Self-inducing fires: the heat source effect

Sneha Gayen¹, Pritha Pal¹, Prayas Bhawalkar¹, Vinayak Malhotra¹, T Selvakumaran¹
¹Department of Aerospace Engineering, SRM Institute of Science and Technology, Kattankulathur Chennai – 603203, TN, India

Abstract. Scholars and scientists have been trying to find ways to control and alleviate the consequences of concurrent fires such as forest fires, building fires and various space fires but no compelling solutions have been concluded from their studies so far. The basic cause of these kind of fires concerns with the unstable nature of the flames and marked unpredictability associated with it. For example, the breakout of one of the deadliest wildfires in California in 2018 and the Amazon fire of 2019 shows us the gravity of the situation and also the immediate requirement to control such mishaps to save lives and properties valuable to us. This led us to make an attempt to study the behavior of such flames – an experimental setup with rather ideal conditions was devised and a thorough home-scale study was carried out. This present study mainly concerns with the study of fire propagation phenomena and the vitality of fire control in our daily life. This study involves the review of the varying regression rates and fire spread rates of flames as observed in matchsticks when spaced in both linear and non-linear orientation for different configurations. The behavioral instability of the flames will give us an insight into the heterogeneous fire propagation phenomenon and its control. An insight 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 knowledge along with the existing information, it might help us quantify the extent of fire propagation by means of a non-dimensional entity which might as well give us some possible solution to the reduction of such kind of fires in forests, buildings, large scale fires in industries, space propulsion systems.

1. Introduction
Over the years, uncontrolled fire has caused predominant damage to human and animal lives, forests, lands and properties. From the review of literature we get to know that Masayuki N. in the paper “Explosion of the space shuttle Challenger”, Failure Knowledge database/100 selected cases, 1986 wrote that as people all over the world watched on TV, NASA's space shuttle Challenger exploded immediately after launch, and took lives of all 7 members of the crew. The causes were loss of elasticity in an O-ring due to low temperature and fuel leak due to faulty design [1]. Richardson. E. H’s work on “Solid Rocket Launch Vehicle Explosion Environments” claims that from corresponding research and investigation, the results suggest that a typical Solid Rocket Launch Vehicle explosions are not similar to high explosives [2]. Peak overpressures are low, wave speeds are near sonic and fragments tend to go much slower than Mach 1. Kim, J. S. and De Ris, J proposed in their research, titled as ‘Laminar burning between parallel fuel surfaces’ at International Journal of Heat and Mass Transfer, a theoretical and experimental study is made of the factors influencing the burning rate.
between two vertical parallel fuel surfaces facing one another [3]. No radiation, infinite gas phase reaction rates and unit Lewis number are assumed. From the work of Malhotra, V., and Kumar, A in ‘Effect of gas phase heat sink on suppression of downward flame spread over thin solid fuels’, we get to know about the first effort to explore the spatial distribution of the burning rates in group fires consisting of a large number of fire points, by analyzing regression rates and burn-out time data from experimentations. The numerical model for opposed flow spreading flame is formulated and modelled to study the regression rate of the array of heat sources [4]. In ‘Multiple fire interactions: A further investigation by burning rate data of square fire arrays’, Analysis shows that the fire layer burning rates vary from outer to inner in definite nonlinear modes which also involves distinct spatial fluctuations in fire arrays. The spatial fluctuations of the two interaction effects are significantly affected by the two major parameters, fire spacing and fire array size. The average burning rates of all fire layers involve consistent variations versus fire spacing or fire array size, and the fire layers involve high comparability to the entire fire array for variations of burning rates [5]. Drysdale, D. D., and Macmillan, A. J. R. also investigated on the rate of slope on the upward flame spread over a combustible solid. Studies of upward flame spread at vertical orientation is proved to remain unsteady until and unless a constant ‘burn-out’ zone is established. The varying geometry provides interesting opportunities to study the interaction of diffusive transport mechanisms on the spread process. These transport mechanisms are changed when the flame interacts with other flames [6]. Most practical heterogeneous combustion processes involve interacting discrete burning fuel elements, consequently owing largely to this practical importance flame interactions have been an area of active research for Urban D.L to study ‘Interactions between flames on parallel solid surfaces’ [7]. Finally, a new approach is presented for initial simulation analysis for fire propagation in an array of discrete fuel sources by addressing the reverse effect of the pilot fuel on the adjacent heat sources in the publication named as ‘Multiple fire interactions: A further investigation by burning rate data of square fire arrays’ [5].

Even recently, the Amazon and the Australia fire created havoc at a global scale and costed millions of lives and destruction of forest areas which poses a significant negative impact to the ecosystem. We are taking up this project to put forward the gravity of such catastrophes and for better understanding of enhanced fire safety for futuristic space missions, forest fires, building and compartment fires. The knowledge will be helpful to device accurate prediction systems and to enhance safer and faster rescue missions in case of any fire disaster.

With that motivation in mind, the specific objectives of the work are:

a) To investigate combustion characteristics and the role of key controlling parameters for operations under diverse conditions to understand the necessity of an efficient fire control system.

b) To develop appropriate correlations based on the experimental and numerical results for effective heat energy transfer prediction in an array of heat sources which is similar to the concurrent fires that occur in everyday life.

2. Experimental Setup and Solution Methodology

A simple home-scale experimental setup was designed using matchsticks as the fuel (for both pilot as well as external heat sources). Primarily, all the matchsticks were marked at an intermediate distance of 0.5 cm along the vertical centerline (figure 1) and each matchstick was placed at a surface-to-surface distance of 0.5 cm as well, for each configuration. Initially, a base case experiment was conducted to validate this approach of the project. A single matchstick was marked and manually ignited for number of times and it gave different burning rates each time even when kept in the same surroundings.
This incurred the following observations:

1. Predictability was defined.
2. Sensing of external energy source in the immediate vicinity.
3. Energy transfer occurs.
4. Variation of data for every trial makes it believable enough.

Following this, two different categories of experimental setup were taken into consideration namely, general cases and special cases with each having multiple configurations under them.

2.1 General Cases
This category follows the linear equidistant arrangement of the external heat sources beside the pilot fuel, along a straight line for both asymmetric (configuration – 1) and symmetric (configuration – 2) conditions.

The number of external heat sources (N) is varied from (1-4) and (2,4) for configurations 1 and 2, respectively.

![Diagrammatic representation of configuration 1 setup for (a) N=1 (b) N=2 (c) N= 3 and (d) N=4](image)

**Figure 2**: Diagrammatic representation of configuration 1 setup for (a) N=1 (b) N=2 (c) N= 3 and (d) N=4
Figure 3: Pictorial representation of configuration 1 setup for (a) N=1 (b) N=2 (c) N=3 and (d) N=4

Figure 4: Diagrammatic and pictorial representation of configuration 2 setup for (a) N= 2 and (b) N=4

2.2 Special Cases
This category follows the symmetric geometry with equidistant arrangement of the external heat sources beside the pilot fuel, in a triangular design (configuration – 3) with the intermediate angle is $120^\circ$ and in a cross fashion (configuration – 4) with the intermediate angle is $90^\circ$. The number of external heat sources (N) is varied from (3,6) and (4,8) for configurations 3 and 4, respectively.
Figure 5: Diagrammatic representation of configuration 3 setup for (a) \( N = 3 \) and (b) \( N = 6 \)

Figure 6: Pictorial representation of configuration 3 setup for (a) \( N = 3 \) and (b) \( N = 6 \)

Figure 7: Diagrammatic representation of configuration 4 setup for (a) \( N = 4 \) and (b) \( N = 8 \)
After noting down the observed burn times, the rate of burn is calculated using the following formula.

\[
\text{Flame spread rate} = \frac{\text{Total distance burnt along vertical centerline}}{\text{Total burn time}} = \frac{dx}{dt}
\]  \hspace{1cm} (1)

It is to be noted that, in all the data obtained through these experiments, a repeatability and reproducibility of 3rd order was observed.

3. Results and Discussion
The experimental results led to the understanding of three different categories of outcomes:
1. Complete Combustion Case
2. Partial Combustion Case
3. Extinguished / Unburnt Case

Figure 8: Pictorial representation of configuration 4 setup for (a) N= 4 and (b) N=8

Figure 9: Pre-requisites and types of combustion [source: Wikipedia]
From the above schematic, it is clear that heat energy is a necessity for combustion to occur. So the level of energy transfer determines the type of expected outcome. The 2nd Law of thermodynamics states that heat transfer can’t occur if there is no thermodynamic source or sink present at the immediate vicinity. As from our experimental outcomes, it can be seen that the energy transfer that takes place from the pilot fuel to the atmosphere is significant enough to ignite the consecutive external heat sources – it can be said in this case that atmosphere is the sink and the energy of the pilot fuel gets converted into atmospheric energy which in turn becomes the energy supply source for the external fuels. So, the opposed flame spread rates for the pilot as well as the external heat energy for every experimental configuration, is measured and compared with the burn rate obtained from the base case experiment to study the effect of the external heat energy on the pilot fuel. The obtained values are then plotted to analyse the variation.

3.1 Graphs for base case experiment

![Figure 10: Graph depicting (a) variation of time elapsed through burning along the vertical centerline and (b) Variation of opposed flame spread rate as a function of time taken to burn along the vertical centerline.](image)

3.2 Study of the effect of flame spread rate on the pilot fuel due to the influence of external heat sources

The following plots portray the different opposed flame spread rates of every individual external fuel in a particular configuration as well as the burn rate of the pilot fuel for each configuration as a whole, when the number of external heat sources are varied. The cumulative plots for the pilot fuel of each configuration is compared with the validation case and categorized into i) all complete combustion cases and ii) all partial combustion cases only. The extinguished cases are not taken into consideration in this research.
3.2.1 Configuration 1.

**Figure 11:** Plot depicting the cumulative opposed flame spread rate for all complete combustion cases for configuration 1.

**Figure 12:** Plot depicting the cumulative opposed flame spread rate for all partial combustion cases for configuration 1.
(a) 
(b) 
(c)
Figure 13: Variation of opposed flame spread rate as a function of time taken to burn along the vertical centerline in configuration 1 for (a) N=1 (b) N=2 (c) N=3 (d) N=4

From the above graphs, for the asymmetric linear configuration, the complete combustion cases are effects of significant rise in burn rate of the pilot fuel due to external energy influence which however might also contribute negatively by slowing down the flame spread, leading to partial combustion cases.

3.2.2 Configuration 2.

Figure 14: Plot depicting the cumulative opposed flame spread rate for all complete combustion cases for configuration 2.
Figure 15: Plot depicting the cumulative opposed flame spread rate for all partial combustion cases for configuration 2.
From these above plots, it is evident that the transfer of energy due to fire propagation from the pilot fuel to the external ones is uneven, even for a symmetric geometry of arrangement which leads to most cases of partial combustion. However, even for the complete combustion cases of this configuration, the burn rates of the individual additional fuels precisely vary in both sides of the ignited matchstick.

3.2.3 Configuration 3. In this particular symmetric arrangement, significant inhibition of the fire spread has been noticed for every trial which is why it only resulted in a few partial combustion cases.

Figure 16: Variation of opposed flame spread rate as a function of time taken to burn along the vertical centerline in configuration 2 for (a) N=2 (b) N=4

Figure 17: Plot depicting the cumulative opposed flame spread rate for all partial combustion cases only for configuration 3.
3.2.4 Configuration 4. In this cross configuration, the intermediate angle of $90^\circ$ has resulted in ample amount of partial and few complete combustion cases. The notable observation in this case is that the heat transfer occurs almost simultaneously to the matchsticks placed nearer to the pilot fuel, but flame

![Figure 18](image-url)
spread from thereon is very uneven. The burn rate of the pilot fuel follows nearly the same trend for all partial and complete combustion cases.

Figure 19. Plot depicting the cumulative opposed flame spread rate in configuration 4 for (a) all complete combustion and (b) all partial combustion cases.
Figure 20: Variation of opposed flame spread rate as a function of time taken to burn along the vertical centerline in configuration 4 for (a) N=4 (b) N=8

Upon analyzing all these plots, the % changes in the burn rates for the experimental configurations with respect to the base case are calculated to provide the outcomes of the intensity

A. Maximum Drop – (%)
   - Due to minimum energy transfer.
   - Transferred energy is not sufficient enough to supply the self-ignition temperature.
   - Since energy transition was uneven, the fire can't sustain for long.
   - Leads to extinguishing of fuel.
Hence, the fire burns off automatically which gives us maximum control and rescue time.

**Table 1:** Lowest and highest percentage of drop and rise values with respect to the base case.

| DROP %     | Lowest Value | Highest Value |
|-----------|--------------|---------------|
| DROP %    | Lowest Value | 100           |
|           | Highest Value| -2.243767313  |
| RISE %    | Lowest Value | 3.217315004   |
|           | Highest Value| 91.37744035   |

**Table 2:** Maximum drop percentages divided into three ranges.

| DROP       | Range 1                  | Range 2                  | Range 3                  |
|-----------|--------------------------|--------------------------|--------------------------|
|           | -2.243 until -34.829     | -34.829 until -67.415    | -67.415 until -100       |

**B. Maximum Rise – (%)**

- Due to maximum energy transfer.
- Leads to extensive and fast fire propagation.
- Minimal control time obtained.

**Table 3:** Maximum rise percentages divided into three ranges.

| RISE       | Range 1                  | Range 2                  | Range 3                  |
|-----------|--------------------------|--------------------------|--------------------------|
|            | 3.217 until 32.603       | 32.603 until 65.206      | 65.206 until 91.3774     |

From studying the inferred result of variation, a non-dimensional number termed as the Heterogeneous Fire Behavior Identification Number \([H_b]\) is defined to quantify the extent and rate of flame spread. \(H_b\) is calculated as the ratio of burn rate of the actual configuration case to that of the base case.

To generalise the results for all kinds of fire accidents, the values were non-dimensionalised in order to make that characteristic number viable and applicable for wide range of conditions as the non-dimensional quantities are not restricted by conditional limitations.

The \(H_b\) values can be categorized into 3 different regimes as follows: High fire spread regime: \([0.8 < H_b < 1.25]\) gives the extent of fire spread which is so drastic that nothing can be done. It is totally uncontrollable. Intermediate fire spread regime: \([0.4 < H_b < 0.8]\) is further classified into low and high intermediate zones. The low intermediate zone \([0.4 – 0.6]\) defines the instance when the fire propagation is comparatively slow and sufficient control time is provided for taking remedial actions whereas the high intermediate zone \([0.6 – 0.8]\) proves to be very uncertain zone since the flame spread behaviour becomes really unpredictable. It allows minimum control time and eventually leads to uncontrolled fire within less period of time. Minimum fire spread regime: \([0 < H_b < 0.4]\) is the zone...
that provides the maximum control time and minimum risk factor as the fire has a tendency to extinguish on its own or with least human intervention.

4. Conclusion
As mentioned before, this project was aimed at studying the characteristics of heterogeneous fire propagation, the research has been performed to test the various configurations by systematic small scale experimentation that was carried out with match sticks as potential fuel and external energy source and a detailed analysis of the sectional propagation was done. The experimental setup predictions were firstly validated with the preceding heat transfer theories. All data obtained happens to follow repeatability and reproducibility of 3rd order. Notable cases of completely burnt, partially burnt and extinguished external energy sources, for different configuration were observed. The primary reason for the same, may be attributed to energy transition and redundancy.

From the experiments, it was evident that there is always a critical limit to the distance beyond which heat energy transfer is not optimum and thus it is an essential parameter. It may be because of the kinetic energy for the heat transfer at the micro-scale slowly diffuses outward thus reducing inter-particle collisions. However, the energy transfer is unsteady, variable, non-linear and heterogeneous in nature which explains why the fire propagation time is not same for all solid fuels even though the composition is homogenous. Along with that, the downward flame spread rate is also asymmetric and unpredictable. As some of the partial and complete combustion cases also included reignition conditions that can be accounted for the fact that a heat source can relight due to induction of heat energy from adjacent sources after some time, even if it had initially burnt off. This mainly occurs due to the transformation of the solid fuel into its gaseous state again, after some time, upon receiving significant amount of heat energy from the surroundings to meet the threshold level of temperature that is required to burn.

Through this experimental analysis, a new non-dimensional number called the Heterogeneous Fire Behavior Identification Number (Hb) has been introduced to simplify the understanding and classification of origin-source combustion propagation. This defined term gives us an overview for predicting the extents of damage that might be caused from fire hazards. Based on the physical insight, new guidelines in fire safety on normal and extra-territorial atmosphere can be framed. The knowledge is expected to give us some possible solution and extensive application to the prevention of fires in forests, buildings, and large scale fires in industries, space propulsion systems.

5. References
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