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Enhancing Combustion Characteristics of Callophyllum Inophyllum Fuel Using Magnetic Fields

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Abstract

The challenges of energy security and environmental sustainability have driven the development of eco-friendly alternative fuels, among which second-generation biodiesel has gained significant attention. This study aims to analyze the combustion quality of biodiesel derived from Calophyllum inophyllum oil (CIME) under the influence of an external magnetic field on the laminar flame speed in a premixed flame system. CIME biodiesel was produced through a transesterification process following degumming and esterification stages. Experimental tests were conducted using a stainless-steel Bunsen burner with a T-junction configuration and integrated heating system, in which magnetic fields with strengths ranging from 7000 to 10000 gauss were applied directly to the flame region. The equivalence ratio (ϕ) of the fuel-air mixture was varied between 0.4 and 1.4. Laminar flame speed was calculated from flame visualization data based on the observed flame angle. The results indicate that the magnetic field significantly enhanced the laminar flame speed, with the highest value observed at ϕ = 0.8 and a magnetic field strength of 10000 gauss. This phenomenon is attributed to the increased oxygen concentration in the reaction zone, induced by the magnetic attraction of paramagnetic O_2 molecules. These findings suggest that the integration of magnetic fields into biodiesel combustion processes can potentially improve energy efficiency and reduce emissions, offering an innovative approach for advancing renewable energy systems.

Keywords: Biodiesel; Magnetic field; Laminar flame speed; Renewable energy; Combustion

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1. Introduction

The combustion process is a key factor in determining engine performance and efficiency, as well as the amount of emissions produced. In diesel engines, incomplete combustion can cause increased emissions of harmful gases such as carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx) [1], [2]. One of the main challenges in the use of alternative fuels such as biodiesel is in achieving optimal combustion quality because the physical and chemical properties of biodiesel are different from conventional diesel. Although biodiesel has the potential as an environmentally friendly fuel, its combustion efficiency and its effect on flame characteristics are still issues that need to be studied further, especially from the perspective of combustion kinetics and flame dynamics.

As the need for sustainable energy sources increases, second generation biodiesel derived from non-food sources such as Calophyllum inophyllum is gaining widespread attention due to its renewable nature and potential to reduce greenhouse gas emissions. [3]-[5]. Several studies have conducted experiments on the performance and emissions of biodiesel in engines, as well as combining it with nanoparticle additives to improve combustion efficiency. [6], [7]. However, most of these studies focus on evaluating engine performance and exhaust emissions, while in-depth analysis of the combustion quality itself, especially the influence of external factors such as magnetic fields, is still very limited.

The use of magnetic fields in fuel combustion processes is starting to attract attention because of its potential to improve atomization, accelerate oxidation reactions, and reduce the formation of harmful emissions. [8]-[10]. Although the experimental results show an increase in thermal efficiency and a decrease in specific fuel consumption, the physical and chemical mechanisms underlying the changes in combustion quality due to magnetic fields are still not fully understood. Therefore, an experimental approach is needed that can directly observe the flame characteristics and specific combustion parameters.

This study aims to analyze the combustion quality of Calophyllum inophyllum (CIME) biodiesel by applying a magnetic field directly to the premixed flame using a Bunsen burner. The main focus is to measure the laminar combustion velocity as an indicator of combustion quality and evaluate the effect of variations in magnetic field strength and air-fuel ratio (AFR). This study is expected to provide a deeper understanding of the effect of magnetic fields on the biodiesel combustion process, both from a physical and kinetic perspective, and pave the way for innovation in efficient and environmentally friendly combustion technology.

2. Methods

2.1 Biodiesel Preparation

Biodiesel is an alternative fuel that can be produced from biological resources, one of which is Calophyllum inophyllum. The biodiesel production process begins with the collection of Calophyllum inophyllum fruit which is then dried naturally using solar heat for approximately two days, to facilitate the separation of the seeds from their shells. After the seeds are separated, a further drying process is carried out for four days to reduce the water content in the seeds, so that the quality of the oil produced increases.

The next stage is to refine the Calophyllum inophyllum seeds using a grinder until they become small grains, with the aim of increasing the surface area of the seeds so that the oil extraction process is more efficient. The refined seeds are then pressed using a screw-type press to obtain crude Calophyllum inophyllum oil. The extracted oil still contains polar compounds and impurities, so an initial purification process is needed through the degumming stage. This process is carried out by adding phosphoric acid (H_3PO_4) as much as 1% of the oil volume, then the mixture is stirred using a magnetic stirrer at a temperature of 60°C for 30 minutes, and left for four hours to separate the gum and impurities.

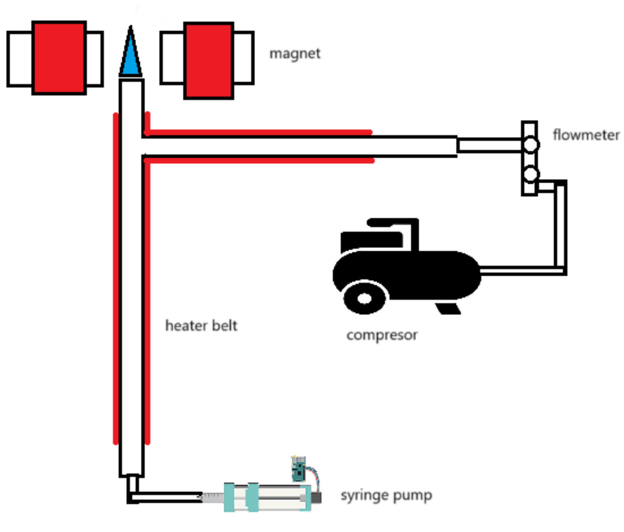


Figure 1. Schematic of Bunsen Burner Test Equipment

After degumming, the esterification process is continued to reduce the free fatty acid (FFA) content. [11]. At this stage, sulfuric acid (H_2SO_4) is added as much as 1% of the oil volume, as well as methanol with a molar ratio of 1:22 to the oil. The stirring process is carried out for two hours at a temperature of 60°C, then the mixture is left for eight hours until two layers are formed, namely the ester layer and the remaining methanol layer. The next process is transesterification, which aims to convert triglycerides into methyl esters (biodiesel) [12]. In this stage, sodium hydroxide (NaOH) is added as much as 1% of the weight of the oil as a catalyst, as well as methanol with a molar ratio of 6:1 to the oil. The mixture is stirred for three hours at a temperature of 60°C, then left for eight hours to separate the biodiesel from the glycerol. Through this series of processes, Calophyllum inophyllum oil can be converted into biodiesel that is suitable for use as a renewable fuel.

2.2 Bunsen Burner Schematic

Figure 1 shows the Bunsen burner schematic used in testing the flame characteristics under the influence of an external magnetic field. The Bunsen burner is a laboratory-scale combustion tool that is widely used to analyze combustion quality because of its easily controlled parameters and good flame visualization. [3], [13]. This burner is made of stainless steel with an inner diameter of 0.6 cm and uses a T-junction geometry configuration for mixing fuel and air. The fuel flow is precisely controlled using a syringe pump, while the air flow is supplied through a compressor and regulated by a flowmeter. The fuel evaporation process is carried out in the pipe using a heater belt at a temperature of 200°C. To maintain temperature stability in the mixing chamber, the air is also heated to the same temperature, which is 200°C. Before testing, each piece of equipment used is calibrated to ensure the accuracy of the data obtained.

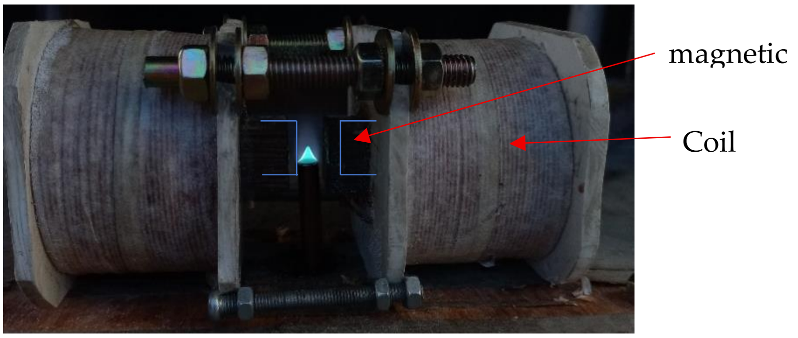


Figure 2. Flame with the Influence of Magnetic Field

The fuel and air flow rates were adjusted based on the equivalent ratio (φ) with variation values of 0.4; 0.6; 0.8; 1.0; 1.2; and 1.4. The effect of magnetic fields on the flame was tested using artificial magnetic fields with varying strengths, namely, 7000 Gauss, 8000 Gauss, 9000 Gauss, and 10000 Gauss. The magnetic fields were installed on both sides of the flame with a distance of 0.3 cm and only using the north–south (N–S) magnetic pole configuration. For documentation and visual analysis purposes, the flame was recorded using a full high definition 1080p camera with a 64 megapixel sensor, positioned at a distance of 18 cm from the burner. Data collection was carried out three times for each combination of variables to obtain valid and representative results. The recorded videos were then converted into static images using DVD Video Soft Free Studio software as a basis for further analysis. **Figure 2** shows the flame and magnetic field used in the study.

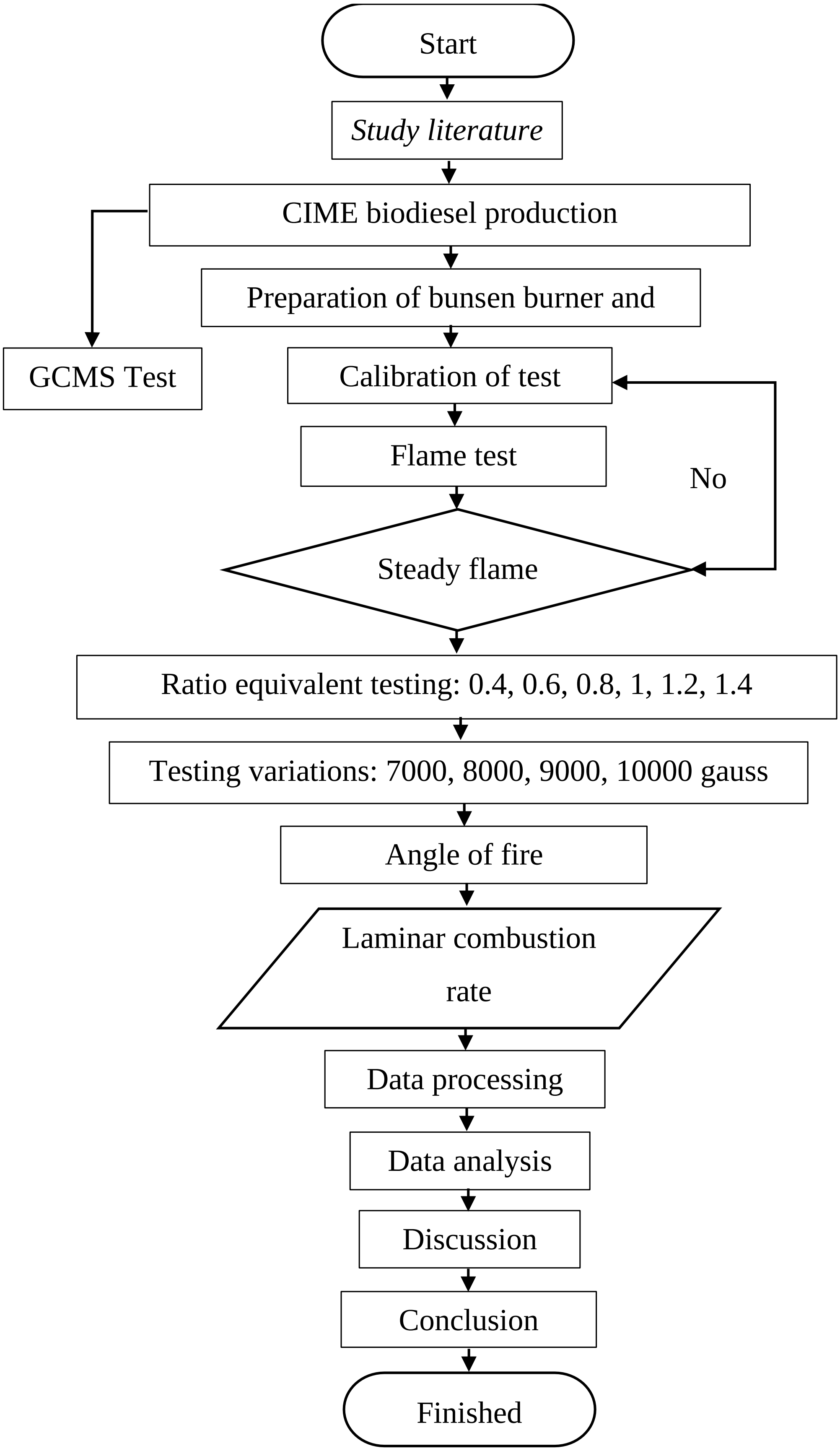


Figure 3. Research Flow Diagram

2.3 Data processing

The primary data is obtained from measuring the angle of the premixed flame. After obtaining the primary data, it is then converted into laminar flame speed data using equation (1) and equation (2).

$$SL = Uo \sin\alpha \quad (1)$$

With:

SL = Laminar flame speed (cm/s)

Uo = Speed of reactans (cm/s)

Sin α = Half of the angle the bunsen burner flame (°)

The speed of the reactants is determined by the equation (2) :

$$Uo = \frac{Qfuel+Qair}{A} \quad (2)$$

With:

$Qfuel$ = Fuel flow rate (cm^3/s)

$Qair$ = Air flow rate (cm^3/s)

A = Burner cross-sectional area (cm^2)

Experimental tests were carried out using equivalent ratios of 0.4, 0.6, 0.8, 1, 1.2 and 1.4 with the equivalence ratio defined by equation (3):

$$\varphi = \frac{AFRstoic}{AFRactual} \quad (3)$$

To clarify the methodological stages applied in this study, a research flow diagram is presented as shown in **Figure 3**. The diagram systematically summarizes the research flow which includes the stages of problem formulation, goal determination, data collection, data analysis, and interpretation of results.

3.Results and Discussion

3.1 Properties Biodiesel CIME

Figure 4 shows the results of the GCMS (Gas Chromatography-Mass Spectrometry) test of CIME biodiesel. Methyl ester is the main component formed from the reaction of triglycerides in raw materials such as microalgae with methanol to form biodiesel. The content of methyl ester in biodiesel plays an important role in determining the quality and characteristics of the fuel. [14]. In this study, the composition of biodiesel is presented in **Table 1**. Based on the data obtained, it can be seen that the main compounds that dominate CIME biodiesel in this study are methyl palmitate at 43.77% and methyl oleate at 45.82%. The methyl oleate content in CIME biodiesel in this study was higher than the content in castor oil-based biodiesel (38.108%) and palm oil (42.72%) [10].

Methyl oleate is a free fatty acid that has an important role in biodiesel because it can improve performance at low temperatures and has a positive impact on the oxidation stability of biodiesel [15]. This shows that CIME biodiesel has good quality to be developed further. From all the chemical compounds contained in biodiesel, the stoichiometric combustion reaction can be calculated. After knowing the combustion reaction of the chemical compounds, the stoichiometric air-fuel ratio (AFR) of CIME biodiesel was obtained at 13.2.

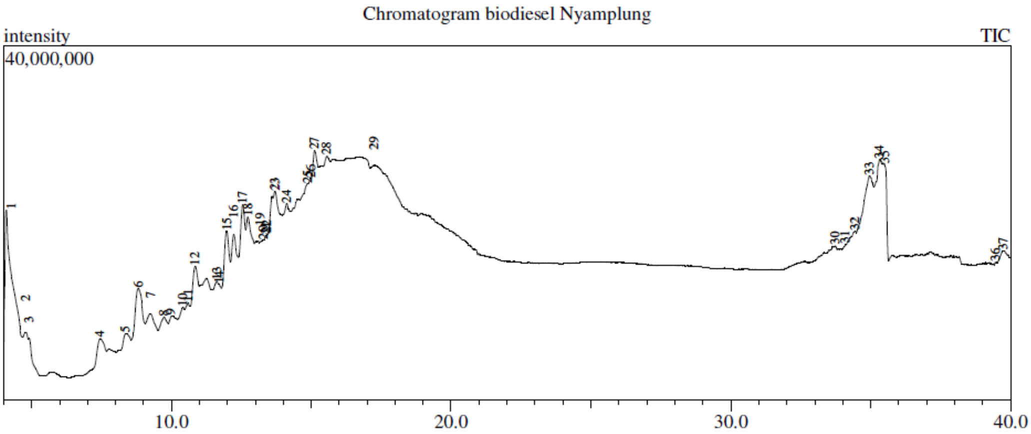


Figure 4. GCMS (Gas Chromatography-Mass Spectrometry) Test Results

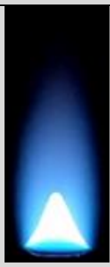
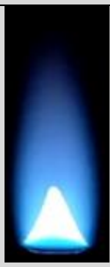
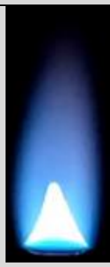
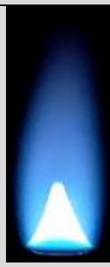
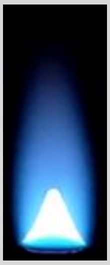
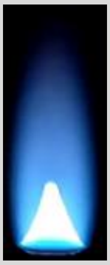
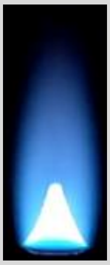
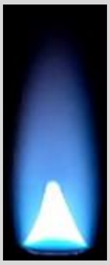
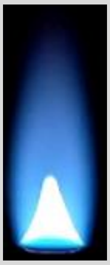
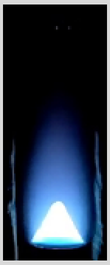
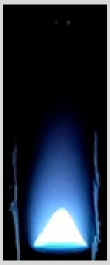
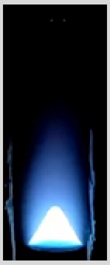
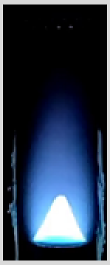
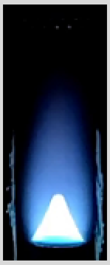
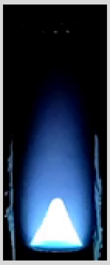
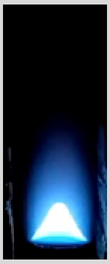
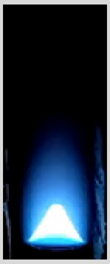
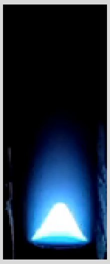
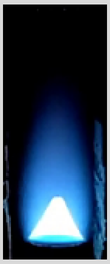
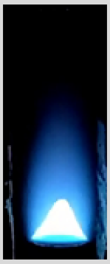
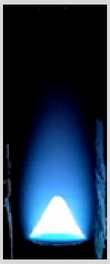
Table 1. Chemical composition of CIME biodiesel

Number	Trivial Name	Molecular Formula	%	%
1	Methyl oleate	$C_{19}H_{36}O_2$	45.82%	0.4582
2	Methyl palmitate	$C_{17}H_{36}O_2$	43.77%	0.4377
3	Methyl myristate	$C_{15}H_{30}O_2$	2.97%	0.0297
4	Methyl arachitate	$C_{21}H_{42}O_2$	2.71%	0.0271
5	Methyl linoleate	$C_{19}H_{34}O_2$	2.25%	0.0225
6	Methyl arachidonate	$C_{21}H_{34}O_2$	1.44%	0.0144
7	Methyl laurate	$C_{13}H_{26}O_2$	0.62%	0.0062
8	Methyl margate	$C_{18}H_{36}O_2$	0.41%	0.0041

3.2 Flame Visualization

The flame visualization is shown in Table 2. The resulting flame shows a two-zone reaction structure, first an inner premixed flame, where the fuel is converted to CO and H_2, and an outer diffusion flame where CO and H_2 are further oxidized to form diffusion combustion. In a lean fuel mixture, the flame has a shorter structure and a duller flame color. This is in line with previous studies that explain that flame color can be used to observe the ratio of fuel and less and more air [3]. While in a rich mixture, the flame structure becomes higher. This high flame structure is because some of the fuel is not completely burned in a premixed manner. The fuel that is not burned in a premixed manner then comes out of the premixed reaction zone and forms a diffusion combustion with the surrounding air.

Table 2. Flame visualization

	0.4	0.6	0.8	1.0	1.2	1.4
7000 gauss						
8000 gauss						
9000 gauss						
10000 gauss						

3.3 Flame Height Analysis

Figure 5 presents data on changes in the height of the premixed flame due to variations in the equivalent ratio and variations in the strength of the magnetic field. From the graph, it can be seen that the flame height has an increasing trend from an equivalent ratio of 0.4 to 1.4. This is because the rich fuel mixture causes the biodiesel fuel to not burn completely, thus forming diffusion combustion and making the flame structure higher. In previous research, Perdana 2018, explained that changes in AFR also provide different flame heights, at AFR 2.2 the flame height is 68.44 mm while the lowest flame height at AFR 35 is 8.73 mm [16]. This study explains that the decrease in the height of the flame is caused by the combustion that occurs is getting closer to perfect where the remaining fuel that has not been burned then burns by diffusion with the surrounding air experiencing a decrease. The combustion that occurs is truly premixed combustion, diffusion combustion is reduced so that the flame that occurs is only a few mm near the nozzle.

In a lean fuel mixture, the flame approaches the blow-off condition because the fuel composition is less, causing the flame structure formed to be shorter. Meanwhile, with variations in magnetic field strength, the flame height becomes shorter as the magnetic field is given. This decrease in flame height indicates a faster combustion process due to the greater supply of O_2 into the combustion reaction zone. The reaction of O_2 molecules and changes in hydrocarbon orientation are the main factors in reducing the flame height. This decrease in flame height is in line with the increase in laminar combustion speed with a stronger magnetic field.

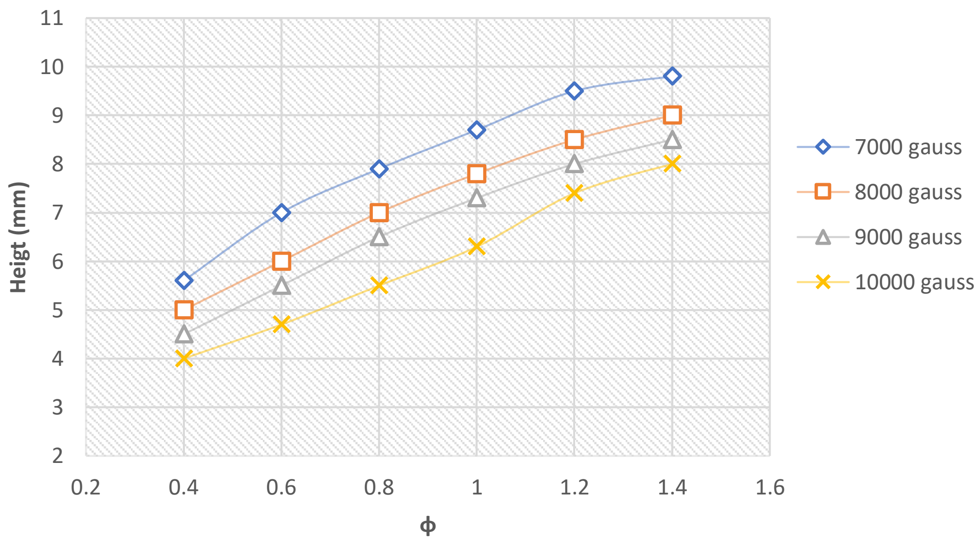


Figure 5. Flame height graph

3.4 CIME Biodiesel Laminar Combustion Rate Analysis

Data processing on laminar combustion speed is shown in **Figure 6**. From the graph, it can be seen that the application of a magnetic field increases the laminar combustion speed of CIME fuel in all variations of the magnetic pole direction. The highest speed value was recorded at an equivalent ratio of 0.8 and at a magnetic field strength of 10,000 gauss. The graph shows that the laminar combustion speed decreased after passing an equivalent ratio of 0.8. This is because the higher the fuel mixture, the more unbalanced the combustion occurs, so that some of the fuel does not burn perfectly. Maulana 2020, explained that a magnetic field can affect the combustion speed of premixed coconut oil and B50 castor oil flames where the combustion flame lasts longer than without the influence of a magnetic field [17]. Theoretically, the most ideal combustion is combustion at an equivalent ratio of 1, but the graph shows a different phenomenon, the highest combustion speed occurs at an equivalent ratio of 0.8. This phenomenon is related to the influence of the magnetic field given. It can be seen that the higher the strength of the magnetic field given, the higher the laminar combustion speed. In a study conducted by Nufus, 2020, it was explained that the greater the magnetic field given to the fuel, the greater the temperature that occurs in the combustion chamber. This is caused by the magnetized fuel which causes the fuel molecules to vibrate more and become unstable, this affects the reduction in the attractive force between atoms which results in the affinity of the energy of the molecules getting smaller, and the fuel molecules are more numerous and easier to react with oxygen, finally the combustion process becomes more homogeneous and the fuel that burns more and the pressure becomes greater [18].

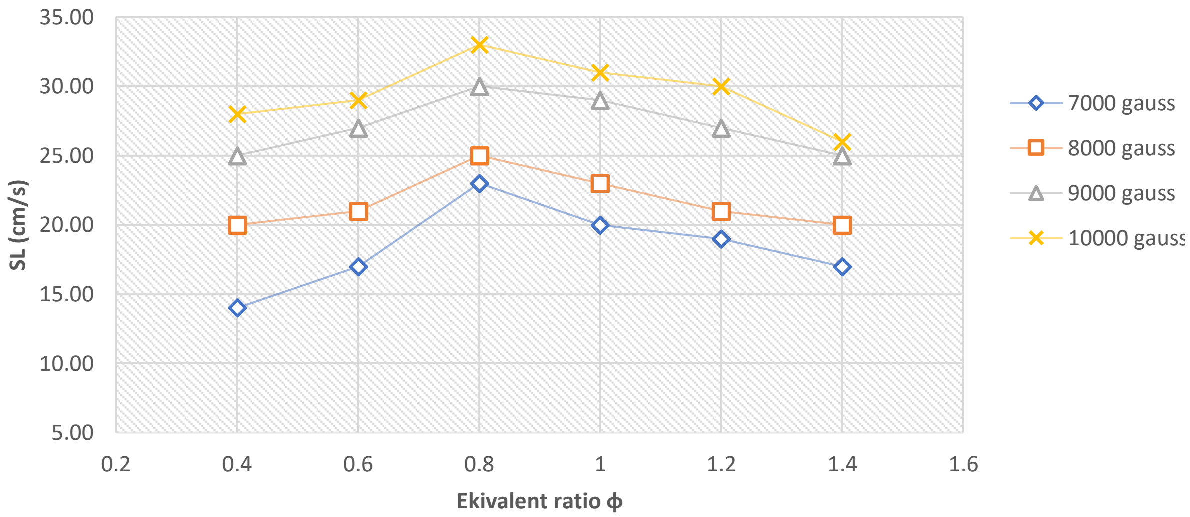


Figure 6. Laminar combustion velocity (SL) graph

The laminar combustion rate increases due to the influence of the magnetic field caused by the magnetic field force affecting the movement of O_2 around the flame. The magnetic field will attract paramagnetic compounds, including O_2 which theoretically has two unpaired electrons and is classified as paramagnetic. With the magnetic field force that attracts between the two poles N and S, the movement of O_2 is affected by the direction of the magnetic field and moves towards the combustion reaction zone. While oxygen is the main oxidizer in combustion, so it can accelerate and optimize the oxidation process between fuel and O_2. This is in line with the research of Suganda, 2025 which analyzed droplet combustion [15]. In his research, he explained that the addition of a magnetic field can accelerate the rate of evaporation, because the effect of the magnetic field increases the reactivity of oxygen. Oxygen molecules are attracted closer to the reaction zone and the focused magnetic flux accelerates the supply of oxygen to the droplet surface and causes the collision of fuel particles with O_2 to become greater so that the bonds of fuel molecules become weak. When the molecular bonds weaken, the distance between the molecules widens, making it easier for O_2 to enter, resulting in a faster reaction between the fuel and O_2. This phenomenon explains that at an equivalent of 0.8 it shows the highest laminar combustion rate because it gets an external O_2 supply from the magnetic force. The reaction that occurs between combustion and the magnetic field is illustrated in Figure 7.

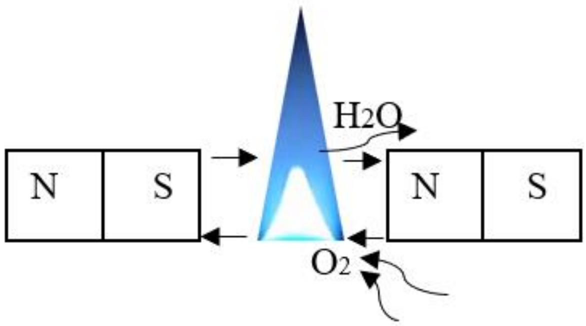


Figure 7. Illustration of the effect of magnetic fields on combustion.

In previous research, magnetic fields were applied to the fuel lines of diesel engines [19]. Under the influence of magnets, fuel molecules are re-aligned, easier to interlock with oxygen and produce complete combustion. This leads to better fuel atomization, better fuel-air mixing, and reduced carbon dioxide emissions. The magnetic field not only affects oxygen, but also affects the H_2O molecules produced during the combustion process [20]. H_2O acts as a heat source in the flame and has diamagnetic properties, which causes its movement away from the direction of the magnetic field. The graph shows that a magnetic field of 10,000 gauss shows the highest burning speed. Previous research also explained that the stronger the magnetic field given, the greater the impact [21]. This phenomenon explains that the stronger the magnetic field, the greater the movement of O_2 into the combustion reaction zone and the faster H_2O exits the combustion reaction zone, so that the combustion reaction becomes faster and more optimal.

4. Conclusion

This study shows that the use of an external magnetic field has a significant effect on improving the combustion quality of Calophyllum inophyllum (CIME) biodiesel in a mixed flame system. Variations in magnetic field strength and fuel equivalent ratio have a direct effect on the flame height and laminar combustion speed. The highest combustion speed is found at an equivalent ratio of 0.8 with a magnetic field of 10,000 gauss, indicating that this condition is the optimal combination for CIME biodiesel combustion. The increase in combustion speed is caused by an increase in oxygen supply to the reaction zone as a result of the interaction of the magnetic field with the paramagnetic O_2 molecules. The results of this study provide an explanation that the stronger the influence of the magnetic field given, the more optimal the combustion becomes. This study can be a reference in the development of combustion enhancement with magnetic field technology in its application to diesel engines.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

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