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The Combustion Characteristics of *Calophyllum inophyllum* Fuel in the Presence of Magnetic Field

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ABSTRACT

The study objective is to investigate the combustion characteristics of *Callophyllum inophyllum* fuel in presence of a magnetic fields. To conduct the experiment, a bunsen burner was utilized, with fuel and air being dispensed via a syringe pump and compressor, both regulated by a flowmeter. The fuel and air pipes were heated to 532.15 (K) to facilitate fuel evaporation. The equivalent ratio of 0.5, 1, and 1.5 was adjusted to control air discharge and fuel. An 11,000 gausses artificial magnet was used, with N-S, N-S, N-N, and S-S being the various magnetic pole configurations. The study found that the magnetic field can enhance combustion quality by affecting the molecules involved in the combustion process. The magnetic field's force also intensifies the movement of O_2, making it more energetic. As O_2 travels from the North Pole to the South Pole through the combustion reaction zone, it quickens the oxidation-reduction process and curtails diffusion combustion. The red color's intensity diminishes with the magnetic field's effect, indicating this phenomenon. When a magnetic field is applied, the polarity of C.*inophyllum* biodiesel fuel becomes highly favorable. The triglyceride carbon chain bonds become unstable, and the van der Walls dispersion forces are weakened, which facilitates easier O_2 binding to the fuel, resulting in more efficient combustion. An increase in the laminar burning velocity value can be noticed when exposed to a magnetic field.

Keywords: *Biodiesel, laminar burning velocity, magnetic field, premixed flame, RGB color*

I. Introduction

One of the problems facing the world today is the depletion of petroleum reserves and environmental pollution which has an impact on global warming. The industrial sector is heavily dependent on fossil energy, especially diesel fuel, which is mostly used in trains, ships, power plants, buses, trucks, and an increasing number of cars. Several researchers have developed alternative energy as a substitute for fossil energy which is more environmentally friendly and has lower production costs. The second generation of biodiesel is a step forward in the development of sustainable fuels and does not conflict with food raw materials [1], [2]. The use of biodiesel in diesel engines produces lower carbon dioxide, hydrocarbon, and carbon monoxide emissions than fossil fuels [3], [4]. Some of the raw materials that have been developed as second-generation biodiesel are crude jatropha curcas oil, crude sterculia foetida oil, crude ceiba pentandra oil, and crude *C. inophyllum* oil [5].

The plant of *C. inophyllum*, that grows abundantly in unproductive land and tropical/sub-tropical climates [6], has the potential to become an excellent material of

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biodiesel production. The seeds contains a significant oil yield by 65.8%, surpassing even palm oil and jatropha, which typically yield only 40-60% [7]. Promising results have emerged from tests conducted on engine performance and emissions using *C. inophyllum* biodiesel. Researchers discovered that blending 10% *C. inophyllum* biodiesel with diesel oil augmented brake thermal efficiency by 2.3% and reduced fuel consumption by 3.06% compared to pure diesel oil [8]. Furthermore, replacing pure diesel oil with a combination of diesel oil and *C. inophyllum* can result in decreased opacity of CO and reduced production of smoke [9].

C. inophyllum biodiesel still has some drawbacks such as higher viscosity, density, and flash point when compared to diesel fuel [10]–[13]. When fuel viscosity is high, carbon buildup occurs on critical engine components such as the fuel filter, injectors, and piston ring[14]. Additionally, high viscosity negatively impacts injector spray atomization, while also impeding the formation of a fuel-air mixture by slowing down evaporation [12]. Moreover, fuel density plays a role in its combustibility, and high-density fuel is harder to burn, leading to reduced heat generation [15]. Meanwhile, a higher flash point causes the fuel to require a longer burning time. Fuel quality can also affect the ignition delay time which affects engine performance and the resulting emissions [16]. Ignition delay is a condition where the first drop of fuel enters the combustion chamber until the slightest flash point is seen. Ignition delay itself is affected by engine speed, load, and fuel temperature. The combustion process occurs with the presence of physical and chemical processes [17]. Physical delivery delays are affected by the automation of fuel spray, evaporation, and fuel-air mixing. Meanwhile, chemically it is affected by fuel decomposition, aggregation, and oxidation-reduction processes. In addition, *C. inophyllum* biodiesel contains O_2, which causes *C. inophyllum* biodiesel to produce higher NOx emissions [9], [18].

Several researchers have attempted to improve the combustion quality of *C. inophyllum* biodiesel fuel, including the addition of additives [19], mixing with fossil fuels [18], and the provision of a magnetic field in the fuel line [20]. By adding a catalyst to biodiesel, it can weaken the triglyceride atomic bonds, resulting in more efficient combustion [21]. The degree of polarity of the fuel can also affect the instability of the hydrocarbon chain bonds [22]. Studies have shown that the magnetic field application into fuel pipes enhance combustion quality as well as minimize pollution [23]. Magnetic field causes fuel ionization, making it easier to bind with oxygen molecules and burn efficiently [24]. One experiment saw the installation of 3000 Gauss neodymium permanent magnets on fuel pipes, resulting in a 7% increase in efficiency, a 13% reduction in CO2, and a 19% decrease in NOx emissions [25]. This is due to the magnets' ability to alter fuel properties, aligning and orienting hydrocarbons for improved atomization [25]. The strength of the magnet used has a direct impact on reducing emissions and fuel consumption [26].

Using a magnetic field as a means of improving engine performance is a highly efficient and cost-effective method. With its simple construction and easy-to-obtain raw materials, the initial installation cost is the only expense. However, while research on internal combustion engines typically focuses on performance and emissions, more in-depth analysis of flame behavior is necessary to truly optimize engine function. As such, the study sought to investigate the influence of a magnetic field on premixed flames when using *C. inophyllum* biodiesel fuel. To achieve optimal flame characteristics, various magnetic field pole variations (N-S, S-N, N-N, S-S) and equivalent ratio variations (0.5, 1, 1.5) were employed.

II. Material and Methods

1. The Production of C. inophyllum Biodiesel

The process of producing crude oil from *C. inophyllum* seeds involves crushing them into granules and then extracting the oil using a screw press. Methanol, H_3PO_4, H_2SO_4, and distilled water are utilized to create biodiesel. The Jember University Energy Conversion Laboratory is where the process of making *C. inophyllum* biodiesel occurs. The combustion process can be disrupted by impurities and high FFA levels present in crude oil. Hence, the transformation of crude oil into methyl ester requires the use of several processes such as degumming, esterification, and transesterification are required to get methyl ester from crude oil [27], [28]. The degumming process eliminates impurities and latex from crude oil, achieved by adding a 1% volume of H_3PO_4 to *C. inophyllum* oil, and stirring it for 30 minutes at 60°C. After stirring, it is left to stand for 4 hours. The esterification process is then employed to decrease the FFA levels in *C.inophyllum* oil. This is achieved by adding a 1% volume of H_2SO_4 to the oil, followed by methanol at a ratio of 1:22 mol. The mixture is stirred for 2 hours at 60°C before being left to stand for 8 hours for separation. The final step is transesterification, where fatty acids are converted to methyl esters. For this process, a 1% weight of NaOH is added to *C.inophyllum* oil, followed by methanol at a ratio of 1 to 6 mol. The mixture is stirred for 3 hours using a magnetic stirrer.

2. Composition of Biodiesel C. inophyllum

In order to analyze the fatty acid makeup of pure *C. inophyllum* biodiesel (B100), a Gas Chromatography Mass Spectrometry (GCMS) test was carried out. Table 1 illustrates the percentage composition of the biodiesel B100 molecules, which revealed that methyl oleate comprised the majority of the biodiesel B100 compound at 45.82%. This notable presence of methyl oleate is significant as it contributes to the improvement of low-temperature performance and also has a positive impact on the oxidation stability of biodiesel [29]. The methyl oleate content in this study was higher than the 38.108% castor oil biodiesel content [30] and palm oil 42.72% [31]. This shows that biodiesel B100 has good quality to be developed further. Of all the chemical compounds contained in biodiesel, the stoichiometric combustion reaction can be seen as shown in Equation (1). After obtaining the combustion reaction of chemical compounds, the stoichiometry AFR of biodiesel B100 13.2 can be determined using Equation (2). In contrast, diesel fuel has a higher AFR of 14.59. This is because biodiesel compounds contain O_2 compounds, so biodiesel requires less air in combustion while diesel fuel compounds do not contain O_2.

Combustion reaction:

$$0.4582C_{19}H_{36}O_2 + 0.4377C_{17}H_{36}O_2 + 0.0297C_{15}H_{30}O_2 + 0.0271C_{21}H_{42}O_2 + 0.0225C_{19}H_{34}O_2 + 0.0144C_{21}H_{34}O_2 + 0.0062C_{13}H_{26}O_2 + 0.0041C_{18}H_{36}O_2 + 27.00685(O_2 + 3.76N_2) \longrightarrow 18.0456CO_2 + 17.9225H_2O + 101.545568N_2 \quad (1)$$

$$\text{AFR stoichiometry} = \frac{\text{air mass}}{\text{fuel mass}} \quad (2)$$

$$= 27.00685(O_2+3{,}76N_2) \;/\; 0.4582C_{19}H_{36}O_2 + 0.4377C_{17}H_{36}O_2 + 0.0297C_{15}H_{30}O_2 + 0.0271C_{21}H_{42}O_2 + 0.0225C_{19}H_{34}O_2 + 0.0144C_{21}H_{34}O_2 + 0.0062C_{13}H_{26}O_2 + 0.0041C_{18}H_{36}O_2$$

$$= 3{,}707.493504 / 280.75$$

$$= 13.2 \text{ mol}$$

Table 1. *C. inophyllum* biodiesel fatty acid composition

No	Trivial Name	Molecule formula	Volume (%)
1	Methyl oleate	$C_{19}H_{36}O_2$	45.82
2	Methyl palmitate	$C_{17}H_{36}O_2$	43.77
3	Methyl myristate	$C_{15}H_{30}O_2$	2.97
4	Methyl arachistate	$C_{21}H_{42}O_2$	2.71
5	Methyl linoleate	$C_{19}H_{34}O_2$	2.25
6	Methyl arachidonate	$C_{21}H_{34}O_2$	1.44
7	Methyl laurate	$C_{13}H_{26}O_2$	0.62
8	Methyl margarate	$C_{18}H_{36}O_2$	0.41

3. Flame Testing Scheme

Figure 1 shows the scheme of the bunsen burner used to test the characteristics of the flame under the influence of a magnetic field. Bunsen burners use stainless steel with an inner diameter of 0.6 cm and a Y-junction geometry. The fuel is dispensed via syringe pump while the air discharge is managed by a compressor, regulated with a flow meter. A belt heater, operating at a temperature of 532.15 (K), evaporates the fuel in the pipe. To stabilize the temperature in the mixing chamber, the air is also heated to 532.15 (K). Fuel and air debits are carefully controlled to maintain equivalent ratios of 0.5, 1, and 1.5. An artificial magnetic field with a strength of 11000 gausses is applied on both sides of the flame, with pole variations of N-S, S-N, N-N, and S-S, and a distance of 0.3 cm. A high-definition camera with 1080 and 64 megapixels specifications is positioned with a distance of 18 cm, parallel to the burner. Video footage is captured in three trials for each variation, later converted to images using the software of DVDVideoSoft Free Studio.

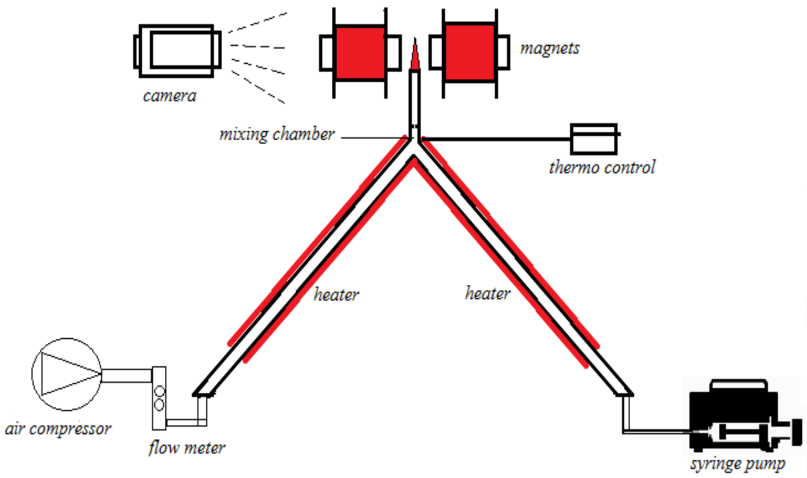
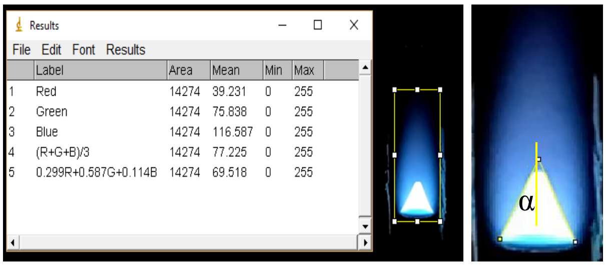


Fig. 1. Bunsen burner research tool schematic

4. Data Analysis Method

Data analysis of the laminar burning velocity and intensity of RGB color was conducted based on visual flame data. The RGB color analysis focused on the red color intensity, which is considered a diffusely burning fuel, and measured its level using the Image-J program. The results, shown in Figure 2a, were obtained through a series of steps, which included opening the file, clicking on plugins, and analyzing the RGB measure. Flame angle measurements were also carried out using the Image-J program, as shown in Figure 2b, on premixed flames.



a. b.

Fig. 2. Data analysis (a). Intensity of RGB color, (b). Flame angle

Equation (3) is essential to determine the reactant velocity at every equivalent ratio for computing the laminar burning velocity. Once the reactant speed and flame angle are obtained, equation (4) can be applied to determine the laminar burning velocity.

$$Uo = \frac{Qfuel + Qair}{Ab} \qquad \ldots\ldots (3)$$

with:

Uo = Reactants Speed (cm^3/s)
$Qfuel$ = Fuel discharge (cm^3/s)
$Qair$ = Air discharge (cm^3/s)

$$SL = V.\frac{1}{2}\text{Sin}\ \alpha \qquad \ldots\ldots (4)$$

with:

SL = Laminar burning velocity (cm/s);
V = Reactants velocity (cm/s);
$\frac{1}{2}$Sin α = Half flame angle.

III. Results and Discussion

1. Flame Color Intensity Analysis

In Figure 3, the effect of magnetic field variations (N-S, S-N, N-N, and S-S) on the flame's visualization is depicted. The flame comprises two reaction zones: an internal premixed flame that converts fuel to CO and H_2, and an external diffuse flame that further oxidizes CO and H_2 to produce combustion [32]. The flame's structure varies at equivalent ratios of 0.5, 1, and 1.5, with the equivalent ratio having a significant influence on whether the combustion process succeeds or fails [15]. An equivalent ratio of 1.5 indicates a higher flame structure and some diffusion combustion at the tip of the flame. This happens because a less-than-ideal mixture of air and fuel tends to be richer in fuel so that some of the fuel is not premixed. At an equivalent ratio of 0.5, the flame structure is shorter due to the more air mixture and the less fuel mixture. Whereas an ideal mixture of air and fuel close to stoichiometry will produce the most optimal combustion.

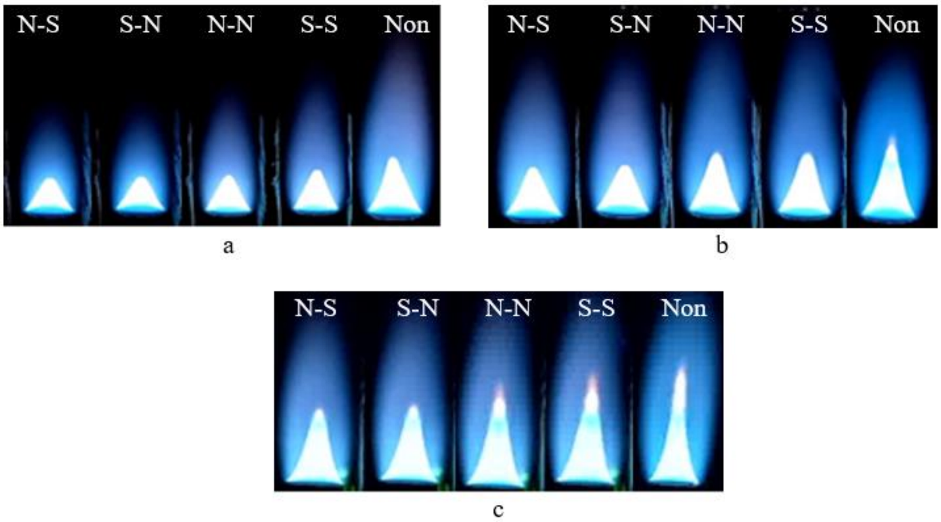


Fig. 3. B100 flame evolution, (a) ratio equivalent 0.5, (b) ratio equivalent 1, (c) ratio equivalent 1.5

The graph in Figure 4 displays the red color intensity on B100 biodiesel flames. Magnetic field variations from the S-S, N-N, S-N, and N-S poles sequentially decrease the red color intensity, with the most significant impact occurring at the N-S pole at 36.29 with an equivalent ratio of φ=0.5. In contrast, the non-magnetic flame shows the highest red intensity value, indicating that the magnetic field can impact molecules involved in the combustion reaction. Molecular orbital theory suggests that O_2 is paramagnetic due to its two unpaired free electrons, which the magnetic field can affect. As the magnetic field force leads from N to S poles, O_2 outside the flame can experience attraction and repulsion between poles, allowing it to oxidize unburned fuel and minimize diffusion combustion.

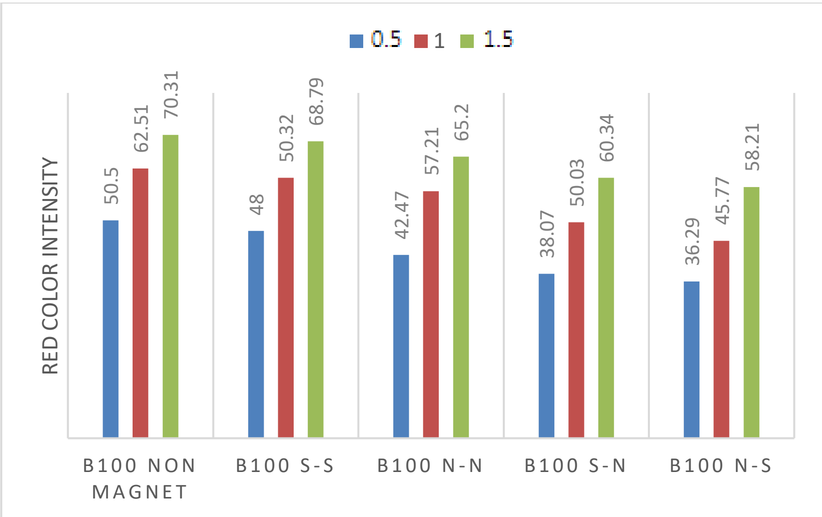


Fig. 4. The intensity of the red color in B100 fuel

2. *Laminar Burning Velocity Analysis*

Researchers can gauge the quality of combustion by examining flame formation and laminar burning velocity. To this end, various parameters are used, including the latter [33]. In Figure 5, the laminar burning velocity of B100 fuel is depicted with changes in equivalent ratio and magnetic field. The results indicate that the velocity increases under magnetic influence, regardless of the magnetic poles' variations. The most significant improvement occurred with N-S poles at 24 cm/s and equivalent ratio φ=1, followed by S-N at 22 cm/s, N-N at 16.17 cm/s, S-S at 15.68 cm/s, and non-magnetic at 14.7 cm/s. Earlier research has also shown that the magnetic field plays a pivotal role in enhancing combustion quality [23], [25], [34], [35]. Under the influence of the magnetic field, hydrocarbons undergo a transition from the para-state to the ortho-state, changing their orientation [20]. The carbon chain of triglycerides is primarily composed of carbon (C) and hydrogen (H) atoms. H atoms exist in two isomeric forms: para, predominant in fuels, and ortho, achieved by magnetic field application. These forms differ in the rotation of opposite nuclei. In the para molecule, H has an anti-parallel rotation, and the spin states of the atoms are in opposite directions, making them diamagnetic. Conversely, in the ortho molecule, H has parallel degrees of rotation, and the spin states of atoms are in the same direction, making them paramagnetic [36]. By passing through a magnetic field, fuel molecules' orientation is altered from the para to the ortho state, resulting in a significant decrease in the intermolecular forces of the triglyceride and an increase in H atom spacing. As the hydrocarbons and O_2 bond more strongly, combustion becomes increasingly efficient.

Research conducted by Nanlohy et al., [21] stated that the addition of a catalyst to biodiesel of jatropha oil created polarization interactions that The molecular bonds of the triglyceride chain were weakened, allowing for easier rotation of bonds. This resulted in increased electron movement and energy, leading to heightened reactivity and efficient fuel combustion. According to Nanlohy et al, [22] the composition of molecular mass and hydrocarbon chain bond instability are critical factors in the combustion process, with the polar properties of *C. inophyllum* biodiesel playing a significant role. Magnetic fields are also important in this process. In the N-S magnetic field, the triglyceride chain bonds get a force of attraction from the magnetic field. This causes a weak van der Waals dispersion force that it will make it easier for O_2 to bind and the combustion becomes more optimal.

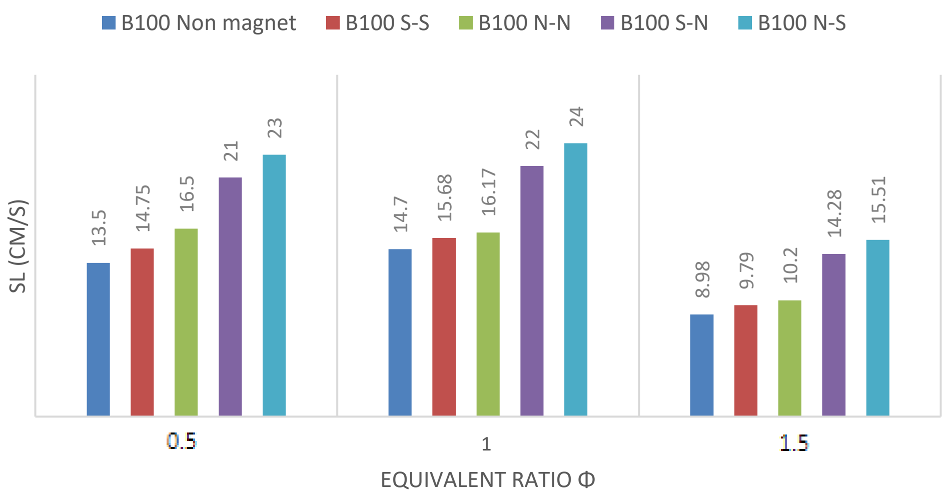


Fig. 5. Laminar burning velocity (SL) fuel B100

The magnetic field's impact on the combustion process is depicted in Figure 6. The S-N magnetic field influences O_2 movement, pulling it from the North pole to South pole and into a combustion reaction zone. Conversely, H_2O exhibits diamagnetic properties that propel it in the opposite direction, from the South pole towards North pole, and out of the flame. This distinctive behaviour results in a more proficient combustion process. The N-S pole proves more powerful, as its direction aligns with the earth's magnetic field during data collection. At N-N poles, the magnetic field pushes O_2 towards the combustion reaction zone from both sides of the magnet, while drawing H_2O out of the flame. Conversely, the S-S pole's direction attracts O_2 from the flame and pushes H_2O into it as a heat source. This phenomenon does not significantly impact the combustion reaction.

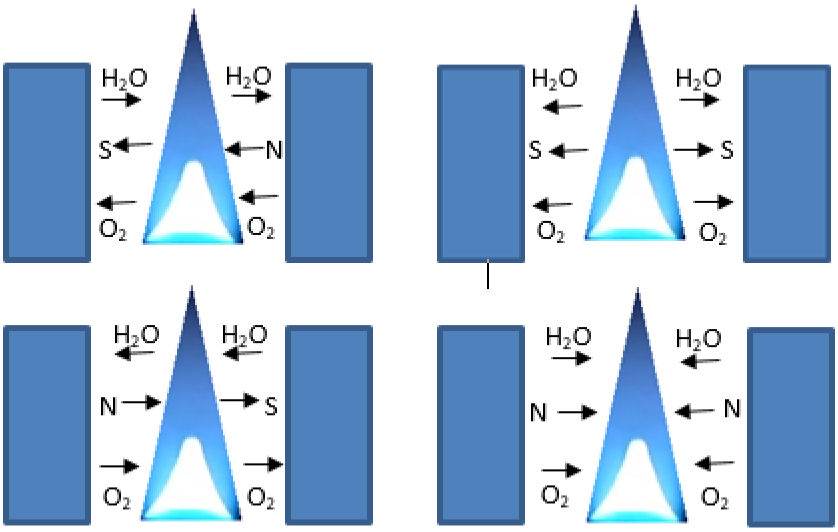


Fig. 6. Illustration of a flame influenced by magnetic field

IV. Conclusion

An investigation was carried out into the impact of magnetic fields on premixed *C.inophyllum* fuel combustion. The results indicated that magnetic fields can influence molecular activity central to the combustion process. The force of the magnetic field causes increased energetic movement of O_2, which travels from N to S poles through the combustion reaction zone. This, in turn, accelerates the oxidation-reduction process and reduces diffusion fires, as evidenced by the reduction in the red color intensity. Additionally, the degree of polarity of *C. inophyllum* biodiesel fuel is enhanced by the influence of a magnetic field. This causes the triglyceride carbon chain bonds to become unstable, weakening van der Walls dispersion forces and making it easier for O_2 to bind to the fuel, ultimately improving combustion efficiency. This is supported by the increased laminar burning velocity observed as impact of a magnetic field.

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