Experimental Investigation of configuration types and array of external heat sources on downward spreading fires

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Abstract. Scholars and scientists have been attempting to discover ways to control and lessen the reverberation of concurrent fires such as forest fires, building fires, and other various space fires but no convincing solutions have been concluded from their studies so far. The fundamental genesis of these types of fires concerns the unstable nature of the flames and considerable unpredictability associated with them. This led us to make an effort to study the etiquette of such flames – an experimental setup with rather ideal conditions was devised and an in-depth study was carried out. The present study predominantly covers the study of fire propagation phenomena and the zeal of fire control in our daily life. This study includes the review of the varying regression rates and fire spread rates of flames as noticed in matchsticks when spaced in a linear orientation. The deportment instability of the flames will give us an insight into the heterogeneous fire propagation phenomenon and its control. Intuition into the heterogeneous fire propagation is expected for essential fire safety and, on its basis, an algorithm for the same is to be formulated. With this understanding along with the existing information, it might give us some possible solution to the reduction of such kinds of fires in buildings, forests, space propulsion systems and, large-scale fires in industries.

Keywords: Forward Heat Transfer, Array of External heat sources, Downward Spreading fires.

1. Introduction

Fire is undeniably one of the exceptional inventions by mankind and it has been a continuous source of human evolution. Efficient utilization of fire has resulted in a magnificent development in the fields of Engineering, Industrialization, the Practical world, Functional and operational systems in diverse domains. While the fire is a very common occurrence almost everyone takes to use its field of engineering, Industrialization, Practical world, Functional and operational systems in diverse domains, it also has the capacity to be out of control, presenting a critical situation to human lives and properties. The fire has also been the origin of the biggest disasters that occurred in the forms of large-scale fires in industries, forest fires, building fires, Aircraft and Rocket crashes, which lead to illimitable loss of mankind, nature, resources, and every year an immense amount of money is being invested on research to prevent fires. From the data given by the National Fire Prevention Association (NFPA), it was recorded that around 8.5 million acres of land are lost due to forest fires, around 10.7 billion dollars (USD) was estimated to be structured fire loss. The loss of residential, industrial, educational institutions
was evaluated to be around 10,700 million dollars (USD). The report suggests that the rate of loss is rising at an alarming rate of 77% each year. The most recent forest fires in Amazon, Australia, and California lead to the loss of more than 1.676,473 hectares of land. The loss is estimated to be around more than USD 1.620 billion (USD) only for California fires have caused utmost damage and danger to human and animal life, property, and the environment. Apart from the forest, the fire propagation in aircraft like in collision of Saudi Arabian Airlines Flight 763 and Kazakhstan airlines B747 leads to the loss of 349 lives.

The present work highlights elementary the in-depth knowledge of the fire propagation phenomenon. To know the physics of fire-related issues, it is required to know about the fire propagation events. The energy spends by the combustion of fossil fuels such as natural gas, oil, and coal is more than 80% of total energy. Combustion is defined as the rapid chemical fusion of a substance with oxygen that involves the production of heat and light. The main factors required to support combustion are (a) oxygen insufficient amount, b) fuel or combustible material, and (c) appreciate heat to reach the ignition temperature. The process of combustion is mainly classified into two types (1) The heterogeneous reaction of solid fuel with an oxidizer is called smoldering combustion, whereas (2) the homogenous reaction of gaseous fuel with the oxidizer which releases more heat is called flaming combustion. The present work emphasis on flaming combustion. In this type of combustion, the flame spread is observed which is the rate of flame movement across the fuel surface. The opposed flame spread rate is defined as the direction of airflow that is opposite to that of flame propagation. The Propagation of the reaction zone or combustion wave through the combustible mixture is Flame Propagation. When the transport of free radicals and heat has started a chemical reaction in an adjacent layer of the combustible mixture, the layer itself becomes the source of heat and radicals and is then efficient of starting reaction in the following layer. The temperature increases to the maximum temperature that flame can attain. For many decades, humankind has experienced plenty of accidents that have occurred due to fire. In essence, most of these accidents transformed as a result of fire (or flame) propagation. Researchers have attempted to quantify the fire spread rate for more than 60 years, and many mathematical models have been developed.

From the conventional work done by Fons [1] firstly by assuming that the fuel is preheated by convective, conductive, and radiative heat transfer from the flaming zone to ignition. Most work investigating flame spread through separate fuels has been performed using wooden sticks of various sizes where the flame spreads in the either horizontal or inclined configuration. Vertical wooden matchsticks were used by Vogel and Williams [2] to model horizontal discrete fuel flame propagation by determining necessary conditions for discrete fuel flame spread and by changing the spacing and length of matchsticks. A convection-controlled theory was started by using a constant flame temperature and stand-off distance, which had good agreement with experimental results. Miller [3] extended the study to arrays in the form of a rectangular lattice. The number of matchsticks per column was 8 and the number of matchsticks per row was varied from 1 to 9. The flame propagation rate appeared to increase asymptotically as the number of rows was increased. A solid array of paper strips separated by space in increasing amount was used by Emmons and Shen [4] for measuring fire-spread rates. Prahl and Tien [5] analyze horizontal flame spread over vertically-oriented matchsticks and paper strips by adding an opposed wind velocity. Correlations between fuel height, fuel spacing, wind velocity, and flame spread were explored by considering fundamental theory. From work, by C.C hwang [6] it was concluded that the rate of flame propagation along vertically orientated matchstick arrays increases as the angle of plate
is increased (positive for uphill burning and negative for downhill burning). From the photographs of the flame zone taken by schlieren and thermocouples, it was concluded that the flame propagation is controlled by the width of the preheated region. Recently, Gollner et al. [7] explored flame spread through a single vertical column of matchsticks. Based on the observed phenomenon, buoyancy was expected to control flame spread between matchsticks, and a theory based on convective heat transfer was developed to predict flame spread and burning rates. Recently, numerical studies on flame spread over parallel thin fuel samples in a reduced gravity environment were reported for the concurrent flame spread in Shih [8] and opposed flow flame spread in Malhotra et al. [9]. In both these studies, the flame spread rate exhibited a non-monotonic variation with a decrease in separation distance. In the following work on composite fabric by Johnston et al. [10], on long thin composite fabric fuels made of 25% fiberglass and 75%, cotton upward flame spread experiments were conducted. The width of the fuel specimen was varied from 2.5 cm to 8 cm. Effect of fuel width on flame blow-off was reported. From the experiments done by Avinash [11], the flame propagation was investigated from degrees -90 to +90 for thin cellulose papers. It was found out that the maximum rate of propagation is at +90 degrees and as the number of external fuel cells increases fluctuations in flame spread rate are observed for upward flame propagation cases and are much larger for the case of 90°. These fluctuations are due to the formation and shedding of vortices, and also because of a sudden shift in the flame location as a result of cracking of the thin fuel. Results from several models based on energy balance were compared against the experimental results. Tiwari et. al., [12] investigated to gain physical institution into the acoustic thermal energy interaction and related implications on smoldering combustion. Experiments were carried on incense stick with a proper variation of fuel to sound source distance with a fixed frequency and variation of surface orientation. Under varying conditions, the effect of acoustics was evaluated with variation in fuel regression rates. The result showed that by varying source separation distance the forward heat transfer rate increases by Thermo acoustics interactions. From the experimental work done by Jiang [13], they studied the flame propagation for different spacing for wooden dowel arrays. It was found out for the smaller 0.75 and 0.875 cm spacings, flames would spread both vertically and horizontally simultaneously were as for the largest spacing, 1.5 cm, flames would spread only vertically along the central column. By considering these predictions, the mass-loss rate was also predicted. Tatnell et. al., [14] inspected the coupling and confinement of current in thermoacoustic phased arrays. The work showed that arrays of these sources generate sound unique to this mechanism. From the sound alone, the current flow was spatially resolved by varying the film geometry and electrical phase.

The specific objectives of the work are:
1) To study the effect of number of external heat sources in the form of distinct configurations on the pilot fuel.
2) To fundamentally understand the role of key controlling parameters.

2. Experimental Setup and Solution Methodology

In a state to study the fire propagation phenomenon, a simple apparatus was upraised coupled with external heat sources. The apparatus consists of a) a mild steel plate, b) a rod to vary the orientation of the plate, c) Matchsticks as a fuel source, and d) a protractor (As shown in fig 4). The match sticks had a 0.5 cm separation region followed by three 1 cm markings (as shown in fig 5). A mild steel plate was
used to fix the match sticks perpendicular to the base. The interspace distance between the match sticks was 0.5 cm. The study is about the fire propagation phenomena and study of fire for various regression rates and fire spread rate of flames.

**Figure 6.** For Unilateral Configuration (a) n=1, (b) n=2, (c) n=3, (d) n=4, (e) n=5.

**Figure 7.** For Bilateral Configuration (a) n=1, (b) n=2, (c) n=3, (d) n=4, (e) n=5.

**Figure 8.** For Trilateral Configuration (a) n=1, (b) n=2, (c) n=3, (d) n=4, (e) n=5.

**Figure 9.** For Quad-lateral Configuration (a) n=1, (b) n=2, (c) n=3, (d) n=4, (e) n=5.

**Forward Transfer Theory**

From the Second Energy Equation we know that:

Energy Change = Energy produced – Energy lost

So,

\[ \rho_s C_s V \frac{dT}{dt} = q_p - q_L \tag{1} \]

where, \( q_p = \Delta H V C_A \alpha e^{(E_a/R)T} \tag{2} \)

\( q_L = hA(T - T_a) \tag{3} \)

Hence, according to Classical Forward Heat Transfer Theory, the Flame spread rate (r) is given by:

\[ r = \frac{\int q_{net}}{\rho_s C_s V (T_{surf} - T_0)} \tag{4} \]

**Measurement**

The rate at which the surface burns is called the Flame spread rate which is linearly calculated as:
The term $q_{net}$ is the difference between the energy generated and the energy lost. Where,

- $\rho_s$: Density of the solid fuel
- $\tau_s$: Thickness of the solid fuel
- $c_s$: Speed of sound in that medium
- $T_{Surface}$: Temperature of the surface
- $T_{\infty}$: Temperature of the surroundings
- $dT/dt$: Change in temperature
- $q_p$: Energy produced
- $q_L$: Energy lost
- $A^*$: Pre-exponential factor
- $E_a$: Activation energy
- $R$: Ideal gas constant
- $T$: Temperature in kelvin
- $H$: Thermal Conductivity constant
- $A$: Cross-sectional area of the material
- $T_a$: Ambient temperature
- $q_{net}$: Total Energy
- $c_s$: Speed of sound in the material
- $T_{\infty}$: Temperature of the surroundings
- $r$: Flame spread rate.

The experimentation was conducted at normal room temperature and readings were taken properly ensuring orderliness and conformity in every case. It is important to note that every data presented here represents the repeatability and reproducibility of third order.

**Figure 10.** Match sticks placed in 4 configurations (a) unilateral (b) bilateral (c) ‘Y’ (d) ‘+’.

**Figure 11.** Matchstick at different orientations (a)0° (b)15° (c)30° (d)45° (e)60° (f)75° (g) 90°

The match sticks were fixed on the mild steel plate for four different configurations (Fig 10): (a) unilateral (b) bilateral (c) Y (Trilateral) and (d) + (Quad lateral). The burn rate was measured at various angles varying from 0 to 90 degrees with a constant interval of 15 (Fig 11). The main objective was to
carry out sets of experiments of the mentioned configurations at various degrees. In each case, the flame spread rate of the pilot fuel was measured by noting down the time taken to burn 1 cm of the match stick. Images and videos were taken in order to capture the special cases of the phenomenon.

3. Results and Discussion

![Figure 12. Effect of Surface orientation on flame Spreading phenomenon.](image)

The initial experimentation was performed to obtain the base case values of the flame spread rate. It is important to note that the flame spread rate of the pilot fuel was measured at all orientations. From the plot, it can be observed that the trend is non-monotonic with the maximum burn rate of 5.142 cm/min at 45 degrees. These values are taken as a reference for comparison of flame rate for different configurations coupled with external heat sources. In accordance with traditional heat transfer theory over thin solid fuels, the propagating front spreads by heat feedback (forward heat transfer) from the burning to the unburnt solid fuel upstream. This results in an increase or decrease in regression rates. It is due to convective buoyant flow, localized velocity, and temperature fields are formed around the fuel surface. Additional energy and preheating are provided by high-temperature smoke which carries heat moving parallel to the fuel surface. High cumulative heat transfer from burnt to unburnt fuel can be attributed to high regression rates. The further results were divided into three cases.

1. Heat Sink Zone: The heat transfer in this regime drops due to the decrease in the localized temperature around the pilot fuel. The reason is not enough oxygen gets enter to fume the pilot fuel. Hence the regression rate for this case is less compared to the pilot fuel.

2. Neutralizing zone: In this case, the heat transfer is constant to that of the pilot fuel. Here the regression rate is the same as that of the base case of pilot fuel.

3. Heat source zone: The cumulative heat transfer is dominating in this region because of buoyancy that carries the heat from burnt to the unburnt fuel. Hence the regression rate for this case is greater than compared to the pilot fuel.

For a particular orientation, the ratio of the flame spread rate at that particular orientation for a given number of external sources to that of flame spread rate without any external source is called the MTS number. These numbers are divided into different regimes MTS<1 is the Heat sink zone, MTS>1 is the Heat source zone and MTS=1 is the neutralizing zone. For a particular orientation, a non-dimensional number was determined. It was done to validate the effectiveness of the configuration and to analyze the effect of configurations, orientations, and external sources to that of single-pilot fuel. The MTS number is defined as the ratio of flame spread rate of the external fuel for any given source (at any orientation) to the flame spread of pilot fuel without any external source (at that orientation).

$$MTS = \frac{\text{Spread rate in presence of external source (cm/min)}}{\text{Spread rate of pilot fuel without any external source (cm/min)}}$$
Based on MTS number new regime is defined – VBS regime

1. **VBS-I**: Potential Heat sink Effect - Here the ratio of MTS number is less than 1. (MTS<1) In this effect energy from external sources is absorbed by pilot fuel.

2. **VBS-II**: Neutralizing Effect. Here the ratio of MTS number is equal to 1. (MTS=1). It does not take part in positive or negative heat sources.

3. **VBS-III**: Heat source Effect. Here the ratio of MTS number is greater than 1. (MTS>1). In this Effect, energy is supplied to external sources by pilot fuel.

**Effect of number of external source variation on Pilot fuel spreading rate**

![Graph](image)

**Figure 13. For Unilateral Configuration.**

**Figure 14. For Bilateral Configuration.**

Figure 13 shows the effect of the regression rates of pilot fuel for unilateral configuration at different orientations. The external sources vary from n=1 to n=5. The plot is compared with the base case of pilot fuel without any external source. The flame spread rate is the same for 0° orientation and the presence of 3 external heat sources (n=3). Which comes under the Neutralizing zone. An interesting thing to note is at 0° orientation when n=4 the regression rate drops by 6%. It comes under the heat sink zone. From the plot, it can be observed that at 90° orientation and when the Number of external heat sources(n) =2 the regression rate is maximum at the percentage of **76.019%**. In most cases, the regression rate comes under MTS>1. The reason is heat transfer is dominating in this region because of buoyancy that carries the heat from burnt to the unburnt fuel.

| Orientation (degree) | n=1  | n=2  | n=3  | n=4  | n=5  |
|----------------------|------|------|------|------|------|
| 0                    | 1.34 | 1.30 | 1.00 | 0.94 | 1.55 |
| 15                   | 1.38 | 1.35 | 1.33 | 1.28 | 1.39 |
| 30                   | 1.60 | 1.39 | 1.73 | 1.60 | 1.33 |
| 45                   | 1.03 | 1.46 | 1.36 | 1.94 | 1.07 |
| 60                   | 2.30 | 1.22 | 2.30 | 1.32 | 1.33 |
| 75                   | 3.20 | 1.68 | 2.00 | 2.91 | 1.89 |
| 90                   | 3.33 | 4.17 | 2.56 | 2.39 | 3.33 |

Table 1. MTS number variation for Unilateral Configuration.

Figure 14 shows the effect of the flame spread rate of pilot fuel for Bilateral configuration at different orientations. The external sources vary from n=1 to n=5. The plot is compared with the base case of pilot fuel without any external source. From the plot, it can be observed that at 90° orientation and when the number of the external source(n) = 4, the regression rate is maximum with a rise of **76.019%**. All the values for flame spread rate for bilateral configuration come under the heat Source zone (MTS > 1). Heat transfer is dominating in this region because of buoyancy that carries the heat from burnt to the
unburnt fuel. An interesting thing to note here is they were no Heat sink effect and neutralizing effect for this configuration.

Table 2. MTS number variation for Bilateral Configuration.

| Orientation (degree) | n=1  | n=2   | n=3  | n=4  | n=5  |
|----------------------|------|-------|------|------|------|
| 0                    | 1.50 | 1.36  | 1.13 | 1.22 | 1.25 |
| 15                   | 1.47 | 1.35  | 1.67 | 1.28 | 1.25 |
| 30                   | 3.75 | 1.85  | 1.23 | 1.55 | 1.37 |
| 45                   | 1.17 | 1.40  | 1.13 | 1.59 | 1.06 |
| 60                   | 1.15 | 1.39  | 1.81 | 1.90 | 1.65 |
| 75                   | 2.00 | 2.29  | 1.85 | 2.09 | 1.78 |
| 90                   | 2.63 | 2.63  | 2.94 | 4.17 | 2.08 |

Figure 15, shows the effect of the regression rates of pilot fuel for Trilateral (Y) configuration at different orientations. The external sources vary from n=1 to n=5. The plot is compared with that of the base case of pilot fuel without any external source. At 45° orientation coupled with 3 external sources (n=3) the flame spread rate is the same as that of the base case. Which makes it a Neutralizing effect. An interesting thing to note here is at 45° orientation and when n=2 the regression rate drops by 20% which is the minimum for this configuration. It comes under the heat sink zone (MTS<1). The maximum rise occurs at 90° orientation and when n=3 the regression rate rises by 77.97%. In most cases, the regression rate comes under the Heat source zone (MTS>1).

![Figure 15](image.png)

**Figure 15.** For “Y” Configuration.

![Figure 16](image.png)

**Figure 16.** For “+” Configuration.

Table 3. MTS number variation for “Y” Configuration.

| Orientation (degree) | n=1  | n=2   | n=3  | n=4  | n=5  |
|----------------------|------|-------|------|------|------|
| 0                    | 1.12 | 1.36  | 1.45 | 1.29 | 1.32 |
| 15                   | 1.22 | 1.51  | 1.72 | 1.45 | 1.67 |
| 30                   | 2.10 | 2.53  | 1.09 | 1.14 | 3.01 |
| 45                   | 1.35 | **0.80** | **1.00** | 1.09 | 1.13 |
| 60                   | 1.31 | 1.44  | 1.41 | 1.52 | 2.23 |
| 75                   | 2.00 | 2.67  | 2.82 | 2.67 | 2.09 |
| 90                   | 3.13 | 3.57  | 4.54 | 3.84 | 2.50 |
Table 4. MTS number variation for “+” Configuration.

| Orientation (degree) | n=1   | n=2   | n=3   | n=4   | n=5   |
|---------------------|-------|-------|-------|-------|-------|
| 0                   | 1.43  | 1.15  | 1.22  | 1.29  | 1.50  |
| 15                  | 1.51  | 1.83  | 2.08  | 1.47  | 1.85  |
| 30                  | 1.47  | 2.00  | 1.60  | 1.76  | 1.60  |
| 45                  | **0.92** | 1.35  | 1.84  | 1.52  | 1.42  |
| 60                  | 1.73  | 1.52  | 1.81  | 1.73  | 1.73  |
| 75                  | 2.82  | 2.67  | 2.53  | 4.36  | 3.43  |
| 90                  | 3.13  | 3.57  | 3.57  | 3.84  | 4.17  |

Figure 16 shows the effect of the flame spread rate of pilot fuel for Quad-lateral “+” configuration at different orientations. The external sources vary from n=1 to n=5. The plot is compared with that of the base case of pilot fuel without any external source. From the plot, it can be observed that at 75° orientation and when the number of the external source is equal (n=4), the regression rate is maximum with a rise of 77.06%. Most of the values for flame spread rate for “+” configuration comes under the heat source zone (MTS>1). An interesting thing to note here is at 45° orientation and when n=1 the flame spread rate is minimum with a drop of 8%. Another point to be noted from this plot is that there is no Neutralizing effect occurred for this configuration.

Effect of configuration type on Pilot fuel spreading rate

Figure 17 shows the comparison of flame spread rate for various configurations at different orientations. For this, the number of external sources is kept constant (n=1) and the flame spread rate of pilot fuels for all configurations are compared. It is interesting to note that the highest flame spread rate is found for the Unilateral configuration for this case. The flame spread rate increases by 69.96%. The reason is, forward heat transfer is dominating in this region because of buoyancy that carries the heat from burnt to the unburnt fuel. The flame spread rate at 45° orientation for Quad-lateral configuration is minimum with a drop of 8%. It comes under the heat sink regime (MTS<1). For all the other cases the heat source effect is observed (MTS >1). Another point to be noted is that there is no Neutralizing zone for this case.

Figure 17. Number of external sources(n=1).

Similarly, in Figure 18, the number of external heat sources is increased to 2, and values of flame spread for pilot fuels were measured for different configurations at an interval of 15 degrees. The values were compared with the Regression rate of pilot fuel without any external source. An interesting thing to note here is that for Tri-Lateral configuration the flame rates drop by 20% which is the minimum for this case. It comes under the heat sink zone (MTS<1). This is because of less oxygen entering the flame of pilot fuel. The maximum rise of about 76.019% for unilateral configuration at 90° orientation is achieved. The reason is, forward heat transfer is dominating in this region that carries the heat from burnt to the unburnt fuel.

Figure 18. Number of external sources(n=2).
For Figure 19, the regression rate of pilot fuel for all different configurations is measured when the number of external sources is fixed to 3 (n=3). It was compared with that of the base case (without external source). Here the interesting thing to note is for Unilateral configuration at 0° orientation and for trilateral configuration at 45° orientation, the regression rates were found to be similar to that of the base case. It comes under the Neutralizing zone (MTS=1). The maximum rise in regression rate was found out at 90° orientation for Trilateral configuration. The maximum rise in flame spread rate was 77.97%. Another point to be noted from this plot is that there is no heat sink zone (MTS<1). Most of the regime comes under the Heat source zone (MTS>1). The reason is, forward heat transfer is dominating in this region. Hence the regression rate for this case is greater than compared to the pilot fuel.

Figure 19. Number of external sources(n=3).

Figure 20 shows the comparison of flame spread rate for various configurations at different orientations. For this, the number of external sources is kept constant (n=4) and the flame spread rate of pilot fuels for all configurations are compared. It is interesting to note that the highest flame spread rate is found at 75° orientation for quad-lateral configuration. The flame spread rate rises by 77.06%. The reason for this rise is connective heat transfer, which is dominating in this region. The flame spread rate at 0° orientation for unilateral configuration drops by 6% which is the minimum for this case. It comes under the Heat sink regime (MTS<1). For all the other cases the Heat source effect is observed (MTS>1). Another point to highlight from this plot is that there is no Neutralizing effect (MTS=1) observed in this case.

Figure 21. Number of external sources(n=5).

In Figure 21, the regression rate of pilot fuel for all different configurations is measured when the number of external sources is fixed to be five (n=5). It was compared with that of the base case (No External heat source). The maximum rise in regression rate was found out at 90° orientation for Quad-
lateral configuration. The rise in flame spread rate was 76.01%. Another point to be noted from this plot is that there is no heat sink zone (MTS<1) and no neutralizing zone (MTS=1). All of the regression rates come under the Heat Source zone (MTS>1). Hence the regression rate for this case is greater than compared to the pilot fuel.

**Effect of configuration type on external heat source spreading rate**

![Figure 22. Flame spread rate at ‘n1’.

In Figure 22, the regression rate of 1st external source (n1) for all the configurations at different orientations is compared with the pilot fuel without any external source. The maximum rise in regression rate was found out at 75° orientation for Quad-lateral configuration with a rise of 72.89%. The minimum raise is about 0.99% at 45° orientation for Quad-lateral configuration. For all the configurations the MTS regime is in the Heat source regime (MTS>1), due to the fact connective heat transfer is dominating in this region, which carries the heat from burnt to the unburnt fuel. Hence the regression rate for this case is greater than compared to the pilot fuel.

**Table 5. MTS Number variation of ‘n1’ for different configurations.**

| Orientation (degree) | Unilateral configuration | Bilateral configuration | Y configuration | + configuration |
|----------------------|--------------------------|------------------------|----------------|----------------|
| 0                    | 1.13                     | 1.36                   | 1.14           | 1.36           |
| 15                   | 1.28                     | 1.43                   | 1.11           | 1.19           |
| 30                   | 1.47                     | 1.33                   | 2.35           | 1.39           |
| 45                   | 1.07                     | 1.17                   | 1.30           | 1.01           |
| 60                   | 2.11                     | 1.27                   | 1.36           | 1.90           |
| 75                   | 3.41                     | 1.71                   | 1.97           | 3.69           |
| 90                   | 3.33                     | 2.78                   | 2.93           | 3.33           |

**Effect of Energy interaction on spreading rate**

In Figure 23, the flame spread rate of unilateral configuration for the first external source (n1) is compared with that of pilot fuel without an external source and with the external source. The maximum rise is at 75° orientation with a rise of 70.61%. The minimum raise is about 6.54% at 45° orientation. Most of the values for flame spread rate for unilateral configuration comes under the Heat Source zone (MTS>1). This is due to forward heat transfer. When compared to the pilot fuel the MTS number rises by 3.63% for 45° orientation and maximum drop is obtained at 0° orientation of about 13.87%. An interesting point to be noted here is for 60° and 90° orientations the flame spread rate is constant for both pilot and first external source(n1). It comes under the Neutralizing zone (MTS=1).
Figure 23. For Unilateral Configuration.
In Figure 24, the regression rate for Bilateral configuration, for the first external source (n1) is compared with that of pilot fuel without external source and with the external source. The maximum rise is at 90° orientation with a rise of 64.02%. The minimum rise is about 14.52% at 45° orientation. A point to be noted is there is no heat sink effect and no neutralizing effect observed for this case. When compared to the pilot fuel the MTS number rises by 2.05% for 90° and the maximum drop is obtained at 30° of about 40.52%. An interesting point to be noted here is for 45° orientation the flame spread rate is constant for both pilot and first external source. Here Neutralizing effect is observed.

Figure 24. For Bilateral Configuration.
In Figure 25, the flame spread rate for the trilateral configuration for the first external source (n1) is compared with that of pilot fuel without an external source and with the external source. The maximum rise is at 90° orientation with a rise of 65.87%. The minimum raise is about 9.90% at 15° orientation. All the values for flame spread rate for trilateral configuration come under Heat Source zone (MTS>1). When compared to the pilot fuel of the configuration the MTS number rises by 8.87% for 15° and the maximum drop is obtained at 45° orientation of about 6.55%. Another point to be noted from this plot is that there is no neutralizing zone.

Figure 25. For ‘Y’ Configuration.
In Figure 26, the regression rate for Quad-lateral configuration for the first external source (n1) is compared with that of pilot fuel without an external source and with the external source. The maximum rise is at 75° orientation with a rise of 72.89%. The minimum raise is 0.99% at 45° orientation. All the values for flame spread rate for Quad-lateral configuration come under the Heat source zone (MTS>1). This is due to the connective heat transfer, which is dominating in this region that carries the heat to
move from burnt to unburnt fuel. A point to be noted is there is no heat sink zone (MTS<1) and no Neutralizing zone (MTS=1) in this case. When compared to the pilot fuel the MTS number rises by 8.93% for 45° and the maximum drop is obtained at 15° of about 17.81%.

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5. Conclusion

An experimental investigation of the characteristics of spread rate for matchsticks arranged in different configuration types (Uni, Bi, Y, and +) and an array of external heat sources were studied on downward spreading fires. The influences of angular orientation and spread rate variation on pilot fuel for various external sources are investigated systematically. Angular orientation was varied from 0 to 90° in the interval of 15. The number of external sources is varied from n=1 to 5 and the effect of flame rate on pilot fuel for each configuration was studied. Also burn rate for the first external source was studied in detail for all four configurations. Based on the results it can be concluded that the external heat source affects forward heat transfer from burnt to unburnt pilot fuel.

1. For Unilateral configuration the plots vary non-monotonically with almost every case (MTS>1). At zero degree for n=3 the MTS number is equal to 1 and n=4 the MTS number is less than 1.
2. For bilateral configuration, flame rates vary non-monotonically and are always in the Heat Source zone for pilot fuel and the first external source.
3. For Tri and quadrilateral configuration, the flame rates vary non-monotonically for both pilot fuel and external heat source. For trilateral at 45 degrees for n=2, the MTS number is less than 1, that is it is in the heat sink zone whereas at n=3 the MTS number is equal to 1.
4. For quadrilateral at n=1, the MTS number is less than 1. For quadrilateral, there is no Neutralizing zone. External heat source results in increasing flame rate owing to enhanced heat transfer to unburnt fuel. Forward heat transfer with a parallel heat source is mostly dominated by radiation from external heat source and conduction from pilot fuel. The governing physics of phenomena include the alternation of the reaction zone.

5. Applications of work: The work carries a wide range of applications including engineering viz., combustion and propulsion, defense systems validation, testing and upgradation like missile systems, industrial with power generation systems, practical, functional, scientific applications.

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