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An Experimental Insight into Laser Smoldering Interactions of Solid Fuels

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Abstract

Combustion is critically important as it provides for about 80% of the world's energy requirement. In the last five decades, the emphasis on combustion has focused on improving the quality of combustion and addressing the hazards. With recent advancements, an aspect which is being researched is the combustion behaviour in the presence of lasers. Lasers are well-known potential, cheaper, point-precise and high-speed energy sources. The major application includes Direct Energy Weapons (DEWs), deep space exploration systems, and fire safety. For the present study, an experimental setup comprising varying wavelength lasers, marked incense sticks, an optical setup (shadowgraph) and a stopwatch was upraised to study smouldering behaviour in the presence of lasers. The quantification of smouldering regression rate variation simplified the effect. The parametric variations include external energy source (laser), interspace distance, wavelength and different source configurations. Systematic experimentation was carried out under normal gravity conditions, and results were compared with the base case of combustion without external influence. The experimental setup has been validated and was found to be in good accordance with the classical theory of heat transfer for thin solid fuels. The study provides details on how the wavelength, orientation and inter-spatial distance significantly affect the smouldering process by altering the regression rates.The result indicates that lasers significantly affect the combustion process, which projects lasers as a potential futuristic energy source to test, validate and analyse combustion systems and design laser-induced combustion systems.

Keywords: Combustion, Laser, Smoldering, regression rate

Nomenclature

r	Regression rate	[mm/min]
l_s	Distance burnt	[mm]
t_{av}	Time	[s]

q_{net}	Heat transfer per unit time per unit area	[W/sm^2]
ρs	Solid fuel density	[kg/m^3]
cs	Solid phase-specific heat	[J/kgK]
T_s	Surface Temprature	[K]
T_a	Ambient Temprature	[K]
q_p	Energy Produced	[J]
q_L	Energy loss	[J]
H_c	Heat of combustion	[J]
V	Volume	[mm^3]
C_i	Concentration of Reactants	[mol]
$E*$	Pre-exponential Factor	[1/s]
E_a	Activation Energy	[J]
h	Connective heat transfer	[W/m^{2}K]
R	Universal gas constant	[J/Kmol]
A	Area	[m^2]
H	Planck's Constant	[Js]
c	Speed of light in vacuum	[m/s]
λ	Wavelength of the light	[nm]
θ	Angle of orientation	[degree]
Ψ	Regression Rate Coefficient	
μ	Regression rate in presence of laser	[mm/min]
α	Regression rate in absence of laser	[mm/min]
ε	Emissivity of solid fuel	[J/s/m^2]
σ	Stefan-Boltzmann constant	[W/m^{2}K^4]
r'	Radius of solid fuel	[mm]
t	Thickness of solid fuel	[mm]

Q	Radiative heat transfer	[J]

1. Introduction

Energy plays a fundamental role in shaping various phenomena in the vast universe, with combustion serving as a crucial source. Among the diverse forms of combustion, smouldering stands out as a slow, low-temperature, flameless process of combustion. It is a leading cause of fire accidents across industries, commercial settings, and space flights. The smouldering front propagates in three zones: degradation, reaction and ash. During combustion, the body reacts with oxygen and undergoes thermal degradation. The molecular bonds break, resulting in the release of energy, part of which is used in product formation while the rest is emitted as heat. The reaction zone experiences active combustion and the highest temperature due to the smouldering combustion. Ash is the burnt solid left after the front propagates further, playing a significant role in preventing heat transfer. Smouldering is classified based on the direction of propagation of the front as forward smouldering, wherein the oxidiser moves in the direction of the smouldering front, and reverse smouldering, wherein the oxidiser moves in the opposite direction of the smouldering front.The heat transfer process takes place through all three processes: conduction, convection and radiation. In the presence of an external energy source (lasers), the heat transfer rates and smouldering behaviour differ significantly. Based on parameters like orientation, laser wavelength, inter-spatial distance, source distance, and configurations, energy can be converted into light or thermal energy, impacting regression "Curcumin: A Natural Therapeutic Powerhouse with Antioxidant, Anti-inflammatory, and Anticancer Potential"rates. These findings have potential engineering applications**.**

Figure 1: Wildfire due to smouldering in Merlin [1]

Figure 2: Smouldering fire in microgravity conditions [2]

2. Literature Review and Objective

Smouldering is a crucial cause of fire accidents. Research into smouldering combustion on solid wood like red oak and white pine has revealed that smouldering can persist under various conditions, especially when the igniting stimulus is prolonged due to its self-insulating nature. Airflow velocity is critical, as low velocities make extinction more likely, while high velocities can lead to a transition into flaming combustion. Radiative transfer is a significant factor sustaining the smoulder process [3]. An interesting aspect is the impact of lasers on smouldering. Depending on the laser wavelength and energy deposition mode, various mechanisms [4], such as thermal initiation [5], non-resonant breakdown, resonant breakdown, and photochemical ignition [6], have been proposed for laser-induced spark ignition. Laser spectroscopic techniques offer detailed insights into the microscopic dynamics and reaction rates of the combustion process [7]. Studies on laser-induced spark ignition have provided insights into plasma formation, flame kernel development, and flame sustainability [8]. Further investigations into smouldering combustion have highlighted its complexity, involving heterogeneous chemical reactions and the transport of heat, mass, and momentum [9]. Research on laser ignition methods concludes that ignition through a laser source requires less energy with an expanded beam diameter [10]. Studies concluded that the smouldering reaction regime consists of char species by competing pyrolysis and oxidation reactions [11]. Experiments exploring the behaviour of self-sustaining and self-extinguishing smouldering in beech wood under external irradiation revealed that the intensity of irradiation influences the critical smouldering front depth, subsequently affecting regression rates. Higher external heat flux led to a decrease in the critical smouldering front depth, resulting in slower regression rates and self-extinguishing behaviour [12]. A novel computational model was introduced to simulate the transition from flaming to smouldering in wildland fires, incorporating a discrete particle model [13]. A study was performed to detect the hydrogen gas generated by smoulder fires by using a low-power capacitive MEMS hydrogen sensor with a microheater [14]. Additionally, a compact dual-gas sensor was developed to detect smouldering fire intensity by monitoring CO2 and CH4 emissions based on time-division multiplexed scanned WMS-2f [15]. Experiments utilising irradiation using sunlight for smoulder ignition revealed that ignition time decreases with higher irradiation concentration. A decrease in irradiation spot diameter results in an increase in both the minimum irradiation necessary for smoulder ignition and ignition energy [16]. Studies on CO2 laser radiation demonstrated stable ignition of air-fuel mixtures at supersonic flows, with efficient combustion reactions observed in the wake behind the optical discharge region. This method of laser-induced combustion was found to be faster, more stable, and efficient compared to traditional ignition methods, particularly in igniting cryogenic mixtures [17] [18]. Research was performed on the combined approach of artificial neural networks, multi-objective genetic algorithm and response surface methodology for micro-channeling in low power fiber laser beam machining [19]. Jian-ying Fu et.al. studied the state of self-sustaining smoldering for remediation of contaminated soil and organic waste [20]. Shaohui Han et.al. conducted research on the impact of power density on heat and mass transfer in porous under the continuous laser radiation, along with the construction of energy management function for defining the efficiency relationship between energy input and remediable depth [21]. Experiments were performed with a focus on the mesoscale for understanding the damage of smouldering wildfires on the ecosystem [22]. Research was conducted to understand the smouldering and thermal remediation effects on properties and the behaviour of porous media [23]. Laboratory studies were performed to investigate the physiochemical characteristics of particles emitted from smouldering Irish peat. The study improved the understanding of size-resolved particle characteristics relevant to near-source human exposure [24]. Experiments were performed to study the effects of soil and environmental conditions on smouldering wildfires [25]. Leveraging insights from laser combustion research, the current study aims to explore the effects of lasers of varying wavelengths and configurations on reverse smouldering spread in solid fuel under different orientations.

3. Materials and Methodology

The experimental setup comprises thermocol board with 360° markings, black background for studying the smoke patterns and incense sticks (solid fuel). Markings at a distance of 1cm were done on the incense stick. 5mW lasers of three different wavelengths, 532nm, 650nm and 405nm, were impinged on the reaction zone. The source distance was divided into three zones: Near zone (0cm to 30cm), Intermediate Zone (30cm to 75cm) and Far zone (75cm to 100cm).

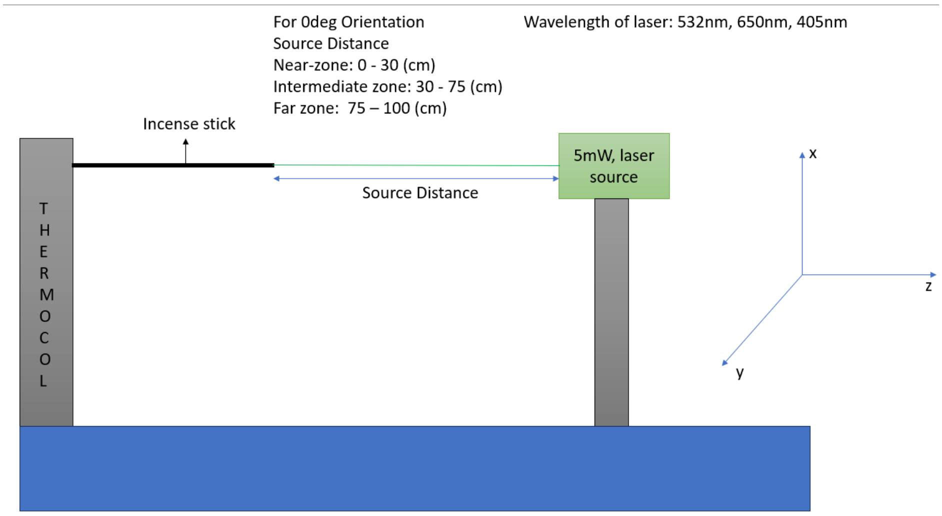

Figure 3: Schematic of Experimental set-up at 0deg orientation

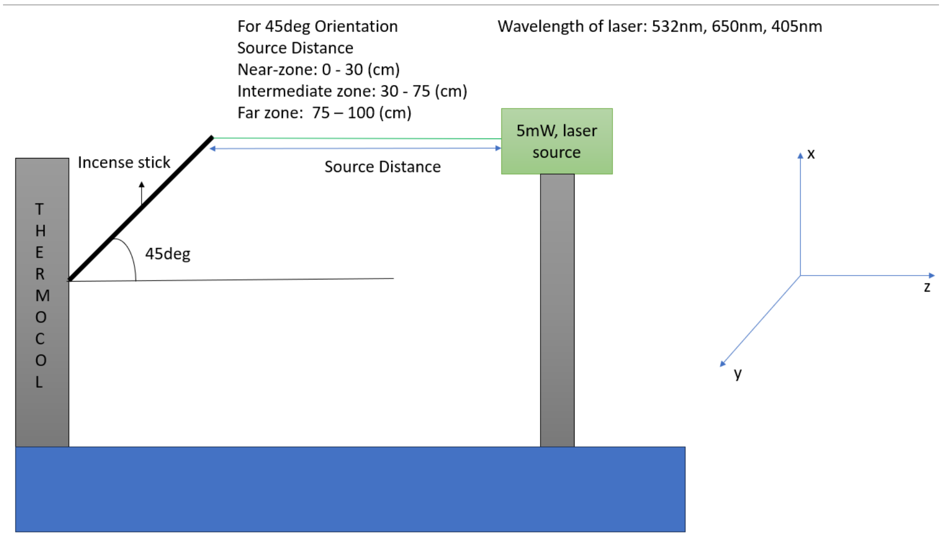

Figure 4: Schematic of Experimental set-up at 45deg orientation

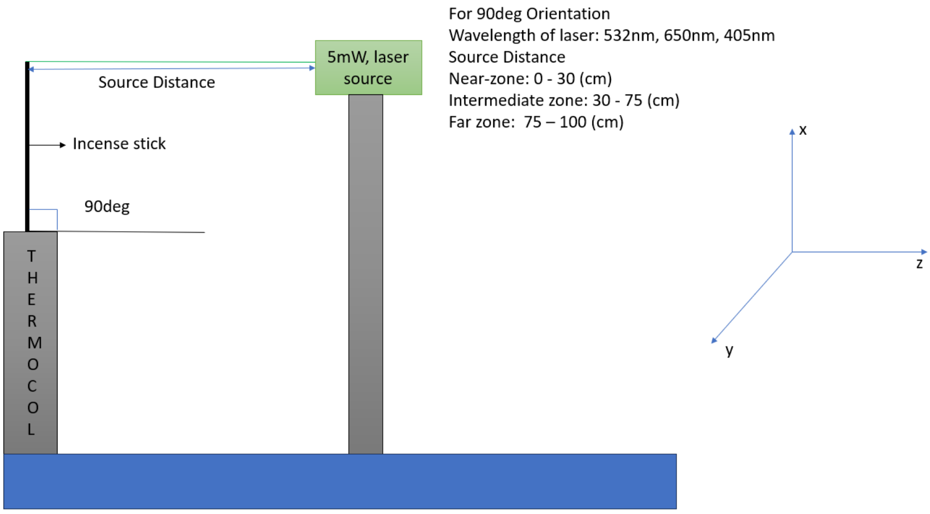

Figure 5: Schematic of Experimental set-up at 90deg orientation

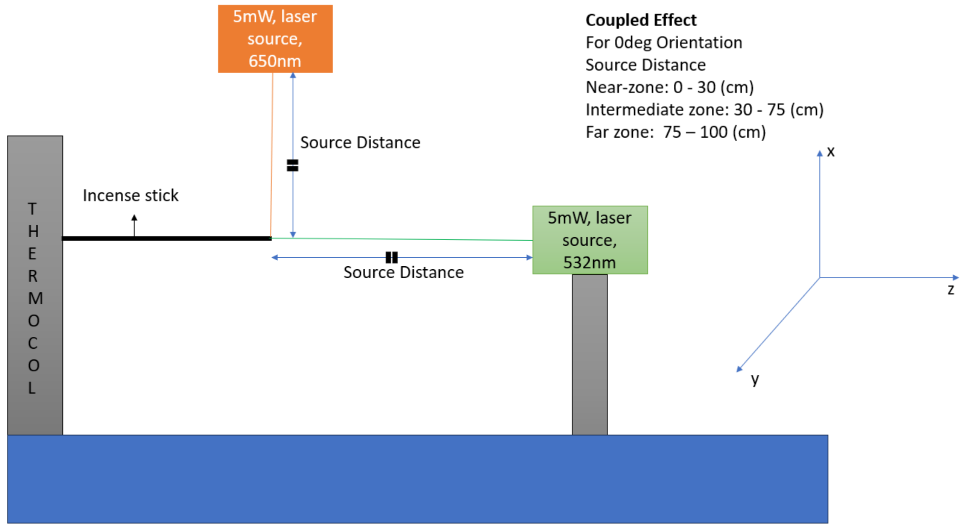

Figure 6: Schematic of Experimental set-up for coupled Effect at 0deg orientation

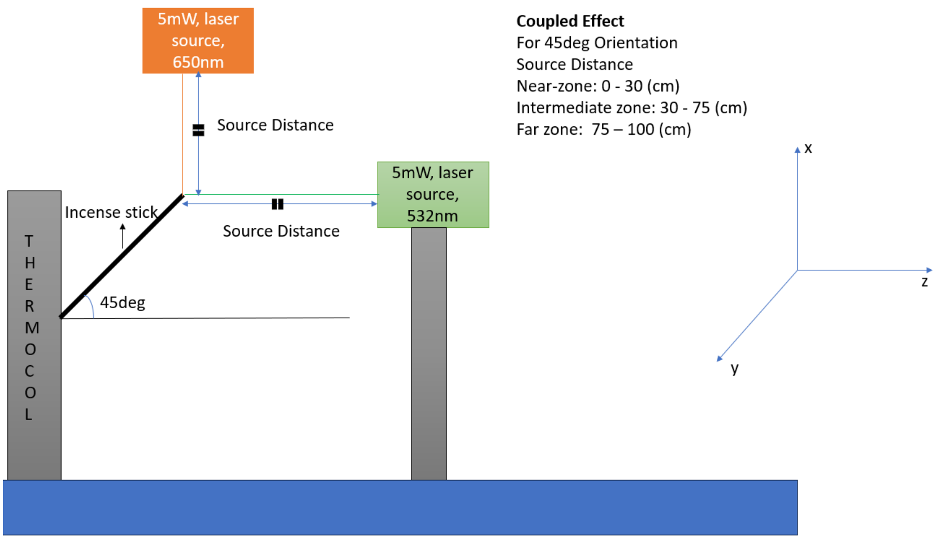

Figure 7: Schematic of Experimental set-up for coupled Effect at 45deg orientation

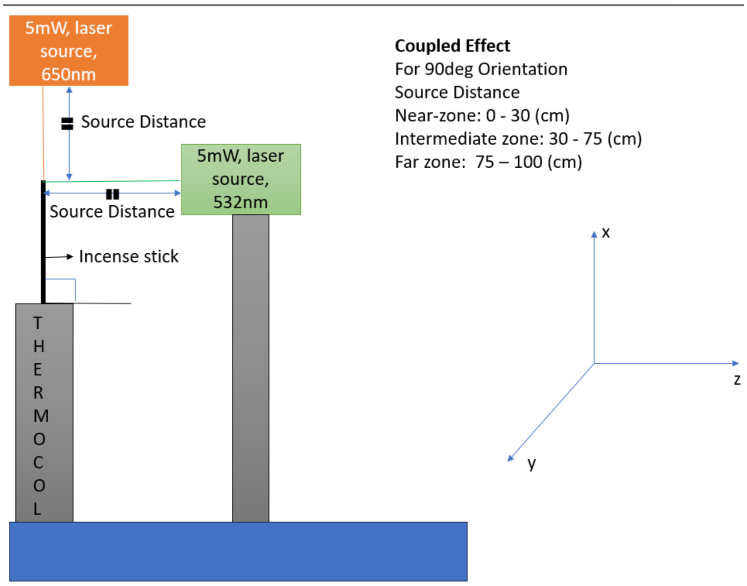

Figure 8: Schematic of Experimental set-up for coupled Effect at 90deg orientation

The time taken to burn 3cm distance in the presence and absence (base case) of laser was noted using a digital stopwatch, and the regression rate was calculated using:

$$r = l_s/t_{avg} \qquad \textbf{(1)}$$

$$r = \frac{\int qnet}{\rho s*cs*t*(Ta-Ts)} \qquad \textbf{(2)}$$

The ignition process consists of energy transition from non-reactive material decomposition to self-sustained reactive combustion. Using energy balance:

Stored energy = Energy Produced – Energy lost

$$q_P = \Delta H_c V C_i A * e^{-Ea/RT} \qquad \textbf{(3)}$$

q_P is given by Arrhenius approximation

$$q_L = hA(T_s-T_a) + \varepsilon\sigma A(T_s^4-T_a^4) \qquad \textbf{(4)}$$

q_L is given by Connective + Radiative heat transfer

$$tC_sV\frac{dT}{dt} = q_P - q_L \qquad \textbf{(5)}$$

$$Q = \varepsilon\sigma(2\pi\, r' l_s \cos\theta + 2\pi R^2)(T_s^4-T_a^4) \qquad \textbf{(6)}$$

Readings were taken at five orientations of the solid fuel concerning the horizontal: 0˚, 30˚, 45˚, 60˚, 90˚. Initially, base case readings were computed, followed by the regression rate variation in the presence of a single laser. 532nm and 650nm wavelength lasers were arranged in a configuration with the 532nm laser in the longitudinal direction and the 650nm laser in the transverse direction placed equidistant from solid fuel. The effect was described as a "coupled effect". A non-dimensional number "regression rate coefficient" was defined for quantifying the experimental data, given by:

$$\Psi = \frac{\mu}{\alpha} \qquad \textbf{(7)}$$

4. Results And Discussions

Systematic experiments were carried out to study the effects of lasers on the reverse smouldering spread. Before the commencement of the main study, the experimental setup was validated following the classical theory of heat transfer over thin solid fuels. From prior studies, it is concluded that the surface orientation of the fuel plays a significant role in affecting the regression rate. At 0°, the propagation front from ash to unburnt fuel is purely due to conduction as the buoyant velocity on the unburnt incense stick is zero. At 90°, the ash is in a convective environment. The smoke moves vertically upwards at high temperatures, reducing heat transfer to the environment. Based on the above factors, the regression rates obtained at both orientations are nearly the same. At 45°, the temperature gradient is effectively split into two components: one aligned along the heat flow direction and the other perpendicular to it. This results in an optimal combination, enhancing the heat transfer and, hence, the maximum regression rate. The base case reading results match reasonably well with the classical theory of heat transfer. The impact of lasers on the regression rate is simplified in terms of the regression rate coefficient (Ψ).

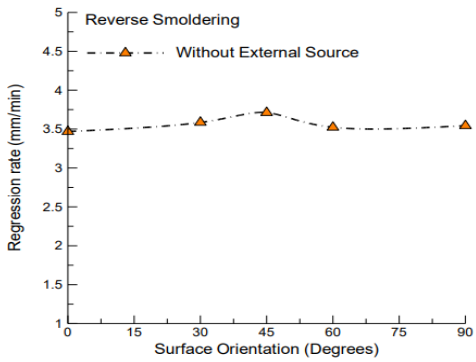

Figure 9: Base case

4.1 Effect of 532nm wavelength laser

Using (Eq. 6), the maximum radiative heat loss is at 0° orientation, resulting in minimum thermal energy. When a 532nm laser is impinged on the incense stick, the light energy gets converted into thermal energy quite efficiently, giving rise to the maximum regression rate (increase by **22.4%**). With a further increase in angle, both conductive and convective heat transfer increase, but radiative heat transfer decreases. This results in an increase in thermal energy. As the total energy is a conserved quantity, when energy is supplied through a laser, light energy is less efficiently converted into thermal energy. An increase by only **1.04%** in the regression rate was observed at 45°. Beyond 45°, the conductive and convective heat transfer is increased. This results in an increase in the regression rate. With the increase in distance, minute diffractions in the laser beam due to smoke and air particles result in a decrease in the regression rate at 0°. The behaviour of reverse smouldering spread at a distance of 30cm and 75cm is similar to the behaviour observed in the near zone. However, at other source distances, there is an increase in the regression rate beyond 0°. The energies and heat transfer rates change and tune in a certain manner that the behaviour is similar to the base case but with increased regression rates. Ψ>1 for all the cases, indicating that 532nm lasers are a potential source.

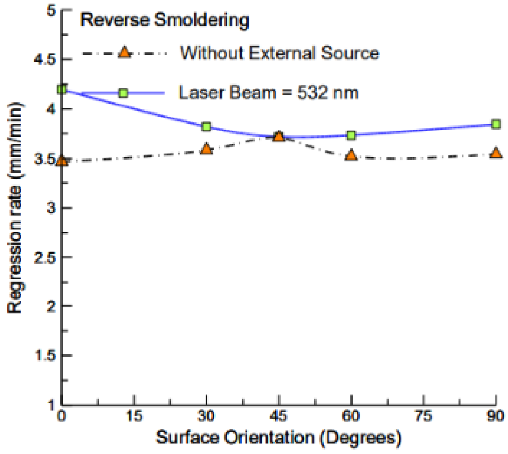

Figure 10: 532nm laser in near zone

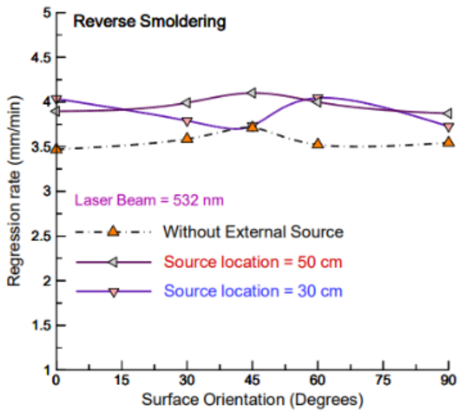

Figure 11: 532nm laser in intermediate zone

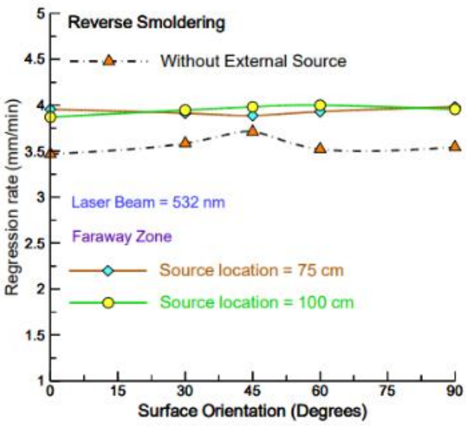

Figure 12: 532nm laser in far zone

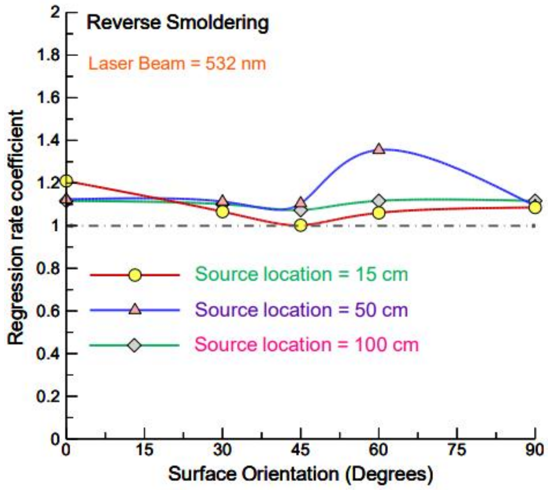

Figure 13: Regression Rate Coefficient variation for 532nm laser

4.2 Effect of 650nm wavelength laser

The 650nm laser has less energy as compared to the 532nm laser, resulting in a less increase in regression rate. 650nm laser has a sufficiently longer wavelength, hence, it is less prone to diffraction of the beam. Therefore, the entire energy is transmitted to solid fuel without much wastage. An increase by **10.42%** at 0° at a source distance of 15cm was observed. The rate of increase falls with a further increase in θ, as observed in the 532nm case. However, there is an increase in the regression rate by **2.54%** at 45° and **12.3%** at 60° due to the excitation of the molecules to higher energy levels and increased radiative heat transfer. For the intermediate zone, a decrease in the regression rate (Ψ = 0.967) was observed at 45°, indicating that some part of the thermal energy was converted into light energy. A change in the orientation of the incense stick leads to a change in the shape factor. As Ψ<1, the influence of the shape factor and wavelength of the beam together prevents the development of the thermal boundary layer, altering the temperature profile of the region. This results in the decrease of conductive heat transfer and, hence, a lower regression rate. On further increase in the orientation, there is an increase in the regression rate. The maximum increase (**9.24%**) in the regression rate was observed at 90° because of decreased convective heat transfer, indicating maximum conversion of the light energy into thermal energy. The maximum increase in the regression rate was observed at 0° (**16.63%**) at a source distance of 100cm. The rise in the regression fell to **5.43%** at 45°, and a sudden increase to 15.45% was observed at 90°.

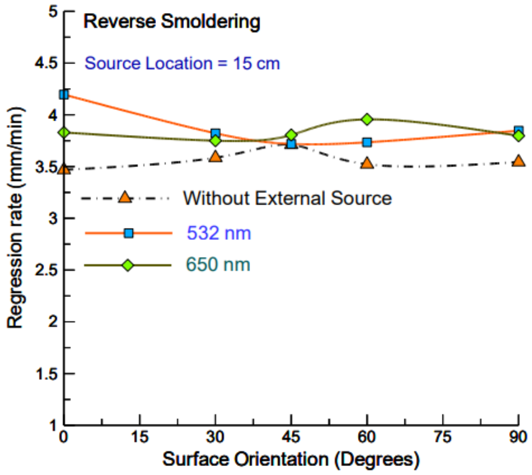

Figure 14: 650nm laser in near zone

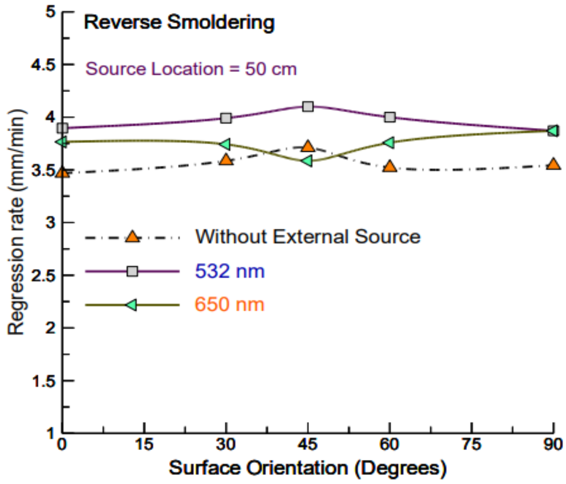

Figure 15: 650nm laser in intermediate zone

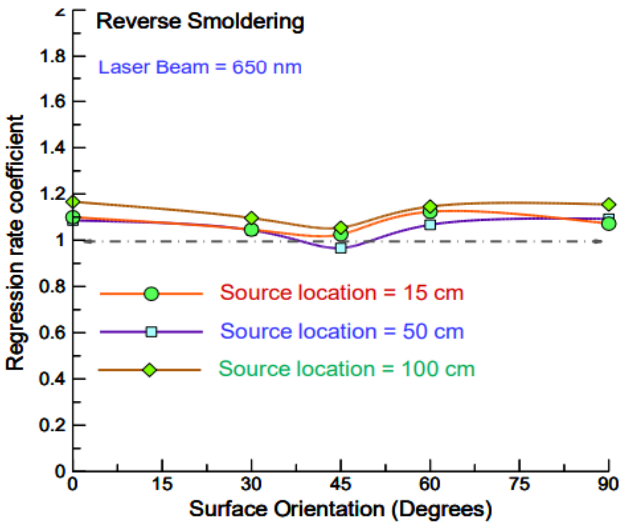

Figure 16: Regression Rate Coefficient variation for 650nm laser

4.3 Effect of 405nm wavelength laser

One interesting factor observed in the case of the 405nm laser is that, despite having the highest energy, the increase in the regression rate was still lower than expected. This is because of the beam diffraction due to the very low value of wavelength in the presence of smoke and air particles. A decrease in the regression rate by **0.59%** at 30°, **5.82%** at 45° and **0.39%** at 90° orientations was observed. Hence, 405nm lasers were mostly behaving as a sink, indicating that blue lasers absorb the thermal energy. There is a significant conversion of thermal energy into light energy. Blue lasers are highly efficient at 0° as there was an increase by **20.69%** in the regression rate as at 0°, the conductive heat transfer is very high. It is observed that the 405nm laser behaves very similarly to the 650nm in the intermediate zone. The trend observed is highly non-monotonic. The lasers behave as a sink at 45° as a decrease in the regression rate (by **2.2%**) was observed. The maximum regression rate was at 0° with an increase of **11.61%**. Blue lasers are quite efficient at 0° and least efficient at 45°. The effect of the 405nm laser was very different at a distance of 100cm. The maximum increase in regression rate (by **11.61%**). One interesting fact observed at 100cm distance was that the 405nm laser contributed to an increase in the regression rate at all the orientations. Therefore, it can be concluded that as beam diameter increases due to increased diffraction at larger distances, the radiative heat transfer rates increase due to alterations in the shape factor, leading to an increase in the regression rate.

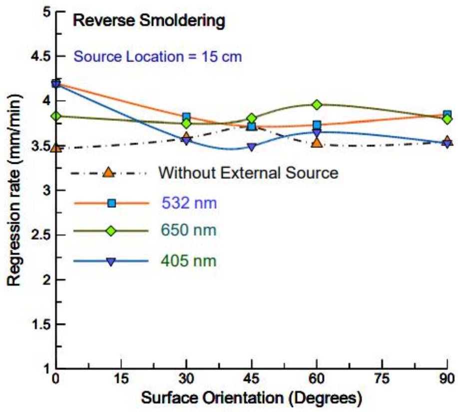

Figure 17: 405nm laser in near zone

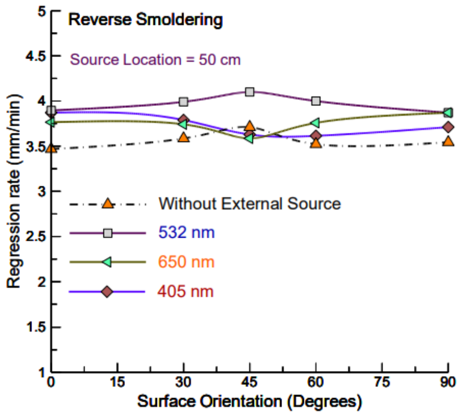

Figure 18: 405nm laser in intermediate zone

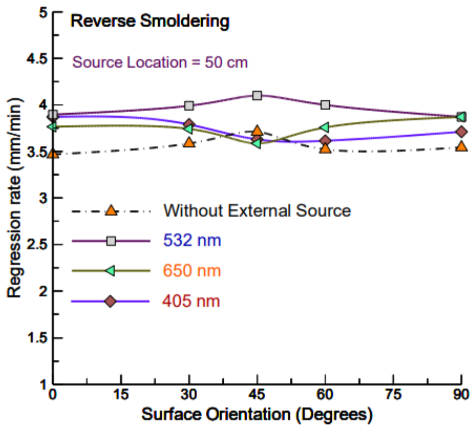

Figure 19: 405nm laser in far zone

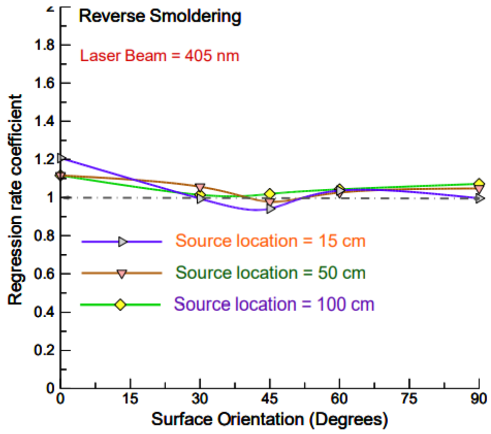

Figure 20: Regression Rate Coefficient variation for 405nm laser

4.4 Coupled Effect

The combined energy transfer of the 532nm and 650nm lasers shows a maximum increase in the regression rate (by **36.63%**) at 60° at a source location of 15cm. The coupled system behaves as a sink at 90° as a decrease in the regression rate by **0.39%** was observed. As total energy is a conserved quantity, the excess energy due to the combined effect effectively gets converted back to light energy. The energy interactions and heat transfer rates are highly non-monotonous. The behaviour in the intermediate zone is quite similar to the base case. There is a significant increase in the regression rates at all the orientations with a maximum at 45° (**24.36%** increase) due to an increase in the external energy source. The coupled system is quite efficient in the intermediate zone. For the far zone, the energy transfer and interconversion of light energy to thermal energy is observed to be non-monotonic. A maximum regression rate is obtained at 45° (4.44 mm/min), similar to the base case. Slight variations were observed at 60° (4.42 mm/min) and 90° (4.22mm/min). The maximum increase from the base case was observed at 0° orientation (an increase by **27.2%**) due to increased conduction heat transfer.

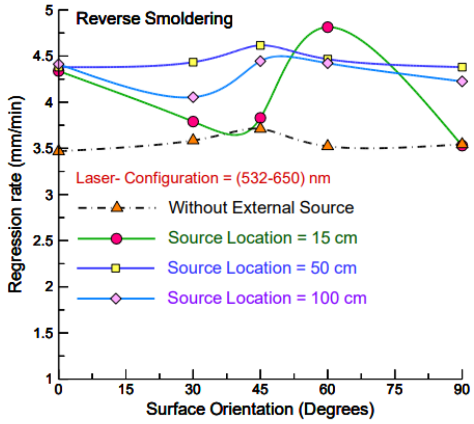

Figure 21: Coupled Effect

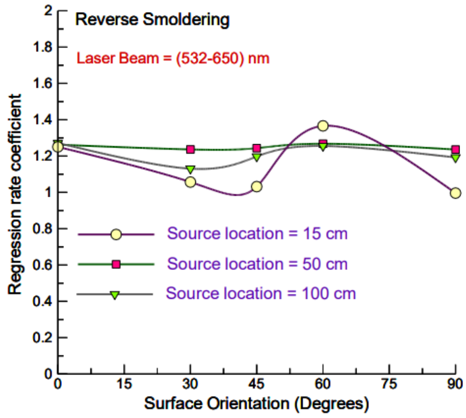

Figure 22: Regression Rate Coefficient Variation for Coupled Effect

5. Conclusions

The experiment showed that lasers have a significant impact on smouldering. Key factors influencing this impact include surface orientation, source distance, laser wavelength, and the number of energy sources.

1) Smouldering combustion is severely affected by the presence of an external light source (laser).
2) Surface orientation, source distance, wavelength of the laser and number of energy sources (lasers) are the key controlling parameters that alter the heat transfer rates, energy conversions and hence regression rate.
3) From the experimental analysis, it can be concluded that all three lasers (532nm, 650nm, 405nm) increase the regression rate by an average of 14.86% in the near zone.
4) In the intermediate zone, the behaviour is similar to the base case with an increase in regression rates.
5) With the increase in the source distance (far zone), an increase in the regression rate was observed, implying an effective conversion of the light energy to thermal energy.
6) For the 532nm laser, the Ψ value was always greater than 1. Hence, we can conclude that 532nm lasers will behave as a source for most of the cases.
7) 650nm lasers were quite efficient in converting light energy to thermal energy. Having the largest wavelength, the losses occurring due to smoke and atmospheric particles are minimal. The maximum regression rate was observed at 100cm distance for 0 ◦ orientation (20.63%).

8) In spite of having very high energy, the 605nm lasers behaved as sinks for most of the cases in near and intermediate zones owing to the fact that the blue laser gets dispersed easily. However, there was a significant increase in the regression rate (by 20.69%) at 0◦ orientation in the near zone (15cm).
9) Even though 405nm lasers were behaving as sinks, they were quite efficient in the far zone (at a distance of 100cm). An average increase of 5.384% was observed for all the orientations.
10) The coupled system of 532nm and 650nm lasers highly increased the regression rates. A sudden rise in the regression rate at 60◦ orientation (by 25.06%) was observed in the near zone (15cm). However, they behaved as a sink at 90◦ orientation.
11) At 50cm distance, the behaviour of the reverse smoulder spread under the coupled effect was similar to the base case with increased regression rates at all the orientations. A slight difference in the curve was observed in the case of the far zone.
12) On analysing the equations for single configurations of 532nm and 650nm laser, the nature of the curve was observed to be polynomial (quartic regression). The energy transfer and heat transfer were highly non-monotonous, and the regression rates differed significantly owing to the change in key controlling parameters.
13) **Applications of the work:** Fires caused due to smouldering have a devastating impact on life and the environment. From the above study, 405nm lasers can be impinged at different orientations from intermediate and far zones, resulting in a decrease in regression rate and controlling the fire spread. Based on the above study, it can be concluded that lasers (532nm and coupled effect) increase the regression rate significantly, making a potential energy source. They can be used as thrust-altering devices by varying the regression rates of fuel, stabilising the combustion in solid fuels, and initiating combustion in hybrid propellants. Thermodynamically, lasers increase the entropy ($\Psi>1$) or decrease the entropy ($\Psi<1$). Hence, they can be used to increase the energy of the velocity boundary layer, delaying the boundary layer separation at higher angles of attack. Lasers also find a potential application as shock deflectors.

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