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Review Article

Effect of acoustic energy on onset of fire propagation phenomenon

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Abstract: Scholars and scientists have been making efforts to discover ways to control and lessen the resonance of concurrent fires such as forest fires, and various space fires; however, no potential solutions have been concluded from their studies so far. The origin of these types of fires concerns the unstable nature of the flames and the considerable unpredictability associated with them. This work led us to do proper experimentation for the effect of sound on the spreading of the flames. Sound energy as a wave is always accompanied by compression and rarefaction. As an external effect, sound in the immediate vicinity of spreading flame can affect the flame spread rates. Appreciable work had been carried out however; the effect of sound on flames in a purely natural convective environment is an aspect yet to be thoroughly understood. Flame spread rate is a direct indication of forwarding heat transfer from burning to non-burning region. Formation of localized pressure and velocity fields occurs around the pilot fuel by the presence of sound waves. Change in heat transfer may results in increment or decrement in spread rates, when compared with one without sound. The present work attempts physical insight into the effect of sound frequency of intermediate range (3500 Hz to 7500Hz) on the spreading of flames in different configurations coupled with external sources. Results advocate the noteworthy impact of acoustics on the fire propagation phenomenon in distinct modes. Experimentation have revealed that acoustics has a critical influence on fire propagation, reducing the spread rate by 100 percent in a unilateral configuration.

Keywords: *Acoustics energy interaction, Compression, Fire propagation, Rarefaction.*

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1. INTRODUCTION

Combustion refers to natural phenomena that were conquered in the earliest period of humankind's development. Being widely involved in myths and legends, fire played a special role in technological advancement. The combustion is widely used for the improvements in the fields of engineering, industrialization, the practical world, functional and operational systems in many domains. With the progression in this field, the propagating fire becomes the cause of the biggest disaster for humankind. Nowadays, because of environmental change and for getting more barren land humankind faces gigantic loss in terms of forest fires. For the developed countries like the United States, the loss due to fire is in billions. From the data of the National Fire Protection Association in the year 2018 around $25.6 billion, property damage is expected due to structured fire including $12 billion from the wildlife fires. It is expecting to increase at an alarming rate of 81% each year. Around 35000+ civilians were injured and 4000+ civilians died due to fire accidents and which is increasing at a rate of 7% each year. The forest fires around $124 million and is increasing at a terrifying rate of 77% each year. The most recent forest fires in Amazon, Australia, Simphal, and California have caused extreme harm and danger to human and animal life, property, and the environment. Likewise, in aviation, 6% of mishaps are caused due to fire engendering which prompts a colossal death toll and economy. The significant reason for the fire is the proliferation and spreading of flame. The present work focuses on the flaming combustion. In this type of combustion, flame spread rate is observed which is the rate of flame movement across the fuel surface. The contradicted flame spread rate is defined as the direction of airflow that is inverse to flame propagation. It is difficult to control these using present extinguisher technology. As far as the experiments it is known, acoustic excitation improves the combustion performance of the flame, due to the instability of the flame caused by the introduction of acoustic waves. Sound energy results in the formation of localized pressure and velocity fields around the pilot fuels, which is affected the forward heat transfer. Researchers have attempted to quantify the spread rate for more than 60 years and many empirical solutions have been provided. As shown in Fig.1 which indicates Black dragon Wildfire. Similarly, Fig. 2 shows the SpaceX starship SN4 explosion which took place because of propagating fire. Fig. 3 indicates the Saudi Arabian Flight crash in which entire crew and passengers lost their life because of engine failure which causes burn of whole aircraft.

Figure 1. Black Dragon Wildfire

Figure 2. SpaceX Starship SN4

Figure 3. Saudi Arabian Flight 763

Following the work of Chiu and Summerfield [1], Schadow and Gutmark [2] an abstract understanding of thermo-acoustics is set. The first study on a flame under acoustic excitation was performed by Lovett and Turns [3], who investigated acoustic excitation in a turbulent jet flame for an excitation frequency ranging from 2 to 1300 Hz and an oscillating velocity amplitude of 0.13–0.89 relatives to the bulk velocity issuing from the burner. Under resonant conditions, a significant change in flame structure was observed at a non-dimensional frequency of approximately 0.2 by the authors. From the work of Saito [4] the reduction mechanism of these substances may be associated with the flow field of the flame, such as flow mixing and the laminar-to-turbulent transition of the flame. Additionally, the bifurcation behavior of a flame under high-amplitude external acoustic excitation has been examined in the literature in relation to the instability of the flame [5-7]. At high oscillation amplitude, when a flame gets acoustically excited then, because of Kelvin-Helmholtz instability of flame, bifurcation can occur resulting in a splitting of flames. Splitting flames visual observation shows that meandering motion is generated in the flame which is synchronous of flame with the acoustic waves, which results in the bifurcation of the flame at high-amplitude acoustic excitation [6]. However, the details of the bifurcation mechanism of a flame require further investigation because of the physical complex. Nair [8] detected the presence of multifractality during combustion noise. Furthermore, they described the transition from combustion noise to thermoacoustic instability as a transition from chaos to order, which is reflected as the loss of multifractality in the pressure fluctuations. Huang [9] conducted experiments to investigate the acoustic-driven extinction of the fast-moving dripping flames under various acoustic environments. Different forms of fast-moving dripping flame under different fall heights were investigated and compared with the stationary candle flame. Dripping flame behaviors before extinction were also analyzed to explore the underlying acoustic extinction mechanism. In Ref. [10], Tiwari explored an actual understanding of the acoustic thermal energy interaction and related applications. Exhaustive analyses were done using incense stick with a deliberate variety of surface direction and distance between sound sources, furthermore fuel for a fixed recurrence sound. The acoustic impact was noticed and assessed with variety in fuel relapse rates under different conditions. Spreading measure on a thin solid fuel under conditions of varying surface orientation and constant exposure to sound varies significantly. The result showed that the thermoacoustic association essentially increment the forward heat move with changing source partition distance. The greatest acoustic impact happens at a moderate sound source area though, the least impact was assessed to close by the arrangement of the sound source. Two particular zones are set up dependent on the outer sound source area showing no impact and radical ascent for upward and descending spread. Mondal [11] performed the characterization of spatiotemporal behavior of the coupled acoustic field and local heat release rate fluctuations in the reaction field during the intermittency route to thermoacoustic instability. George [12] investigated the transition of a thermoacoustic system from combustion noise via intermittency to thermoacoustic instability by examining the spatio-temporal dynamics of a bluff body stabilized turbulent combustor. The incoherent or disordered regions in the instantaneous local acoustic power production were observed during the occurrence of combustion noise and aperiodic epochs of intermittency. The review paper by Magina [13] explores the influence of low and high-frequency oscillations more broadly on non-premixed flames, finding similar scaling in heat release oscillations with frequency as compared with the premixed flame response to excitation. Such fundamental studies enable scaling and dynamical trends to be used in interpreting instability phenomena in more practical configurations. Based on the complex system theory, various mitigation theories were discussed by Sujith [14]. Tantell [15] investigated the coupling and controlling of current thermoacoustic staged clusters. The work discussed that clusters of these sources produce sound special to this instrument. From the sound alone, the current stream was spatially settled by shifting the film geometry and electrical stage. Control concentrated warm to such a degree that the film properties got to be a great extent irrelevant. Within the middle of calculable logical commitments, an aspect that is however to be comprehensively examined is the role of thermoacoustic on external heat sources for various configuration at different orientations. Usually likely to have critical impacts on the engendering wonder and propelled us to study and explore fire propagation.

The main motive of our work is standards of fire safety from functional and practical significance. Appreciable work has been carried out in past but certain aspects are yet to be studied.

The specific objectives of the work are:

1) To consider fire proliferation wonder in the nearness of acoustics,

2) To see the rate of propagation on pilot fuel in presence of external sources for various configurations at a different orientation,

3) To learn about the key controlling parameters.

2. EXPERIMENTAL SETUP AND SOLUTION METHODOLOGY

In order to cogitate the fire proliferation, an experimental setup was raised. It absolutely was done in order that many parameters can be varied and studied accordingly. The setup comprises a mild steel plate as in Fig. 4, a rod to change the orientation of the plate, a matchstick as a fuel supply as shown in Fig. 5, a protractor and a speaker.

The coordinate sticks have 0.5cm division marking for flame stabilization followed by 3 marking of one cm each. The inter distance between the matchsticks was fixed to be 0.5 cm which is referred as the external sources and is varied from 1 matchstick to 5 matchstick for each case.

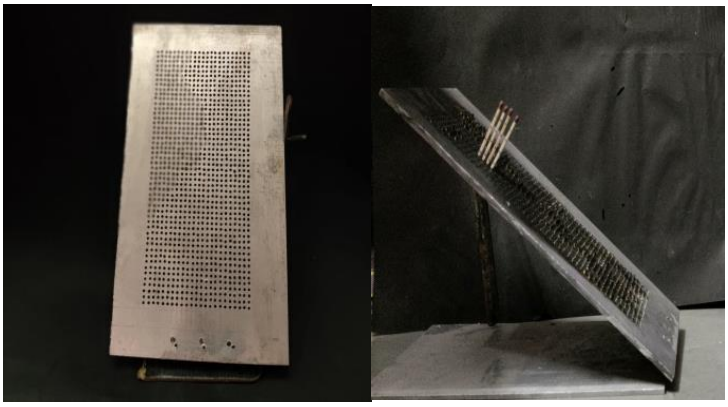
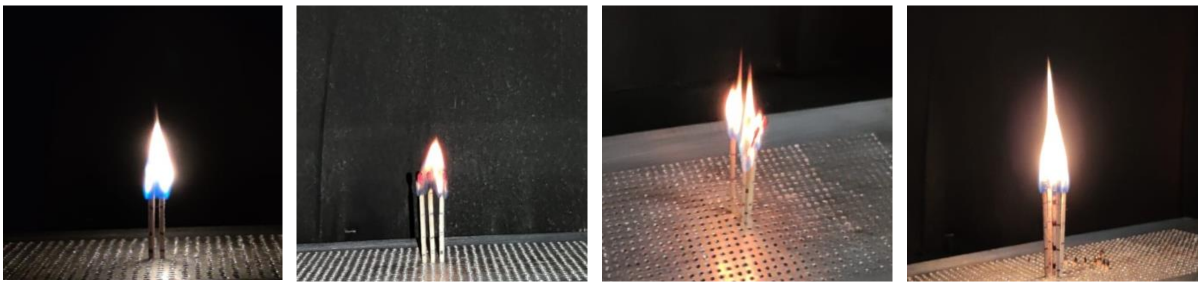


Figure 4. Mild Steel Plate

Figure 5. External Heat Sources



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

Figure 6. Four different configurations: (a) Unilateral, (b) Bilateral, (c) 'Y' (d) '+'

A multimedia system speaker 2.1 was utilized to produce various frequency sounds. The NCH tone generator software was used to produce the sound of changing frequencies. To check the various impacts of acoustic activity heat energy matchsticks were placed at four different configurations viz are 1) Unilateral 2) Bilateral 3) 'Y' or Trilateral and 4) '+' or quadrilateral configuration (Fig. 6).

The speaker was kept perpendicular to the pilot fuel at a distance of 100 cm as shown in Fig. 7. The basic objective was to carry out the test when no acoustic source was placed. In each case, the fire regression rate was measured by taking down the note of the time taken to burn 1cm of the matchstick checking. These values of fire spread rate make the base case for comparison. Taking after this a speaker was kept at 100 cm perpendicular to the pilot fuel and sounds of changing repeat were made utilizing the NCH tone generator computer program. The experimentation was performed under normal room temperature in a non-windy condition. Repeatability of all tests was ensured to the third order. Pictures and recordings were taken to capture the exceptional cases.

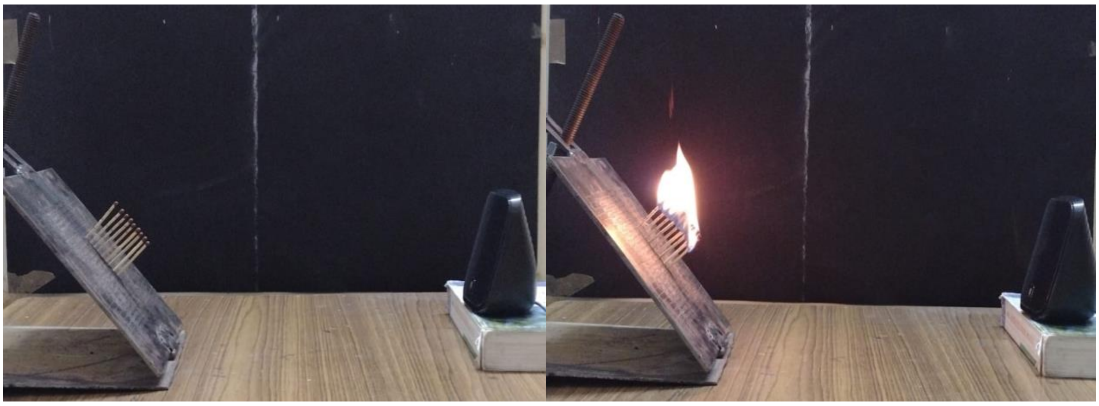


Figure 7. Experimental setup with the acoustic source.

2.1. Forward Transfer Theory

According to Classical Forward Heat Transfer Theory, the flame spread rate (r) is given by:

$$r = \frac{\int q_{net}}{\rho_s \, \tau_s c_s (T_{Surface} - T_\infty)} \tag{1}$$

2.1.1. Measurement

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

$$r = \frac{Distance\ burnt}{Time\ taken\ to\ burn\ that\ region} \tag{2}$$

The term q_{net} is the difference between the energy generated and the energy lost. Here the terms for the formulation are given as follows:

ρ_s: Density of the solid fuel (in g/cm^3)

τ_s: Thickness of the solid fuel (cm)

c_s: Speed of sound in that medium (cm/second)

$T_{Surface}$: Temperature of the surface (K)

T_{∞}: Temperature of the surroundings (K)

q_{net}: Total Energy (erg or $g.cm^2/s^2$)

r : Flame spread rate. (cm/second)

The fire regression rate was calculated in each case where a speaker was utilized to transmit the sound of particular frequencies. The experiment was conducted at typical room temperature and readings were taken legitimately ensuring productivity and congruity in each case. It is imperative to know that each data shown here speaks to the repeatability and reproducibility of the third order.

3. RESULTS AND DISCUSSION

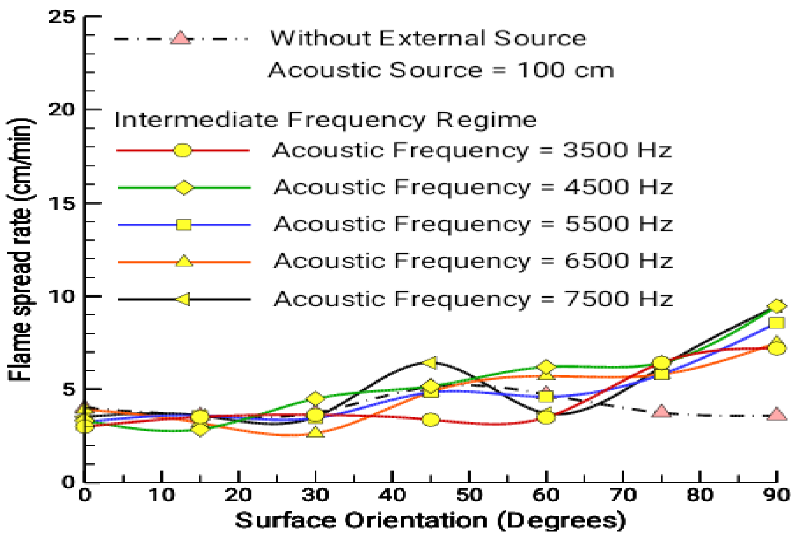


Figure 8. Acoustic fire interaction by varying frequency.

The initial experimentation was performed to obtain the base case values of the fire regression rate. It is vital to note that the flame regression rate of pilot fuel was measured at all orientations with and without acoustic influence. Here Acoustic recurrence was changed from 3500Hz to 7500Hz. Firstly, experiments were conducted for low frequency range (500Hz to 2500Hz) as seen from Vinayak Malhotra et al [16]. Further the experiments were conducted for Intermediate range to see the effect of the flame spread rate and amplitude of flame movements. From the plot (Fig. 8), it can be seen that the drift is non-monotonic for all the cases with the most extreme burn rate of 163.138% at 90^0 orientations for both 4500 and 7500Hz frequency. These values were taken as a reference for the comparison of fire rate for distinctive arrangements coupled with external heat sources.

In understanding with conventional heat transfer hypothesis over thin solid fuels, the propagating front spreads by heat feedback (forward heat transfer) from burning to unburnt solid fuel upstream. This comes about in an increment or diminishes in regression rates. It is because of convective buoyant stream, localized speed, and temperature areas are shaped around the fuel surface. Additional energy and preheating are provided by high-temperature smoke which carries heat moving parallel to the moving surface. High cumulative heat transfer from burnt fuel to unburnt fuel can be attributed to high regression rates. The further results were divided into two cases:

Stabilizing Effect: In this effect, the flame flashing stops, and the flame becomes steady within the impact of acoustic. The coupled energy transfer of acoustic and thermal energy is considered to be the same and no effect is seen in pilot fuel.

*Destabilizing Effect***:** In this case, the blazes begin glinting due to the influence of acoustic, and subsequently the rate changes in that manner. The acoustic coupled thermal energy is dominant or thermal energy is dominant to acoustic energy which effect can be seen by increment or decrement in flame regression rate.

These effects further divide the result into three zones.

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 due to acoustic. Hence the regression rate for this case is less compared to the pilot fuel.

Neutralizing zone: In this case, the heat transfer is constant to that of the pilot fuel hence no effect of acoustic. Here the regression rate is the same as that of the base case of pilot fuel.

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

The ratio of the flame spread rate at that particular orientation for a given number of external sources in presence of acoustics to that of flame spread rate for the same particular orientation without acoustic is called the *Fire Stimulation number*. These numbers are divided into different regimes FS<1 is the Heat sink zone, FS>1 is the Heat source zone and FS=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, acoustics, and external sources with respect to without acoustics.

$$\text{Fire Stimulation number} = \frac{Spread\ rate\ in\ persence\ \ of\ acoustic\ at\ particular\ orientation\ (cm/min)}{Spread\ rate\ of\ pilot\ fuel\ in\ absence\ of\ acoustic\ at\ particular\ orientation\ (cm/min)}$$

Based on the FS number new regime is formed.

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

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

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

Table 1. FS number variation for unilateral configuration when N=1

Orientation (Degree)	3500 Hz	4500 Hz	5500 Hz	6500 Hz	7500 Hz
0	0.66	0.75	0.74	0	0.88
15	1.26	1.26	1	0.85	0.85
30	0.42	0.62	0.68	1.11	0.38
45	0.83	1.06	0.84	1.31	1.69
60	0.69	0.42	0.97	0.48	0.66
75	0.45	0.83	0.42	0.53	0.5
90	1.07	1	0.55	0.55	1

The following graphs show the effect of acoustic on the spread rate of pilot fuel for various frequencies when the number of external sources was fixed at 1.

From the graph (Fig. 9), for 3500 Hz, when the number of external sources was fixed at 1. The result was compared for all four configurations with the single fuel case. The highest value of flame spread was obtained in unilateral with a massive increase of 257.22% (FS>1) at 90^0 orientations as were the least flame spread rate was obtained in bilateral configuration at 45^0 with a decrease of -36.931% (FS<1). In this case, Blow-off (the phenomenon in which fire extinguishers momentarily or permanently) was observed. An acoustic source was placed at a distance of 100cm from the pilot fuel. It was observed that Blow-off was more predominant in this case, especially in the unilateral, bilateral, and 'Y' configuration when orientation was varied from 0^0 to 30^0. The FS number was less than1 for most of the cases the reason is heat transfer is dominating in this region because of buoyancy that carries the heat from burning to the unburnt fuel. It is interesting to note that no neutralizing effect was seen.

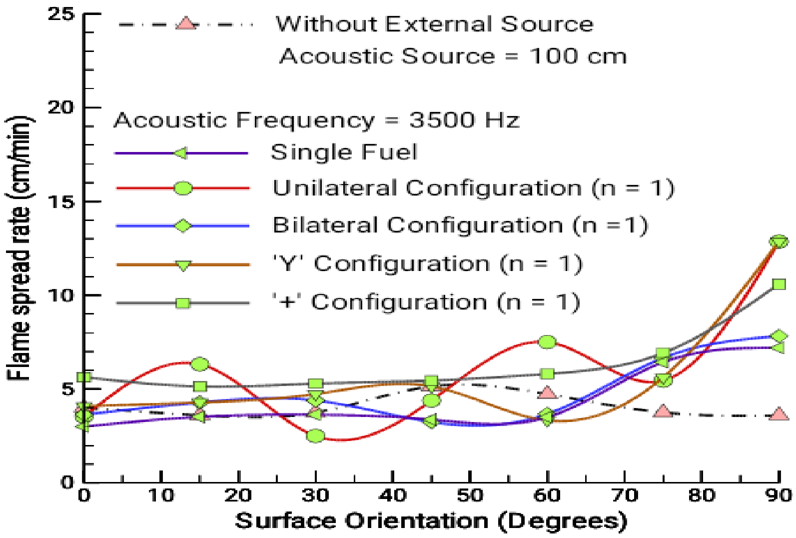


Figure 9. Effect of 3500 Hz on pilot fuel.

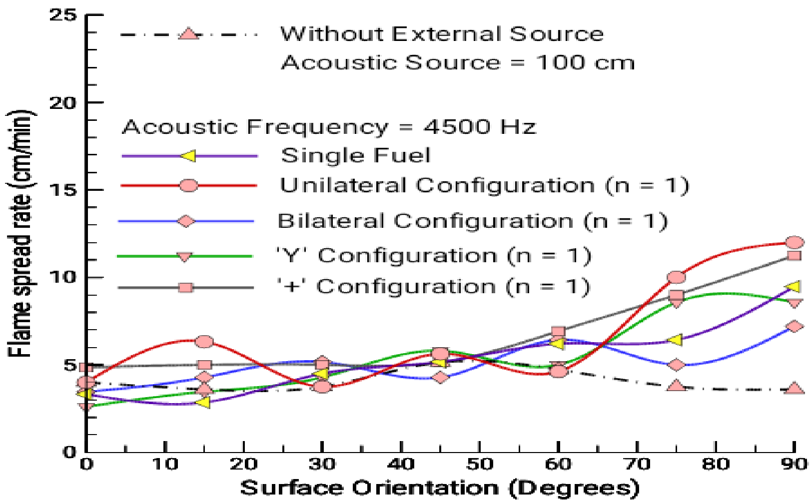


Figure 10. Effect of 4500 Hz on pilot fuel.

For the case of 4500 Hz, from the plot in Fig. 10, it can be seen that all configuration follows the non-monotonic trend. The highest regression rate was obtained for unilateral configuration when 1 external source was present on each side of pilot fuel. The rise of around 233.33% (FS=1) was seen at 90-degree orientation. The maximum drop was seen for the 'Y' configuration of around -34.80% (FS<1) at 0^0 orientation. It comes under blow-off conditions. Blow off was dominant for the unilateral, Bilateral, and

'Y' configuration when orientation was changed from 0 to 30^0. The FS number was less than1 for most of the cases the reason is heat transfer in this regime drops due to the decrease in the localized temperature around the pilot fuel. It is interesting to note that neutralizing effect was seen for unilateral and '+' configuration at 90^0.

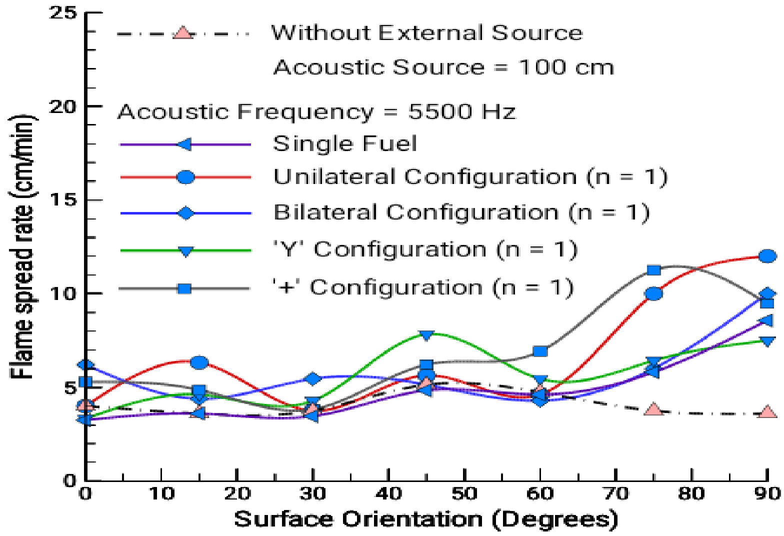


Figure 11. Effect of 5500 Hz on pilot fuel.

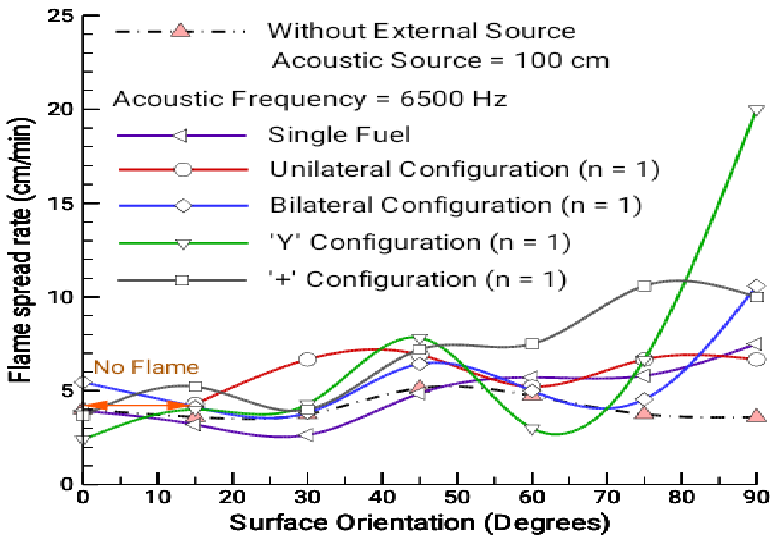


Figure 12. Effect of 6500 Hz on pilot fuel.

In the case of 5500 Hz *(Fig. 11)*, the maximum rise in flame spread rate was seen for '+' configuration with an increase of 200% (FS>1) for 75-degree orientation were as the maximum drop was observed for 'Y' configuration of around -16.75% (FS<1) at 0^0 orientation. It was interesting to note that for Unilateral and 'Y' configuration many cases of blow-off were seen for 0^0 to 45^0 orientations. Interestingly, no neutralizing effect was seen. For most cases, the FS number is less than one the reason is the coupled heat effect from the external sources was dominant to that of acoustic energy.

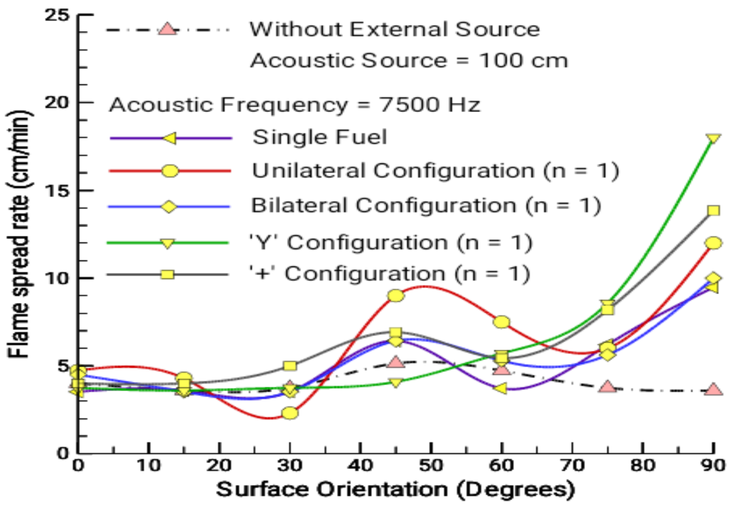


Figure 13. Effect of 7500 Hz on pilot fuel.

For the case of 6500Hz shown in Fig. 12, it can be seen that all configuration follows the non-monotonic trend. The highest regression rate was obtained for the ‘Y’ configuration when 1 external source was present on each side of the pilot fuel. The massive rise of around 455.55% (FS>1) was seen at 90^0 orientations. This shows the increase the flame spread rate due to influence of external heat sources is dominant over the sound energy. The maximum drop was seen for unilateral configuration of around 100% (FS<1) at 0^0 orientations, where the fire extinguished completely before reaching the first 1cm mark. It comes under blow-off conditions. In this case, the distance between the fire source and the mild steel plate is equivalent to the length of a matchstick. When the number of external sources is set to one, the extinguishing effect is observed. As the temperature of the mild steel plate rises due to external causes, the rate of fire propagation rises as well. The flame length rises from 600 to 90^0, and therefore the rate of spread rises. Blow off was dominant for the unilateral and ‘Y’ configuration for angles 0^0 to 30^0. It was interesting to note that there was no change in regression rate for unilateral configuration at zero degrees. The FS number was equal to 1 for the ‘+’ configuration at 75^0 and show neutralizing effect. The FS number was less than1 for most of the cases the reason is heat transfer is dominating in this region because of buoyancy that carries the heat from burning to the unburnt fuel.

In the case of 7500 Hz (Fig. 13), the maximum rise was seen for ‘Y’ configuration with an increase of 400% (FS>1) for 90^0 orientations were as the maximum drop was also observed for ‘Y’ configuration of around -20.458% (FS<1) where the fire blows off permanently. Also, blow-off was dominant only for ‘Y’ configurations except for the 90^0 orientations. In most cases, the regression rate comes under FS<1 The heat transfer in this regime drops due to the decrease in the localized temperature around the pilot fuel. The interesting thing to note is neutralizing effect was seen for unilateral configuration at 90^0 orientations.

Table 2. FS Number Variation for Bilateral Configuration when N=3

Orientation (Degree)	3500 Hz	4500 Hz	5500 Hz	6500 Hz	7500 Hz
0	0.78	0.86	1.21	1.07	0.97
15	0.83	1	0.77	0.79	0.83
30	0.74	0.93	0.91	1.02	1.03
45	0.94	0.72	0.91	0.86	1.07
60	0.41	0.63	0.62	0.81	0.56
75	1.18	0.81	0.81	1.04	0.96
90	1	0.74	0.85	1	0.74

These graphs represent the coupled effect of frequency and external heat sources on pilot fuel regression rates. From the graph, it can be noted that trend is non-monotonic for all the cases.

For Bilateral configuration at 3500Hz (Fig. 14), it can be seen that the massive increase in regression rate of about 194.11% (FS>1) was seen for 90^0 when pilot fuel was accompanied by 3 external sources on the opposite side due to the fact that cumulative heat transfer is dominating in this region because of buoyancy that carries the heat from burning to the unburnt fuel. The maximum drop can be observed at 45^0 of around -36.931% (FS<1) when the number of external sources is 1 on either side. The blow-off condition was seen only when the number of external sources was 1 and 2 at 0 to 30 degrees. The neutralizing effect was seen for 0^0 and 90^0 for a number of external sources 2 and 3 respectively. For most of the cases, the heat sink effect was seen because of thermal effect dominance concerning acoustic energy.

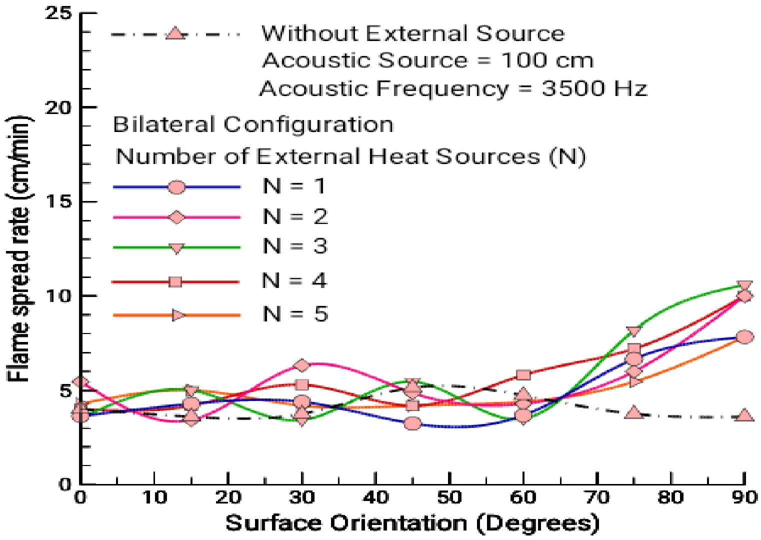


Figure 14. Flame spread rates for bilateral configuration at 3500 Hz

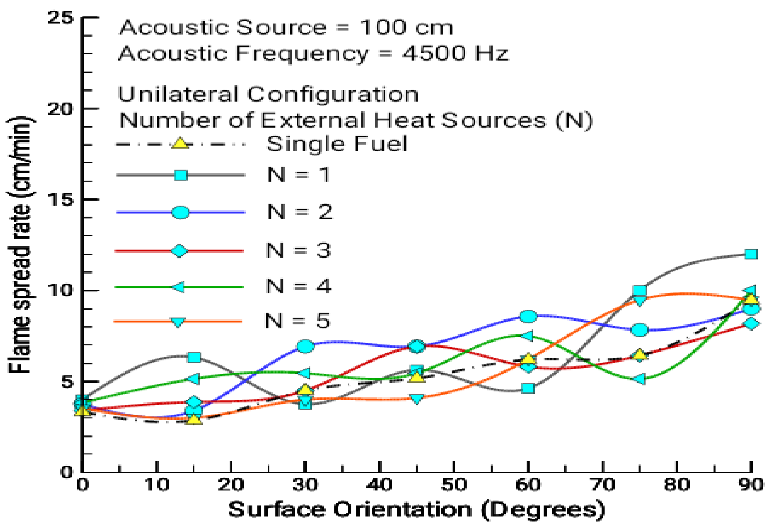


Figure 15. Flame spread rates for unilateral configuration at 4500 Hz.

For unilateral configuration at 4500Hz (Fig. 15), the massive increase of around 233.33% (FS=1) was seen for regression rate at 90^0 orientations when the number of external sources is 1. Whereas a maximum drop of -20.45% (FS<1) was observed at 45^0 when the number of external sources is 5. The FS number is 1 for the first case which also shows the neutralizing effect. Blow off was only seen for 0 to 45 degrees orientations. For most of the cases, the heat sink effect was seen because of acoustic effect dominance with respect to thermal energy. For case N=4 the FS is greater than 1 except 30 and 45 degrees which shows the heat source effect.

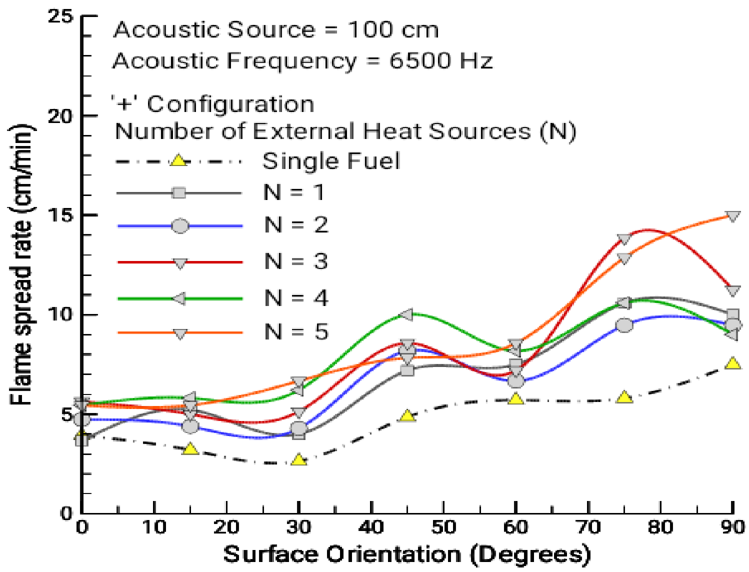


Figure 16. Flame spread rates for '+' Configuration at 6500 Hz.

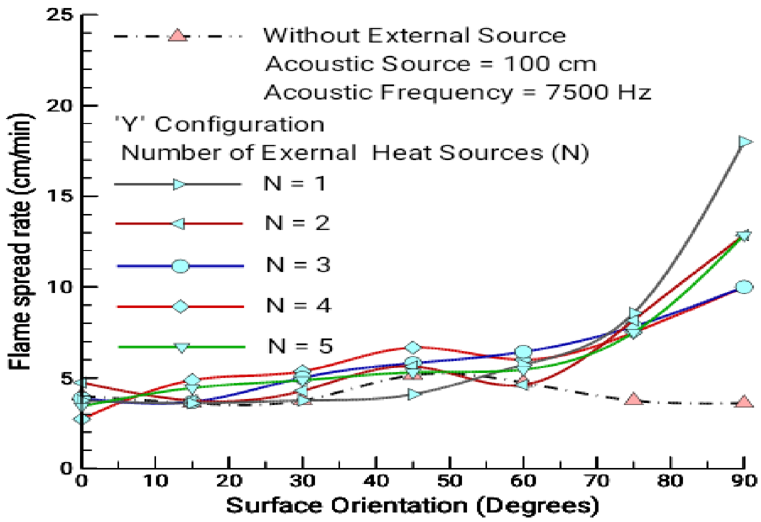


Figure 17. Flame spread rates for 'Y' configuration at 7500 Hz

For '+' configuration at 6500Hz (Fig. 16), it is interesting to note that flame spread rate changes with a massive increase of 316.66**%** (FS=1) at 90^0 orientations when 5 external sources are attached on each side of pilot fuel were as the maximum drop was obtained at 0^0 of around –8.25% (FS<1) when 3 external sources were present on either side. Cases of blow-off were observed when one external source is present for 15 and 30 degrees. The neutralizing effect can be observed at 90^0 when N=1 and N=5, at 60^0 N=4, and at 75^0 when N=5 respectively. Here, acoustic does not affect the flame spread rate since the effect of acoustic energy and thermal energy is considered to cancel each other and flame stops flickering. For most of the cases, heat sink effect is dominant.

For the 'Y' configuration at 7500 Hz (Fig. 17), it was interesting to note that the maximum rise in regression rate is of 400% (FS>1) was observed at 90^0 when 1 external source is present. The FS number was greater than one for this case due to fact that cumulative heat transfer is dominating in this region because of buoyancy that carries the heat from burning to the unburnt fuel. The maximum drop of around -31.825% (FS<1) was observed at 0-degree orientation when 4 external sources are attached. The neutralizing effect can be observed at 90^0. It is worth noting that as the frequency of sound increases, so does the acoustic pressure, but at low surface orientations, the acoustic pressure is dominant.

The following graphs are for the effect of Coupled Interactions for the varying numbers of sources, configurations, on pilot fuel propagation at 3500 Hz. From the graph, it can be seen that the trend is non-monotonic for all the cases

The graph (Fig. 18) is comparing the flame spread rate for all the configurations when the number of external sources is fixed at 1. The massive rise of around 257.22% (FS>1) at 90^0 for Unilateral configuration whereas a drop of around -14.62% (FS<1) at 45^0 is observed. For Bilateral configuration the rise of around 117.38% (FS<1) at 90^0 and a drop of -36.931% (FS<1) at 45^0 was observed. For 'Y' configuration maximum rise of 257.138% (FS>1) at 90^0 and drop of -29.68% (FS<1) at 60^0 whereas for '+' configuration, the rise of 194.66% **(**FS<1) at 90^0 and a drop of 5.989% (FS>1) at 45^0 was obtained respectively. Most of the cases come under the heat source zone due to buoyancy that carries the heat from burning to the unburnt fuel due to the external influence of acoustic. Neutralizing effect was seen for Bilateral at 0^0 and 'Y' configuration at 45^0 respectively Cases of blow-off was seen for Unilateral, Bilateral, and 'Y' configurations when orientation varied from 0 to 30 degrees.

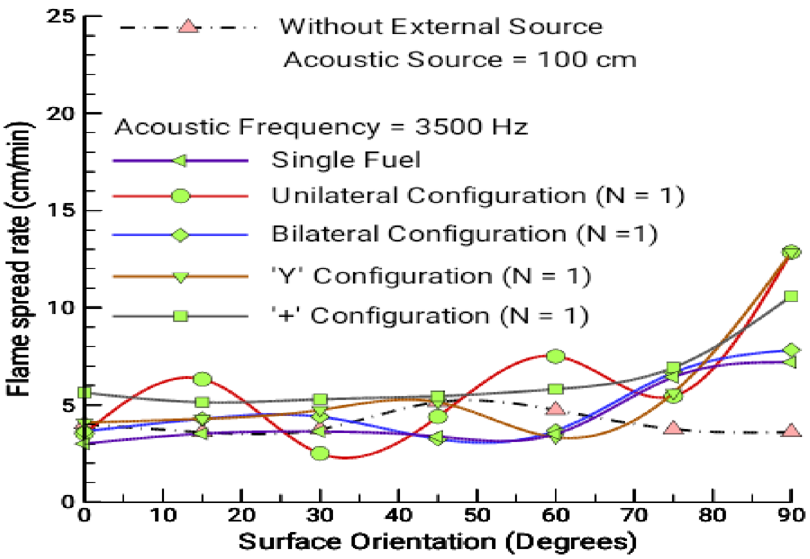


Figure 18. Flame spread rates for N=1 at 3500 Hz.

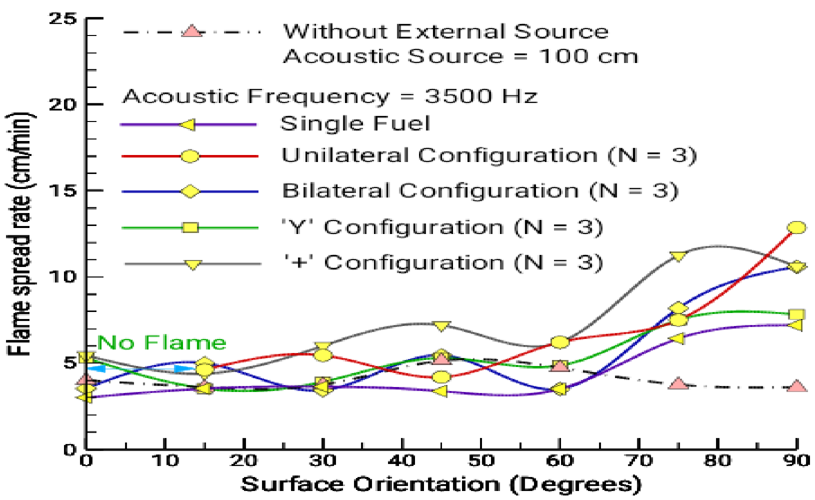


Figure 19. Flame spread rates for N=3 at 3500 Hz.

The graph (Fig. 19) represents the data for regression rates when the number of external sources is fixed to 3 for all configurations. From the graph, it is seen that a massive rise of 257.22% (FS>1) at $90^0$and a drop of -100% (FS=0) was seen for unilateral configuration at 0^0 where the fire extinguished completely before reaching the first 1cm mark. For the Bilateral configuration maximum rise of around 194.11% (FS=1) was obtained at 90^0 were as a drop of -26.097% (FS<1) was obtained at 60^0. For 'Y' and '+' configurations rise of 117.388% (FS<1) and 194.166% (FS<1) were observed at 90^0 and a drop of around -1.972% (FS<1) and a minimum rise of 21.944% was obtained at 15^0 respectively. Most of the cases come under the heat sink zone 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 due to acoustic. Hence the regression rate for this case is less compared to the pilot fuel. The neutralizing effect was seen for Unilateral at 60^0, Bilateral at $90^0$and '+' configuration at 30^0 respectively. Cases of blow-off were seen for unilateral configuration for 0 and 30 degrees.

Table 3. FS Number Variation for 'Y' Configuration when N=4

Orientation (Degree)	3500 Hz	4500 Hz	5500 Hz	6500 Hz	7500 Hz
0	0.36	0.77	0.54	0.69	0.67
15	0.99	0.67	0.57	0.53	0.59
30	1.05	1.02	0.75	1.01	1.22
45	1.69	0.97	1.09	1.13	1.13
60	1.04	0.87	1.04	0.97	0.97
75	0.88	0.9	0.68	0.74	0.74
90	0.72	1	0.52	0.92	0.61

When the number of external sources was fixed at 5 from the graph (Fig. 20) it can be seen that the rise of around 166.66% (FS>1) at 75^0 and a drop of -23.73% (FS<1) was obtained at 30^0 for unilateral configuration. For Bilateral and 'Y' configuration massive rise of 150% (FS>1) and 257.22 % (FS=1) was seen at 90 degrees whereas a drop of -20.45% **(**FS<1) and -14.3% (FS<1) was observed at 45 and 0 degrees respectively. For the '+' configuration rise of 300% (FS=1) was observed at 75^0 whereas the minimum rise of 50% (FS<1) was obtained at 0^0. For all the above cases most of the cases come under the heat sink zone 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 due to acoustic. Hence the regression rate for this case is less compared to the pilot fuel. The neutralizing effect was observed at 90^0 for the '+' and 'Y' configuration. Cases of blow-off were only seen for the 'Y' configuration at 30 and 15 degrees.

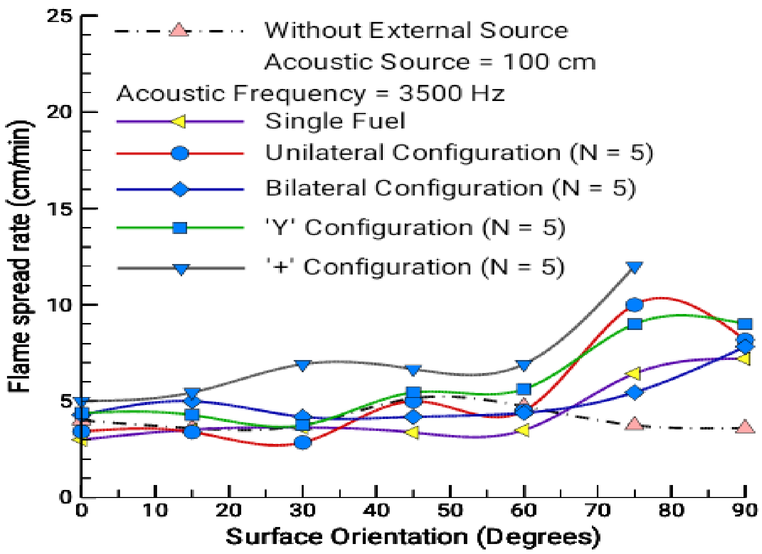


Figure 20. Flame spread rates for N=5 at 3500 Hz

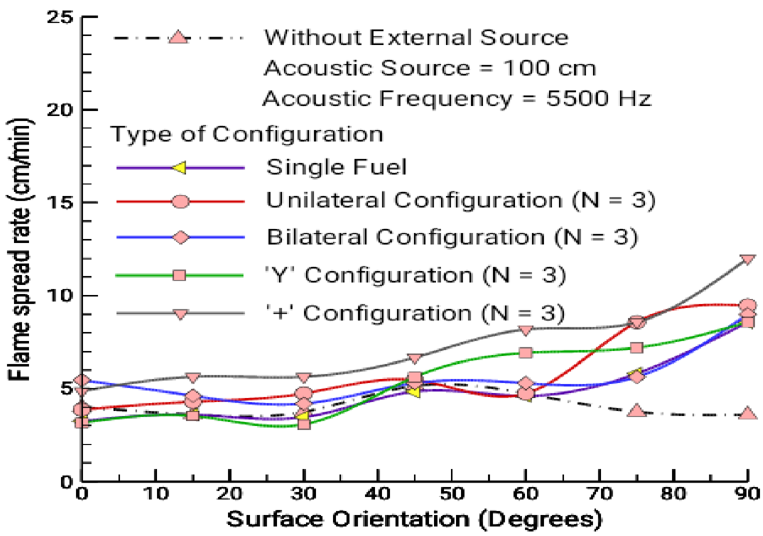


Figure 21. Flame spread rates for N=3 at 5500 Hz.

The next graph (Fig. 21) is for the interaction of energy on pilot fuel when the frequency was fixed at 5500Hz and the number of the external source was fixed to be 3. From the graph, it can be seen that the rise of around 123.60% (FS<1) at 60^0 and a drop of -13.625% (FS<1) was obtained at 45^0 for unilateral configuration. For Bilateral and 'Y' configuration massive rise of 150% (FS<1) and 138.083 % (FS<1) was seen at 90 degrees whereas the minimum rise of 2.956% (FS<1) and drop of -21.075% (FS<1) was observed at 45 and 0 degrees respectively. For the '+' configuration rise of 233.33% (FS<1) was observed at 75^0 orientation whereas a minimum rise of 29.716% (FS<1) was obtained at 45^0. For the cases of Heat source effect cumulative heat transfer is dominating in this region because of buoyancy that carries the heat from burnt to the unburnt fuel due to external influence of acoustic. Hence the regression rate for this case is greater than compared to the pilot fuel. Hence the regression rate for these cases is more compared to the pilot fuel. The neutralizing effect was observed at 0^0 for the '+' configuration. Cases of blow-off were only seen for the 'Y' configuration at 0 to 45 degrees.

Table 4. FS Number Variation for '+' Configuration when N=5

Orientation (Degree)	3500 Hz	4500 Hz	5500 Hz	6500 Hz	7500 Hz
0	0.83	0.79	1	0.91	1
15	0.82	0.77	1	0.82	0.93
30	1.15	0.94	1.04	1.11	1
45	0.92	0.92	1.08	1.08	1.03
60	0.84	0.95	0.91	1.05	1.22
75	0.93	0.88	0.93	1	1.17
90	1.09	0.75	0.71	1	0.92

The next graph is for the effect of Coupled Interactions for a varying number of Sources, configurations, on Pilot fuel Propagation at 7500 Hz. From the graph, it can be seen that the trend is non-monotonic for all the cases.

The graph (Fig. 22) is comparing all the configurations when the number of external sources is fixed at 1. The massive rise of around 400% (FS>1) at 90^0 for 'Y' configuration whereas a drop of around -20.458% (FS<1) at 45^0 is seen. Most of the cases come under the heat sink effect. For Unilateral configuration the rise of around 233.33% (FS=1) at 90^0 and a drop of -38.40% (FS<0) at 0^0. Most of the cases come under the heat sink zone due to buoyancy that carries the heat from unburnt to the burnt fuel due to domination of thermal energy. For bilateral configuration maximum rise of 177.77% (FS>1) at 90^0 and a drop of -5.893% (FS<1) at 30^0 whereas for '+' configuration the rise of 284.722% (FS>1) at 90 degrees and no rise at 0^0 was obtained and most of the cases come under heat sink effect respectively. The cases of blow-off were seen extensively for 'Y' configurations when orientation was varied from 0 to 60 degrees.

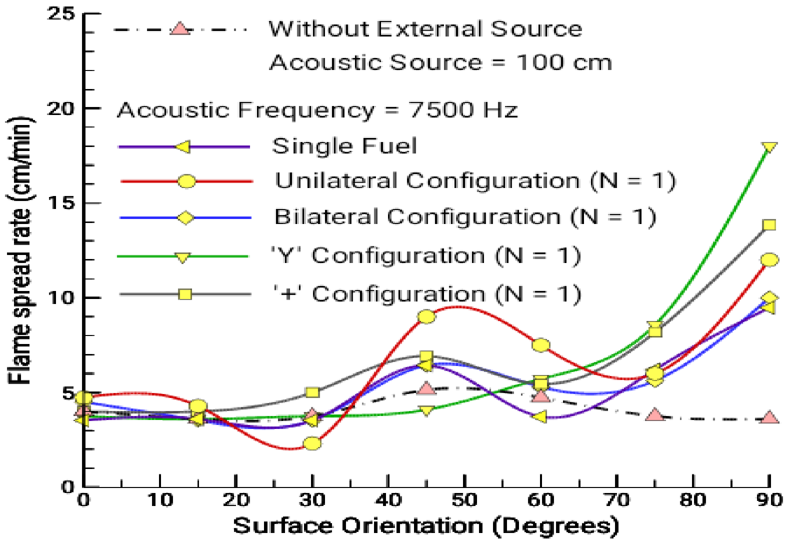


Figure 22. Flame spread rates for N=1 at 7500 Hz.

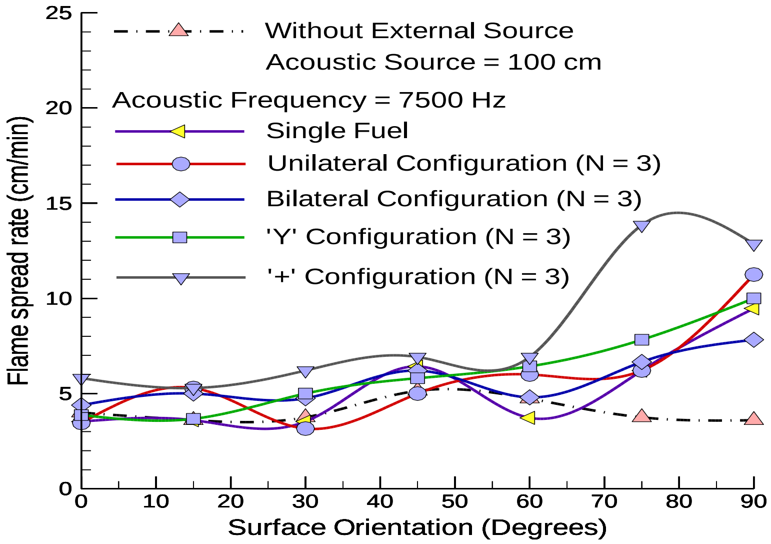


Figure 23. Flame spread rates for N=3 at 7500 Hz.

The graph in Fig. 23 represents the data when the number of external sources is fixed to 3 for all configurations. From the graph, it is seen that for unilateral configuration massive rise of 212.5% (FS<1) at 90^0 and a drop of -15.733% (FS<0) at 30^0. Most of the cases come under the heat sink zone. For Bilateral configuration maximum rise of around 117.38% (FS<1) was obtained at 90^0 whereas a drop of 1.351% (FS<1) was obtained at 60^0. Most of the cases come under the heat sink effect 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 due to acoustic. For ‘Y’ and ‘+’ configurations rise of 177.77% (FS<1) and 257.22% (FS=1) were observed at 90^0 and drop of around –3.25% (FS<1) and minimum rise of 34.57% (FS<1) were obtained at 0 & 45 degrees respectively. Cases of blow-off were seen for ‘Y’ configurations for 0 to 45^0. The neutralizing effect can be seen for 90^0 for the ‘Y’ configuration.

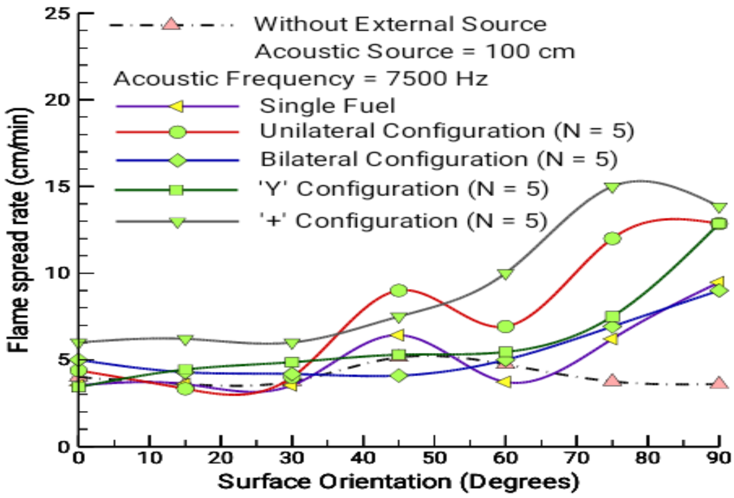


Figure 24. Flame spread rates for N=5 at 7500 Hz.

When the number of external sources was fixed at 5 from the graph in Fig. 24 it can be seen that the rise of around 257.22% (FS>1) at 90^0 and a drop of -7.5% (FS<1) was obtained at 15^0 for unilateral configuration. Most of the cases come under the heat sink zone due to buoyancy that carries the heat from burnt to the unburnt fuel due to external influence of acoustic and hence decreases the regression rate. For Bilateral and '+' configuration massive rise of 150% (FS>1) and 284.722% (FS<1) was seen at 90^0 whereas a drop of -20.458 (FS<1) and a minimum rise of 50% (FS=1) was observed at 45 and 0 degrees respectively. For bilateral, most of the cases come under the heat sink zone whereas for '+' most of the cases come under the heat source zone. For 'Y' configuration rise of 257.138% (FS<1) was observed at 90^0 whereas a drop of 2.956% (FS>1) was obtained at 45^0. All cases come under the heat sink zone other than 30 and 45 degrees. Cases of blow-off were only seen for the 'Y' configuration at 0 to 30 degrees.

The influence of flame spread rate was studied in this work for the intermediate frequency range. According to Ref. [16], acoustic waves are better appropriate for the same acoustic source location at low frequency range from 500hz to 2500Hz because they create a larger amplitude of flame movements and hence have a higher extinguishing effectiveness.

Sound wave consists of compression and rarefaction and they could be responsible for the fluctuation in the flame intensity and flame spread rate. This impact was seen when the blow off condition was met for unilateral configuration at when the number of external sources was set at 1 for various frequencies were as and Presence of external sources increases the influence of acoustic energy drops and thermal energy increases. Presence of sound wave will result in formation of localized pressure and velocity fields around the pilot fuel, which are expected to affect the forward heat transfer. In the influence of sound, the acoustic energy gets dominated over thermal energy which results in the decrease of localized temperature and pressure which results in decrement of regression rate and comes under heat sink effect. In some cases, when thermal energy is dominant over acoustic energy due to influence of additional external sources, which results the increment of regression rate. It indicates the heat source effect. For Both above cases the flame flickers due to interaction of thermal energy and sound energy and it shows destabilizing effect. Interesting to observe that in some cases neutralizing effect is seen, it is appeared when both acoustic and thermal energy interaction is expected to be same in macroscopic level. Here flame does not flicker and regression rate values are same to that of base case. Extensive study was used to gain a true knowledge of the acoustic thermal energy interaction. The auditory impact was observed and evaluated in relation to the variation in fuel relapse rates under various situations. The spreading measure on a matchstick change substantially under conditions of changing surface orientation and continuous exposure to sound. The results shown that the thermoacoustic connection fundamentally increases the forward heat transfer when the source partition distance changes. As observed in Tiwari's work [10], two distinct zones are established based on the outside sound source region, with little effect and extreme rise for ascending and descending dispersion.

4. CONCLUSIONS

From the exploratory examination, it can be derived that acoustics play a critical effect on fire propagation. The impingement of sound results in the repair of the reaction zone of the pilot fuel. The variety inside the reaction zone shows that there's a potential institution of associate degree energy interaction zone between two energies that is heat and acoustic. The arrangement of a relate degree vitality points to the division of a connection between heat and sound energy whenever changes within the last-mentioned sort of energy have an eminent result on the past. Based on the results following conclusions can be drawn:

The gigantic rise of around 455.55% was seen for the 'Y' configuration when one external source was placed from three sides at an angle of 120 degrees each. The orientation was 90^0 with a frequency fixed at 6500Hz. This shows that Thermal energy shows an exceptional result on fire regression rate by dominating from acoustic energy, so the impact of forwarding heat transfers and fire propagation.

The most noteworthy observation is for unilateral configuration when the number of the external source is fixed at 6500 for 0^0 orientations. The flame spread rate decreased by 100% that is no flame was observed since the fire quenches completely before reaching the 1 cm mark. Sound as a wave is often within the center of compression and rare fraction. From the experimentation done and results it can be concluded that sound has extraneous impact and within the proximity, acoustic energy dominates thermal energy.

A few cases of blow and reappearance were seen for unilateral, bilateral and 'Y' configuration when orientation was changed between 0 to 30 degrees. In the presence of acoustics, it demonstrates that acoustics is accustomed directly.

The governing physics of this advancement includes: (a) Adjustment of the reaction zone (b) formation of an energy interaction zone (c) interaction between heat energy and acoustic energy. Based on physical instinct, modern pointers within the fire safety guidelines on the conventional and additional territorial can be framed. The work carries a wide determination of applications which incorporate engineering viz., combustion and propulsion, defense systems validation, testing and upgradation like rocket systems, industrial with power generation systems, practical, functional, scientific applications. Acoustics can be utilized in fire accidents to minimize losses.

Acknowledgments

Our investigation work couldn't have been feasible from the significant work made by former worldwide analysts and researchers. Also, we wish to dedicate our work to the firefighters for their hard work and the ceaseless benefit they have been providing for the past numerous decades. Their quick response time has made a difference in sparing thousands of lives in forest fires, building and compartment fires, industrial and residential fires.

REFERENCES

[1] Chiu HH, Summerfield, M, Theory of combustion noise, Aerospace and Mechanical sciences report. Princeton University, New Jersey; USA, 1973.

[2] Schadow, KC, Gutmark, E. Combustion instability related to vortex shedding in dump combustors and their passive control. *Progress in Energy and Combustion Science* 1992; *18*(2): 117-132.

[3] Lovett JA, Turns SR. Experiments on axis symmetrically pulsed turbulent jet flames. *AIAA Journal*1990; *28:38*–46.

[4] Saito, M, Sato, M, Nishimura, A. Soot suppression by acoustic oscillated combustion. *Fuel* 1998; *77:973*–978.

[5] Hertzberg JR. Conditions for a split diffusion flame. *Combust Flame* 1997; *107:314*–322.

[6] Suzuki M, Atarashi T, Masuda W. Behavior and structure of internal fuel-jet in diffusion flame under transverse acoustic excitation. *Combust Sci Tech* 2007; *179:2581*–2597.

[7] Kozlov VV, Grek GR, Katasonov MM, Korobeinichev OP, Litvinenko YA, Shmakov AG. Stability of subsonic microjet flows and combustion. *J Flow Contr Meas Vis* 2013; *1:108*–111.

[8] Nair, V, Sujith, RI. Multifractality in combustion noise: predicting an impending combustion instability. *J. Fluid Mech*2014; *747*: 635-655.

[9] Mondal, S, Unni, VR, Sujith, RI. Onset of thermoacoustic instability in turbulent combustors: an emergence of synchronized periodicity through formation of chimera-like states. *J. Fluid Mech*. 2017;*811*: 659-681.

[10] Tiwari, P, Ramanan, V, Malhotra, V. An Experimental Insight into Thermoacoustic Smoldering. *Journal of Space Exploration 2017;6*(1): 119.

[11] X. Huang. Critical drip size and blue flame shedding of dripping ignition in fire. *Sci. Rep.*2018; *8*: 1–13

[12] Magina, N, Acharya, V, Lieuwen, T. Forced response of laminar non-premixed jet flames. *Prog. Energy Combust. Sci.*2019; *70*:89–118.

[13] George, NB, Unni, VR, Raghunathan, M, Sujith, RI. Pattern formation during transition from combustion noise to thermoacoustic instability via intermittency. *Journal of Fluid Mechanics* 2018; *849*: 615–644.

[14] Sujith, RI, Unni, VR. Complex system approach to investigate and mitigate thermoacoustic instability in turbulent combustors. *Physics of Fluids*2020;*32*(6): 061401.

[15] Tatnell, DM, Heath, MS, Hepplestone, SP, Hibbins, AP, Hornett, SM, Horsley, SAR, Horsell, DW. Coupling and confinement of current in thermoacoustic phased arrays. *Science Advances, Applied Physics* 2020;*6*(27): eabb2752.

[16] Vinayak Malhotra et al 2021 IOP Conf. Ser.: Mater. Sci. Eng. 1168, 012019