and channel aspect ratio. In the paper 'Explosion of space shuttle challenger', Masayuki Nakao [2] reported that the rocket vehicle with two booster assembly was joined by O-rings.

Due to cold weather, O-ring stiffened and lost elasticity. As Chamber pressure increased in booster, External walls Expanded. Space shuttle developed Flame on the side of Solid Rocket Booster. Fuel leak from gas leak inspection hole was ignited by the flame, resulting in an explosion. Following the work of Drysdale and Macmillan [3] the effect of inclined surfaces on flame spread rate was understood. Urban [4] worked on the interactions between downward spreading flames over parallel solid sheets of paper studied in normal gravity and in microgravity, where the tests were conducted over a variety of pressures and separation distances to expose the influence of the parallel sheets on oxidizer transport and on radiative feedback. Malhotra and Kumar [5] stated that heat sinks are effective in reducing the flame spread rate when placed at distance less than flame width. Meshed heat sinks with a greater number of wires per unit length are more effective heat sinks. Liu et. al., [6] studied spatial distribution of the burning rates in group fires consisting of large number of fire points. The spatial fluctuations of the two interaction effects are significantly affected by the two major parameters viz., fire spacing and fire array size. Richardson [7] performed an empirical case study of the explosion data from full scale solid rocket launch vehicle accidents. 12 accidents or applicable tests were found and discussed for the blast waves from these explosions. Chemical process proved to be the dominant mechanism for the completeness of the reaction and flame length.

Figure 1.1: California Wildfire (2020). (metro.co.uk)

Figure 1.2: Emirates Airlines flight EK521 Crash Landing.(Popular Mechanics)

National Fire Prevention Association (NFPA) reports significant increase in land forest burned with 8.5 million acres, structured fires loss up by 10.7 billion USD and annual rise in wild-land fires by 77% every year [8]. Every fifth fire death in world is in India. India alone recorded 1.6 million fires and 27,027 deaths in 2017 only [9]. The motivation for taking up this work is to minimize these losses due to fire by developing a better understanding of the physics behind such large-scale fires and then applying it to predict and handle these fires in their initial stages. The specific objectives of the work are:

1. To investigate the combustion characteristics and identify key controlling variables in fire propagation of an array of external thermal energy sources that resemble concurrent fires that occur in real world.
2. To understand the role of key controlling parameters for fire propagation under different conditions.

2.Experimental Setup and Solution Methodology:

A lab scale setup (refer figure 1) was designed and manufactured to perform the experiments. Surface plate of the setup has [15 X 15] matrix of equidistant holes placed at 0.5cm from each other. The setup was so designed that the external energy sources (matchsticks) could be arranged in various configurations and kept at different orientations ranging from 0 to 90 degrees.

Matchsticks were marked as shown in figure 02, first 0.5 cm was left for the flame to stabilize and then it was marked at every 1 cm. The time taken to burn 2 cm of matchstick was noted.

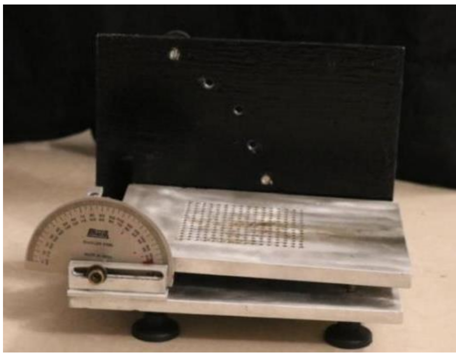
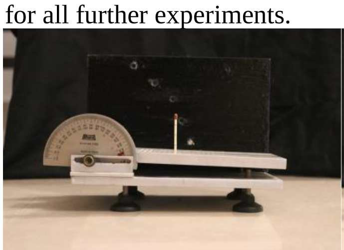
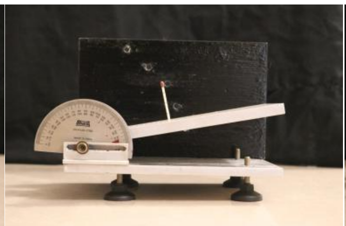
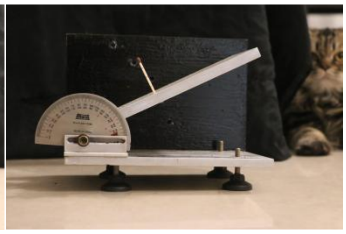



Figure 2.1: Experimental setup. Figure 2.2: Matchstick marking.

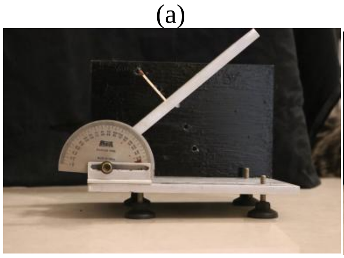
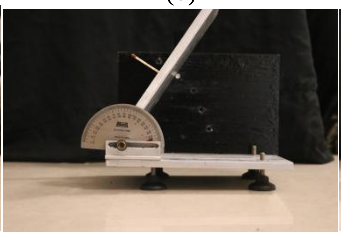
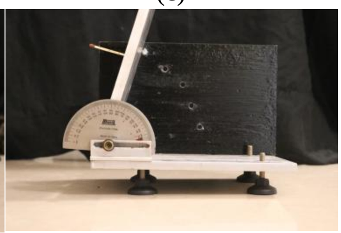
Spread rate is defined as the rate at which flame propagates on a fuel surface specifically denoted as:

$$\text{Spread rate}, r = \frac{Distance\ burnt\ along\ the\ matchstick\ surface\ (2\ cm)}{Time\ taken\ (to\ burn\ 2\ cm\ of\ matchstick)}$$

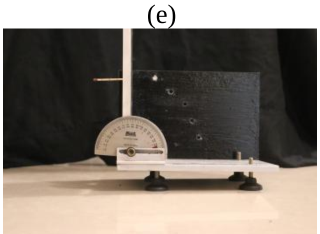
Initially a pilot case experiment was performed with a single matchstick kept at seven different orientations (0, 15, 30, 45, 60, 75 and 90 degrees). The spread rate of the pilot stick was noted for all the orientations and used for validation of the setup and also as a reference value for all further experiments.

(a) (b) (c)

(d) (e) (f)



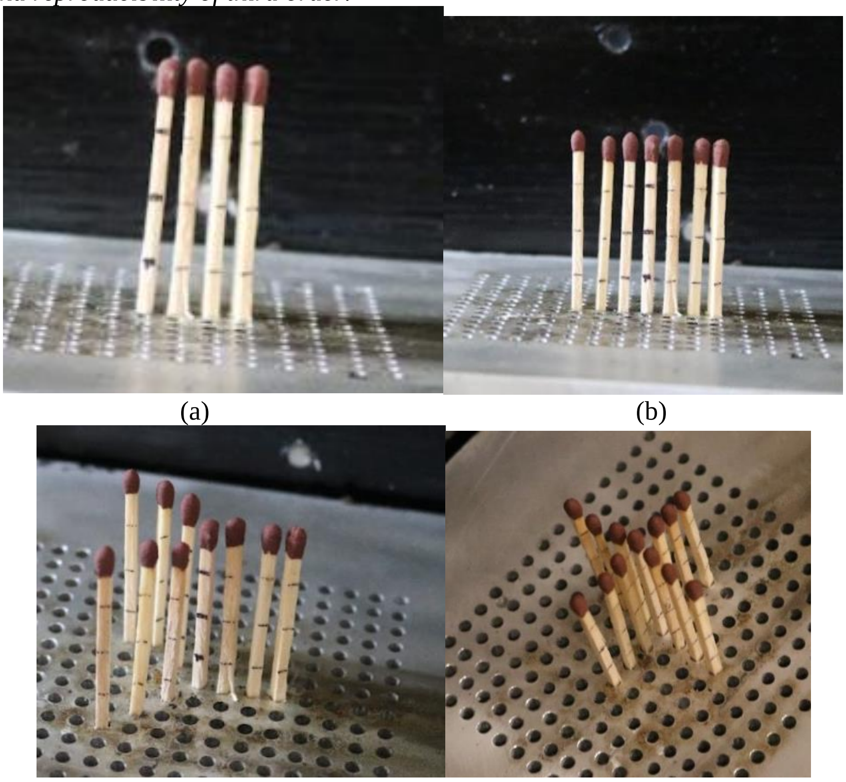
(g)

Figure 2.3: Pictorial representation of the base case experiment with pilot at different orientations - (a)0° (b)15° (c)30° (d)45° (e)60° (f)75° (g) 90°.

External energy sources were introduced in four configurations: Unilateral, Bilateral, Trilateral and Quad-lateral. The matchsticks were kept in a linear fashion with 0.5 cm interspace distance. Experiments were performed for N = 1,2,3,4 (where N denoted the number of external sources in per branch/direction) for all the configurations at all orientations from 0-90 degrees with a 15° interval.

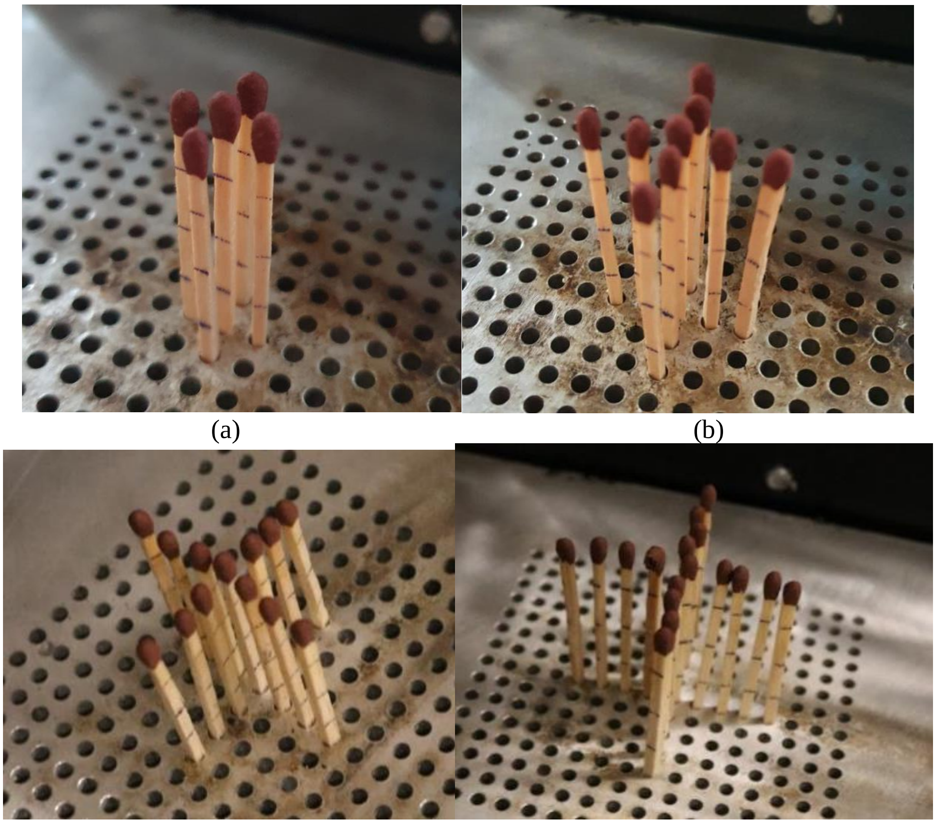
In every experiment, only the pilot stick was ignited which led to ignition of the external sources. The flame spread rate of the pilot stick were noted in each case.

It is important to note that all the experiments were performed at normal room temperature and pressure and the data presented ahead has repeatability and reproducibility of third order.



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

Figure 2.4: Pictorial representation of the different configurations for N = 3 - (a) Unilateral, (b) Bilateral, (c) Trilateral, (d) Quad-lateral.



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

Figure 2.5: Pictorial representation of varying number of external sources in Quad-lateral configuration - (a) N = 1, (b) N = 2, (c) N = 3, (d) N = 4.

According to the Classical Forward Heat Transfer Theory, spread rate is given by:

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

where,
$\int$ q(net) - is the net heat transfer (heat generated minus heat lost)
ρ - is the fuel density,
τ - is the thickness of solid fuel,
c - is the speed of sound for that medium,
T(surface) - is the fuel surface temperature,
$T(\infty)$ - is the ambient temperature.
It is evident from the formula that spread rate is a good indicator of the net heat transfer and consequently the energy interactions taking place between two thermodynamic systems. The pilot matchstick forms the primary system and all other external sources (matchsticks) combined form the second thermodynamic system. Any change in the flame spread rate of the pilot can therefore be directly attributed to the energy interaction between these two systems.

3.Results and Discussion:

3.1 Base case study

Initial experiments were performed with a single pilot fuel to validate the experimental setup prediction and to obtain the reference values of flame spread rate at different orientations. It is evident from figure 3.1 that the spread rate of pilot stick shows a non-monotonic trend with surface orientation. The maximum flame spread rate 8.571 cm/min was noted at 45°, which is in agreement with the Conventional Forward Heat Transfer Theory. Thus, the setup was also validated to give believable results. In presence of external energy sources, flame spread rate of pilot fuel may differ from the reference values owing to the energy interactions between the two thermodynamic systems (Primary system - pilot matchstick, Secondary system - all external energy sources combined). Flame spread rate is directly proportional to the net integrated heat transfer occurring between the two systems. Flame propagates on the pilot fuel stick because of the temperature difference between the flame front and the matchstick surface. Flame spread rate is directly related to the temperature difference between flame front and fuel surface (which remained constant in our case as all the experiments were performed at normal room temperature) and therefor the flame spread rate varies directly with the flame front temperature which in turn is directly related to the amount of heat heat generated by combustion. Inherently the external sources (secondary system) can act either as a heat source or a heat sink or a neutral system.

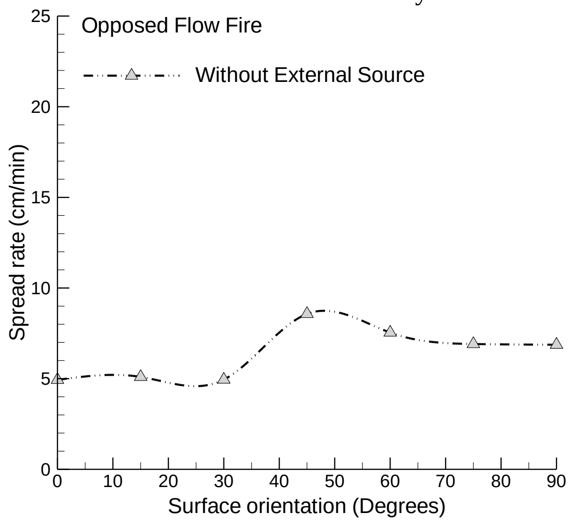


Figure 3.1: Effect of surface orientation on spread rate of pilot fuel without any external sources.

When acting as a heat source the secondary system supplies more energy to the pilot (primary system) than it receives from the pilot and thus net heat transfer is from the external energy sources towards the pilot. The pilot fuel receives extra energy from the secondary system and therefore has more energy than the base case which leads to an increased flame front temperature compared to base case. And therefore, the spread rate increases. Inversely when acting as a heat sink the secondary system receives more energy from the pilot than the amount of energy it supplies to the pilot and thus net heat transfer is from the pilot towards the external energy sources. The pilot fuel supplies a fraction of energy generated to the secondary system, as a result it is left with less energy than the base case which leads to a decrease in flame front temperature when compared to base case. And therefore, the spread rate decreases. In the third case, secondary system supplies the same amount of energy to the pilot that it receives from the pilot and therefore the net heat transfer is zero, and therefore the spread rate is equal to the reference value. For ease of understanding of the results ahead a new non-dimensional number is defined as the Spread Rate Coefficient (ξ). Spread Rate Coefficient is the ratio of flame spread rate in presence of external thermal energy sources to the flame spread rate of pilot fuel without any external sources.

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

$\xi < 1$ signifies that the flame spread rate of the pilot has decreased due to the presence of external energy sources. And therefore, we can say that the secondary system (all external sources combined) acts as a heat sink.

ξ = 1 signifies that the flame spread rate of pilot has not changed due to the presence of external energy sources. The secondary system (all external sources combined) act as a neutral system in this case.
ξ > 1 signifies that the flame spread rate of the pilot has increased due to the presence of external energy sources. The secondary system (all external sources combined) acts as a heat source in this case.

3.2 Effect of configuration type on Pilot fuel spreading rate.

It is evident from the above graphs that for a fixed N value, different configurations of external energy sources have a heterogeneous effect on the spread rate of pilot fuel even though the configurations were linear. The spread rate for each case was compared to reference value from base case experiment. From figure 3.2 and table 1 it can be seen that majority of the points for this case lie above the reference value i.e., ξ > 1 for these configuration and orientation combinations, still there are some points where ξ < 1 and these are the points of interest which might lead to increased control and rescue time in case of an actual fire. From figure 3.2 and table 1, for N = 1 case maximum rise of **72.39%** was seen at 75° in Trilateral configuration. Maximum drop of **42.46%** in spread rate was seen at 60° in Unilateral configuration. At 15° the spread rate values for Unilateral, Bilateral and Trilateral configurations are within a range of 5% from each other and all of them have Spread Rate Coefficient slightly less than one. This leads us to believe that the secondary system is acting as a heat sink in these cases and the direction of net heat transfer is from the pilot fuel towards the secondary system. A part of the energy produced by the combustion of pilot fuel is transferred to the secondary system and therefore the amount of energy left for its own combustion is less than that of the base case, this leads to a decreased flame spread rate in these cases. It is also noted that ξ > 1 for all the configurations at 90° surface orientation.

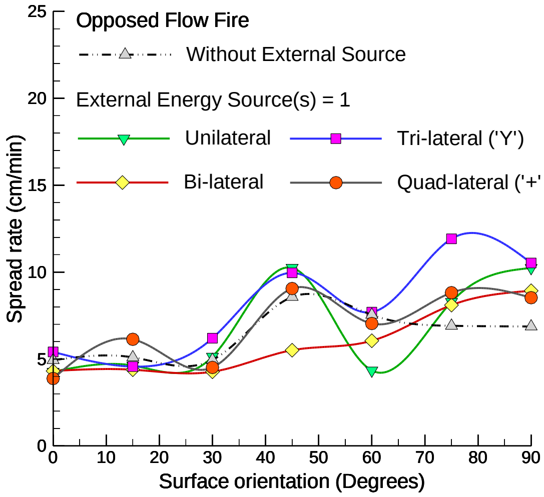


Figure 3.2: For N = 1.

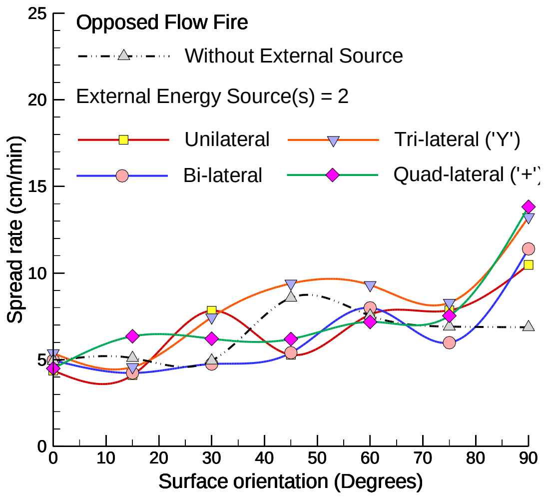


Figure 3.3: For N = 2.

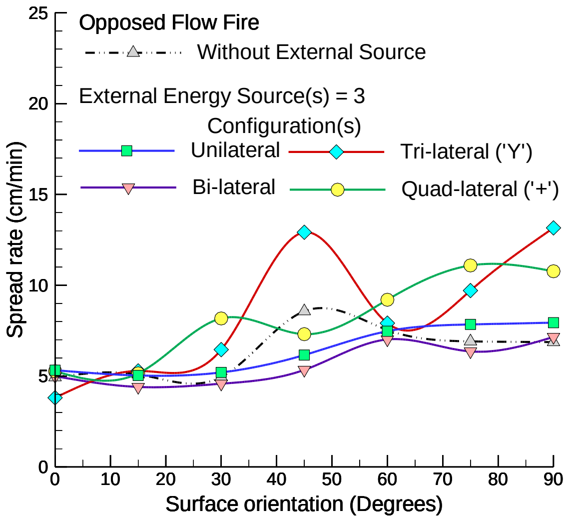


Figure 3.4: For N = 3.

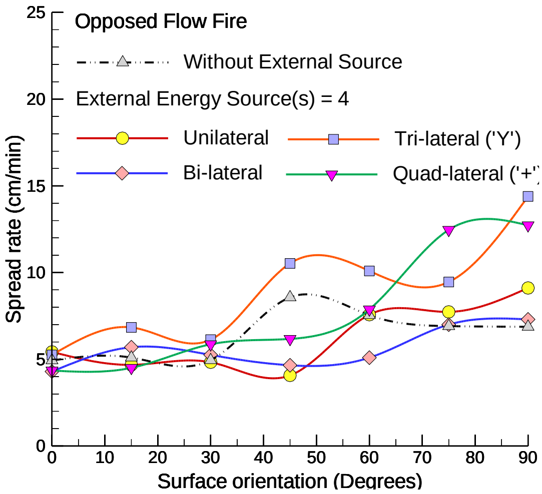


Figure 3.5: For N = 4.

Spread Rate Coefficient (ξ) variation			
UNI	BI	TRI	QUAD
0.865	0.874	1.096	0.786
0.908	0.860	0.896	1.203
1.038	0.862	1.253	0.913
1.196	0.642	1.162	1.057

0.575	0.802	1.021	0.934
1.199	1.172	1.724	1.276
1.490	1.298	1.532	1.241

Table 1: Spread Rate Coefficient for N = 1 case.

From figure 3.3 and table 2, for N=2 the maximum rise of **101.13%** occurred in Quad-Lateral configuration at 90°. The maximum drop of **38.32%** at 45° in Unilateral configuration was also observed. It was noted that the Spread Rate Coefficient (ξ) was well below 1 for all configurations except Trilateral at 45° surface orientation. It means that the secondary system was acting as a heat sink for these cases.

Spread Rate Coefficient (ξ) variation			
UNI	BI	TRI	QUAD
0.886322188	1.00668693	1.089766971	0.911043566
0.80659082	0.830521773	0.897214594	1.245978815
1.581851253	0.959983832	1.504446241	1.255254648
0.616730837	0.630264847	1.096371485	0.722319449
1.007557677	1.059931053	1.234287987	0.952134712
1.135416667	0.865451389	1.198929398	1.090422454
1.523497745	1.658082351	1.924923614	2.011348756

Table 2: Spread Rate Coefficient for N = 2 case.

From figure 3.4 and table 3, for N=3 the maximum rise of **91.43%** was seen at 90° in Trilateral configuration. Maximum drop of **37.67%** was seen at 45° in Bilateral configuration. At 15° the spread rate values for Unilateral, Trilateral and Quad-lateral configurations are within a range of 5 % from each other and also from the reference value, the external energy sources were acting as an almost neutralizing system in these cases. It was noted that the *Spread Rate Coefficient (ξ)* was below 1 for all configurations except Trilateral at 45° surface orientation, the secondary system was acting as a heat sink for these cases.

Spread Rate Coefficient (ξ) variation			
UNI	BI	TRI	QUAD
1.079027356	1.012158055	0.771631206	1.067274569
0.987642213	0.863672028	1.036484896	1.009807768
1.051535974	0.925828618	1.305173808	1.651980598
0.718702602	0.623264497	1.507058686	0.852642632
0.990586051	0.930389817	1.049456378	1.220100769
1.134693287	0.919994213	1.404513889	1.604600694
1.155390659	1.041030118	1.914302342	1.567146806

Table 3: Spread Rate Coefficient for N = 3 case.

From figure 3.5 and table 4, for N = 4 the maximum rise of **109.34%** was seen at 90° in Trilateral configuration. Maximum drop of **52.51%** was seen at 45° in Unilateral configuration. And it is again observed that the *Spread Rate Coefficient (ξ)* was below 1 for all configurations except Trilateral at 45° surface orientation, the secondary system was acting as a heat sink for these cases.

Spread Rate Coefficient (ξ) variation			
UNI	BI	TRI	QUAD
1.099088146	0.869908815	1.064032421	0.881864235
0.917614751	1.117104747	1.341114162	0.88387603
0.975545675	1.061236863	1.239086500	1.184721099
0.474857076	0.542993816	1.228094738	0.720102672
1.003712543	0.67528507	1.338106603	1.044020154
1.118489583	1.012297454	1.368055556	1.802806713
1.325621999	1.061981667	2.093408992	1.851447694

Table 4: Spread Rate Coefficient for N = 4 case.

4.2 On Specific role of configuration Type on the Effect of Irregular Energy Transfer on Linear time invariant dynamic fire spread system(s).

For a given configuration, the effect of number of external sources per branch was heterogeneous with some notable special cases. From figure 3.6, for Unilateral configuration the spread rate was almost equal for all cases except N = 1 at 60°, also these points coincide with the reference value i.e., ξ = 1, the secondary system was a neutral system for these cases. At 75° the spread rate for all the four cases falls in a 10% range of each other and is greater than the spread rate for base case. Secondary system was acting as a source at these points and therefore the *Spread Rate Coefficient (ξ)* was greater than 1 for all of them. The maximum percentage rise was seen at 30° for N = 2 case.

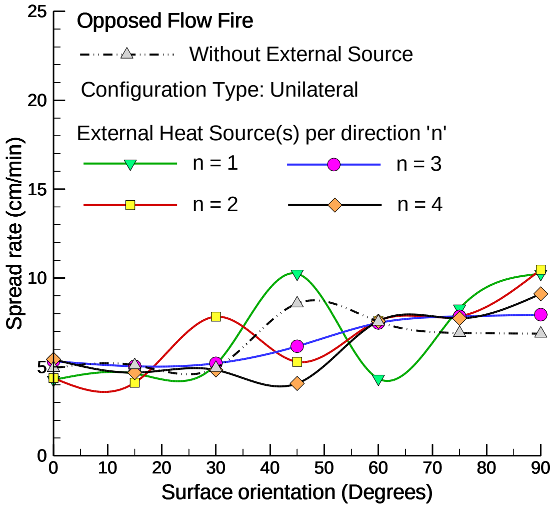


Figure 3.6: Unilateral Configuration.

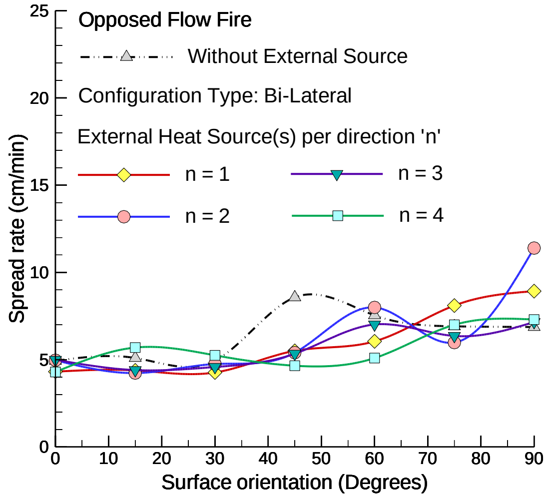


Figure 3.7: Bilateral Configuration.

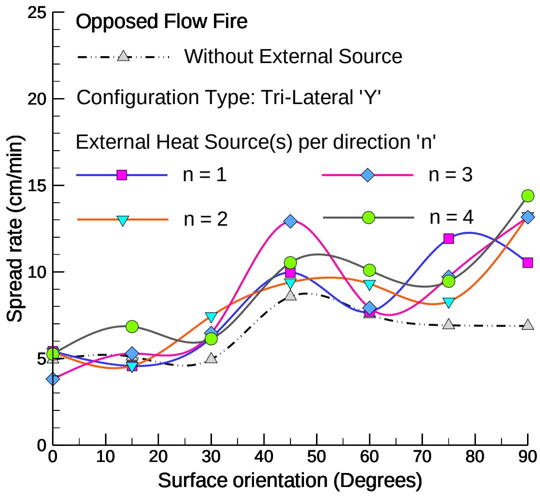


Figure 3.8: Trilateral Configuration.

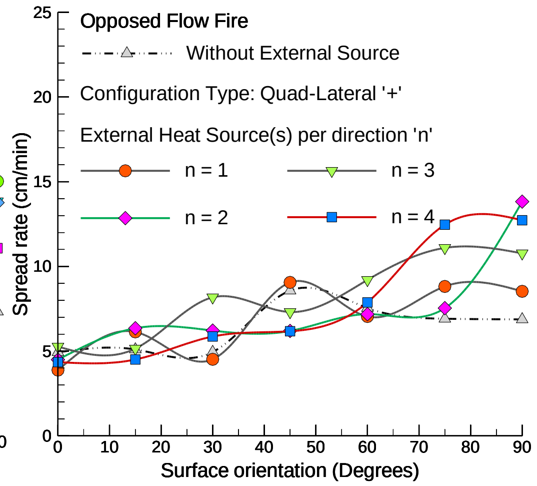


Figure 3.9: Quad-lateral Configuration.

From figure 3.7, for Bilateral configuration it is evident that for majority of the cases $\xi < 1$ i.e. the secondary system (all external sources combined) acts as a heat sink for all these cases and therefore the spread rate is less than the base case value for these points. Also, the trend for all cases except N = 4 resembled each other from 0° to 45°. From figure 3.8, for Trilateral configuration it is evident that for majority of the cases $\xi > 1$ i.e. the secondary system (all external sources combined) acts as a heat source. This configuration has the maximum heat transfer from external sources to the pilot, which leads to an increased spread rate. From figure 3.9, for Quad-lateral configuration it is seen that $\xi > 1$ for all cases at 75° and 90°, the secondary source acts as a heat source for all these cases. $\xi < 1$ for all cases except N = 1 at 0° and 45°, the secondary source acts as a heat sink for all these cases.

4.Conclusion:

The objective of this project was to investigate the characteristics of heterogeneous fire propagation in real time scale. This was done by fabricating a setup and performing a number of experiments for four configurations: Unilateral, Bilateral, Trilateral and Quad-lateral. The number of external sources per branch were varied from 1 to 4 and the surface orientation was varied from 0° to 90° with a 15° interval. The setup was first validated by a base case experiment and the reference values of flame spread rate were obtained. The base case experiment showed that the variation of flame spread rate of pilot fuel even without any external sources is non-monotonic.

The results were different for almost every combination of a particular configuration and N and this showed the heterogeneity of fire propagation. Few special cases of crossovers were observed. A novel non-dimensional number entitled the *Spread Rate Coefficient (ξ)* was introduced for ease of understanding of the results, it directly gives inferences on the nature of secondary system (all external sources combined). $\xi > 1$ specifies that the secondary system is acting as a heat source, $\xi < 1$ specifies that the secondary system is acting as a heat sink and $\xi = 1$ denotes that the secondary system is a neutral one. This term indicates the extents of damage that might be caused by fire accidents.

Application of the work:

Based on the results obtained the work has direct applications in minimizing the loss of natural resources by prediction and better handling of forest fires. One specific application of the work is in Space Propulsion and results state clearly that: On local scale, the understanding and application of data obtained would result in better testing, validation and designing of future rocket vehicles. On global scale, in terms of initialization, manufacturing, and maintenance, it is expected to result in better management of time, energy and money investment for space agencies. Based on these results new framework and guidelines for fire-safety can be formed. The knowledge gained might lead to some solution and application in predicting large scale fires in buildings, industries, forests, airplanes and rockets and that would give us sufficient control and rescue time to minimize the damage.

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