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Characterization of Biodiesel Fuel Preheating with Variations in Fame Content on Ignition Delay

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Abstract

Objective: This experimental study aimed to investigate the relationship between fuel preheating temperature and ignition delay for conventional diesel fuel (B0), a 50% biodiesel blend (B50), and palm oil-based biodiesel (B100) in a laboratory-scale, open-ended swirl burner. Method: The experimental setup employed a burner equipped with a 0.60-gallon-per-hour (GPH) fuel nozzle, operating at a constant air velocity of 7.37 m/s and a fuel injection pressure of 25 bar. Fuel preheating temperatures were varied from 30°C to 90°C in 10°C increments. Ignition delay was determined using high-speed video recordings by measuring the time interval between igniter activation and the first appearance of a stable flame. Results: The influence of fuel preheating on ignition delay varied according to fuel composition. B0 exhibited its shortest reported ignition delay at approximately 50°C, while further temperature increases produced inconsistent responses. B50 demonstrated relatively minor variations in ignition delay across the investigated temperature range. In contrast, B100 exhibited the most pronounced reduction in ignition delay as preheating temperature increased, achieving its shortest reported ignition delay at 90°C. These differences were consistent with variations in fuel viscosity and volatility, although the underlying physicochemical mechanisms were not independently verified. Conclusion: The findings indicated that fuel composition was an important consideration when determining appropriate preheating temperatures for swirl-burner applications. The identified operating conditions were specific to the experimental apparatus and should not be generalized to other burner configurations without further validation. Moreover, the study did not directly assess exhaust emissions, fuel atomization characteristics, or long-term combustion stability, highlighting the need for additional experimental investigations.

INTRODUCTION

Rising global energy demand, coupled with growing environmental concerns, has accelerated the development of cleaner and more sustainable energy technologies. Biodiesel, produced from renewable feedstocks such as palm oil through transesterification, has attracted considerable attention as an alternative to conventional petroleum diesel because of its biodegradability, low sulfur content, and potential to reduce life-cycle greenhouse gas emissions (Alptekin & Canakci, 2008; Demirbas, 2008). In Indonesia, the government has introduced biodiesel blending programs to reduce dependence on imported diesel fuel and support national renewable energy targets, positioning biodiesel as an important component of the country's energy strategy.

Despite these potential environmental advantages, high-concentration biodiesel blends present several technical challenges. One of the primary concerns is their generally higher viscosity and density compared with conventional petroleum diesel (Tesfa et al., 2010). Increased viscosity can impair fuel atomization during injection, producing larger droplets and reducing the effectiveness of air–fuel mixing. These conditions may contribute to incomplete combustion, increased fuel consumption, elevated pollutant emissions, and reduced combustion efficiency, depending on the operating conditions and combustion system (Das et al., 2018; El Araby et al., 2018).

One important combustion characteristic influenced by fuel atomization is ignition delay. In externally ignited burner systems, ignition delay can be defined operationally as the time interval between igniter activation and the establishment of a stable flame. Prolonged ignition delay may indicate unfavorable fuel evaporation, mixing, or ignition conditions, potentially contributing to unstable flame development, ignition failure, and increased pollutant formation (Anis & Budiandono, 2019; Hazar et al., 2019). Unlike compression-ignition engines, where ignition delay primarily reflects the interval between fuel injection and the onset of autoignition, externally ignited burners depend on successful flame initiation and stabilization. In open-ended burners, excessive ignition delay may increase the likelihood of unsuccessful ignition and compromise operational reliability and safety.

Fuel preheating has been widely investigated as a potential strategy for improving the combustion characteristics of biodiesel and its blends. Increasing fuel temperature generally reduces viscosity and surface tension, potentially improving atomization, accelerating evaporation, and enhancing air–fuel mixing (Ganjekhaviri et al., 2016; Hazar et al., 2019; Mekonen & Sahoo, 2018). Previous studies have demonstrated the influence of fuel temperature on ignition characteristics in diesel engines. Reddy et al. (2020) experimentally demonstrated that preheating Calophyllum inophyllum methyl ester (CAOME) to 70°C significantly reduced ignition delay in a four-cylinder diesel engine. Similarly, Kodate et al. (2020) reported that preheating Karanja oil methyl ester (KOME) to 95°C improved combustion characteristics and shortened ignition delay. Kodate et al. (2021) further showed that preheating B30, B50, and B100 blends of Dhupa seed oil biodiesel to 95°C lowered fuel viscosity, improved spray characteristics, and increased brake thermal efficiency in a single-cylinder diesel engine. Outside the engine environment, Zaid et al. (2026) found that heating a B50 waste cooking oil biodiesel from 30 to 70°C reduced its density and viscosity, widened the spray angle, and shortened spray penetration. Research involving rapeseed biodiesel blends (B7 and B20) in a tractor diesel engine indicated that ignition delay decreased with increasing biodiesel content, which was attributed to differences in fuel cetane number (Miron et al., 2021). Furthermore, experiments conducted in constant-volume combustion chambers using various biodiesel fuels, including JME, CME, SME, and PME, demonstrated that increasing ambient temperature reduced ignition delay across the investigated fuels (Oo et al., 2015). However, these investigations primarily focused on compression-ignition engines or controlled combustion chambers, where elevated injection pressures, high ambient temperatures, and confined combustion environments substantially influence fuel atomization, evaporation, and ignition behavior (Oo et al., 2015).

In contrast, practical burner applications, including industrial oil burners, residential heating systems, and small-scale thermal energy units, frequently operate under conditions that

differ substantially from those of compression-ignition engines. These systems may employ comparatively lower fuel injection pressures and externally supplied combustion air, with ignition initiated by an external ignition source rather than compression heating (Al-Abd & Masri, 2007; Lefebvre & McDonell, 2017). Experimental studies in swirl burners, swirl-stabilized combustors, and semi-industrial boilers have shown that biodiesel blending alters flame length, flame temperature distribution, and pollutant formation under burner conditions (Hidegh et al., 2023; Masoud et al., 2023; Saleh & Allawi, 2024). Open-ended burner configurations also permit greater interaction between the combustion process and the surrounding atmosphere, potentially affecting flame stabilization and heat transfer. Furthermore, small-capacity burners commonly employ low-flow-rate nozzles, resulting in spray characteristics that depend on nozzle geometry, injection pressure, fuel properties, and interactions with the surrounding airflow. Under these conditions, droplet trajectories, evaporation behavior, and fuel–air mixing may be particularly sensitive to aerodynamic forces generated by the combustion air stream (Al-Abd & Masri, 2007).

Under such operating conditions, the effects of fuel preheating on ignition delay may differ from those observed in compression-ignition engines. As fuel temperature increases, reductions in viscosity and surface tension may promote the formation of smaller droplets, potentially improving evaporation and fuel–air mixing. However, changes in droplet size and spray momentum may also alter interactions between the fuel spray and the surrounding airflow, affecting local fuel–air concentrations and flame stabilization. Strong aerodynamic strain can influence flame propagation and stability through flame-stretch effects, although these effects should be distinguished from the autoignition processes characteristic of diesel engines (Heywood, 1988). Moreover, the evaporation of smaller droplets may increase local cooling because of the latent heat required for vaporization, potentially affecting mixture temperature and ignition behavior under certain operating conditions (Oo et al., 2015). The relative importance of these mechanisms depends on fuel properties, burner geometry, airflow conditions, and heat transfer characteristics. Consequently, fuel preheating may not consistently reduce ignition delay across different biodiesel concentrations, particularly when changes in atomization and evaporation interact with flame stabilization processes.

Another important research gap concerns the limited systematic comparison of fuel preheating effects across different biodiesel blending ratios under identical burner operating conditions. Previous studies have frequently examined individual biodiesel fuels or specific blending ratios without directly comparing their ignition responses over a consistent preheating temperature range. Conventional petroleum diesel (B0), a 50% biodiesel blend (B50), and pure biodiesel (B100) exhibit differences in physicochemical properties, including viscosity, density, volatility, and cetane number, which may influence their combustion characteristics (Tesfa et al., 2010). Nevertheless, comparative experimental evidence concerning the relationship between fuel preheating temperature and ignition delay for these three fuels in laboratory-scale swirl burners remains limited. This gap highlights the need for controlled experimental investigations that isolate fuel composition and preheating temperature while maintaining consistent burner operating conditions.

Therefore, this study aimed to investigate the relationship between fuel preheating temperature and ignition delay for B0, B50, and B100 in a laboratory-scale, open-ended swirl burner. Specifically, the study sought to (i) measure ignition delay at seven preheating

temperatures (30, 40, 50, 60, 70, 80, and 90°C) using a burner equipped with a 0.60-US-gallon-per-hour (GPH) nozzle and operating at a constant air velocity of 7.37 m/s; (ii) compare ignition delay responses among the three fuel types and identify the preheating temperatures associated with the shortest observed ignition delays under the experimental conditions; (iii) interpret the observed differences in relation to relevant fuel properties and potential combustion mechanisms, including viscosity reduction, volatility, evaporation cooling, and flame stabilization; and (iv) provide experimentally informed recommendations for optimizing fuel preheating in small-scale swirl burners operating with biodiesel and its blends. The findings were expected to contribute to a better understanding of fuel-dependent ignition behavior while providing a basis for further investigations into atomization characteristics, combustion stability, and burner performance.

METHOD

The experimental methodology involved the selection of fuel materials, configuration of the experimental apparatus, and implementation of standardized testing procedures. Instrument specifications and measurement protocols were documented to support the accuracy, consistency, and reproducibility of the experimental results.

Experimental Setups

The experiments were conducted using a laboratory-scale oil burner developed in collaboration between Universitas Gadjah Mada and the Research and Development Center for Electricity of PT. PLN (Persero). The burner was equipped with a swirl at the end of blower tube to promote air-fuel mixing, an electric igniter, a fuel preheating system, and a human-machine interface (HMI) for controlling and monitoring operating parameters. A schematic of the experimental setup is presented in Fig. 1.

The nozzle used in this study was a Steinen Type-S oil burner nozzle with a capacity of 0.60 GPH and a spray angle of 60°. This nozzle was selected based on repeated preliminary experiments, as it provided the most stable and repeatable spray pattern under the tested conditions while maintaining near-stoichiometric combustion, making it the most suitable choice for this particular burner setup. The fuel pressure was maintained constant at 25 bar (2.5 MPa) using a three-phase AC fuel pump. The air velocity was measured using a Pitot tube and kept constant at 7.37 m/s for all test conditions. This velocity was chosen based on preliminary tests that ensured a stable flame without blow-off for the 0.60 GPH nozzle across the entire preheating range.

Fuel Properties

Three fuel types were used in this experiment: B0 (pure diesel), B50 (50 % diesel + 50 % palm oil FAME – Fatty Acid Methyl Ester by volume), and B100 (pure palm oil FAME). The diesel used was produced by PT. Pertamina (Persero), and the biodiesel was derived from crude palm oil (CPO). The fuel properties are listed in Table 1. B0 had the lowest density and viscosity, whereas B100 had the highest. The flash point of B100 (163°C) was substantially higher than that of B0 (64°C), indicating a lower volatility (Hazar et al., 2019).

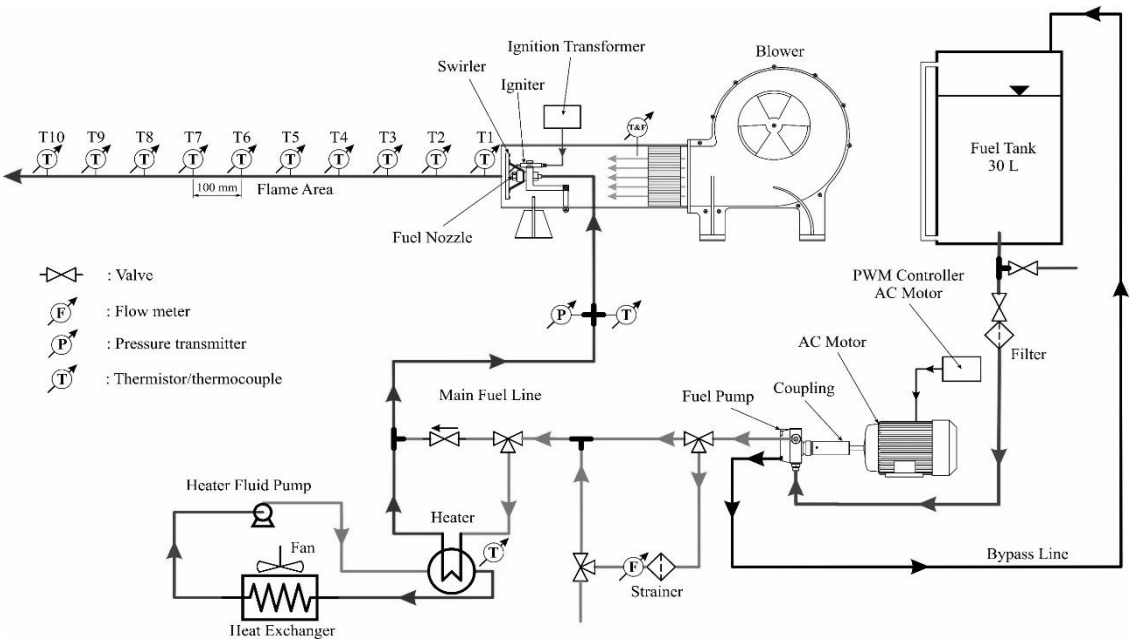


Figure 1. Burner Schematic with Additional Heater System for Fuel Heating Process

Source: Gambar sebagaimana disajikan dalam naskah asli.

Table 1. Properties of B0, B50, and B100

Property	Unit	B0	B50	B100
Density, at 15°C	kg/m^3	816.5	845.7	875.7
Kinematic Viscosity, at 40°C	mm^2/s	2.55	3.299	4.62
Flash Point	°C	64	82	163
Cetane Number	-	51.2	56.8	57.7
Surface Tension	mN/m	19.78	22.29	29.29

Source: Data presented in the original manuscript.

Table 2. Properties of UPS Silicone Oil Grade 100 F.302

Property	Unit	Value
Composition	-	Dimethylpolysiloxane
Viscosity	cSt	100
Flash Point	°C	300
Specific Gravity, at 25°C	-	0.970

Source: Data presented in the original manuscript.

Preheating System

Preheating was achieved using an indirect heating system, with the heater schematic presented in Fig. 2. The fuel was passed through a copper coil immersed in a container filled with UPS Silicone Oil Grade 100 F.302 with the properties listed in Table 2.

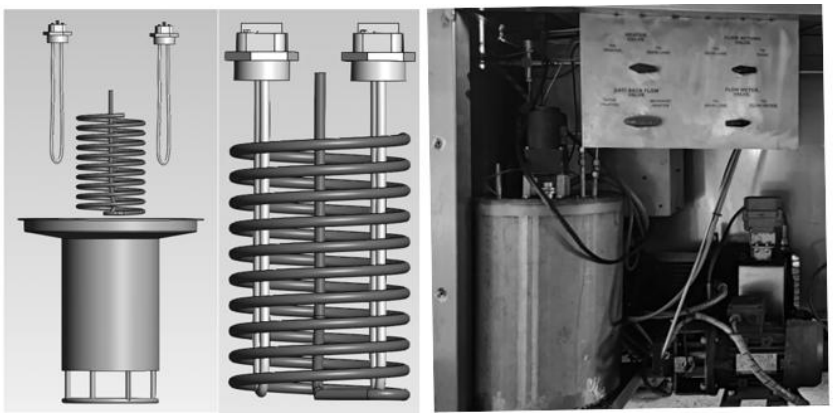


Figure 2. Heater Unit and Schematic, Consist of Spiral Copper Tube with Heating Elements
Source: Gambar sebagaimana disajikan dalam naskah asli.

The silicone oil was heated using heating elements inside the heating chamber, and the temperature was controlled via the HMI using a thermocouple feedback loop. The fuel temperature was measured at the nozzle inlet using a K-type thermocouple. The preheating temperatures were set to 30, 40, 50, 60, 70, 80, and 90°C.

High-Speed Imaging

In this study, the camera was operated at 3000 frames per second (fps) at full resolution. The camera was connected to the burner control system via communication cable connection and controlled by PCC Phantom software on laptop using Ethernet cable, allowing the recording to start automatically when the igniter was activated or record manually when needed. A black background was placed behind the burner to enhance contrast, minimize optical noise, and eliminate any possible reflection that could affect capturing processes. The camera was positioned approximately 2.5 m from the burner tip, and calibration was performed before each series of tests using a checkerboard pattern with 10 mm × 10 mm squares to ensure accurate spatial scaling and lens focus, as shown in Fig. 3.



Figure 3. Burner Setup with High Speed Camera Position approx. 2.5 meters from Burner Tip
Source: Gambar sebagaimana disajikan dalam naskah asli.

The recorded high-speed videos were imported into the PCC Phantom software, which allows frame-by-frame playback. The frame number at which the igniter first became active, as indicated by a visible spark, was recorded as the starting frame. Subsequently, the frame number at which a stable flame first appeared was recorded as the ignition frame.

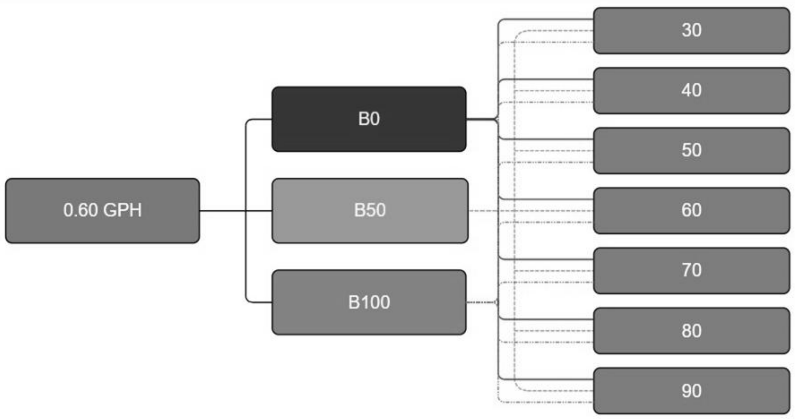


Figure 4. Experiment Matrix

Source: Gambar sebagaimana disajikan dalam naskah asli.

A stable flame was defined as the first frame in which a continuous luminous region was visible and sustained for at least three consecutive frames. The number of frames between the two events (ΔN) was counted manually by the operator. The ignition delay was calculated using the following equation:

$$\tau_i = \frac{\Delta N}{fps} \times 1000 \quad (1)$$

where τi is the ignition delay in milliseconds (ms), ΔN is the number of frames between igniter activation and first flame detection, and fps is the frame rate of the camera (in this experiment 3000 s-1). The manual counting process was repeated for each test condition with three independent experimental repetitions, and the average ignition delay was reported.

Experimental Conditions

All experiments were performed at the same time of day using a black fabric background behind the burner. The fuel pressure (25 bar) and air velocity (7.37 m/s) were monitored continuously using the HMI and DAQMaster software to ensure consistency across all tests. The experimental matrix consisted of three fuel types, seven preheating temperatures, and three repetitions, resulting in 63 individual ignition delay measurements. The matrix of fuel and preheat temperature is shown in Fig. 4.

Interpretive limitation: The experimental comparison holds nozzle, fuel pressure, and air velocity constant but does not independently isolate droplet-size distributions, local heat transfer, and flame-stretch mechanisms. Mechanistic explanations are therefore proposed interpretations of the ignition-delay patterns, not separately measured causal pathways.

RESULT AND DISCUSSION

Ignition delay was examined using high-speed visualisation data presented as a function of the preheating temperature and nozzle capacity. The ignition delay was investigated in correspondence with the nozzle capacity of 0.60 GPH under the established preheating conditions.

Ignition Delay of B0

The effect of various preheat temperatures on B0 diesel fuel using a 0.60 GPH nozzle is presented in Fig. 5. This long delay is attributed to the high viscosity of diesel at room

temperature, which produces moderately large droplets that require sufficient time to evaporate and mix with air before autoignition occurs (Das et al., 2018; Hazar et al., 2019). When the fuel was preheated to a moderately high temperature, the delay decreased substantially and reached its lowest point at 50°C. This improvement indicates that even a modest temperature increase is sufficient to substantially reduce the viscosity, leading to finer atomization, faster evaporation, and more rapid formation of a combustible mixture (Kodate et al., 2020; Reddy et al., 2020).

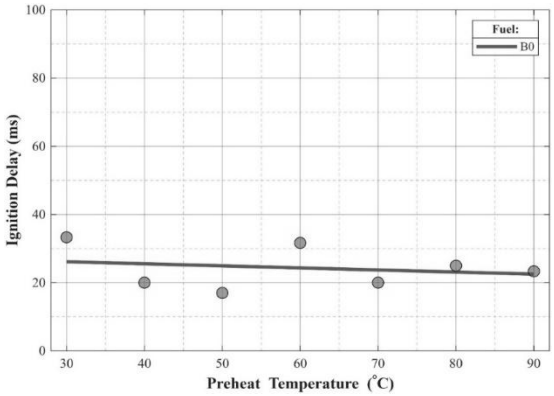


Figure 5. Effect of preheat on B0 ignition delay shows decline in ignition delay

Source: Gambar sebagaimana disajikan dalam naskah asli.

As the temperature continued to rise toward 60°C, the ignition delay increased again and was almost the same as that at 30°C. Beyond that, the delay fluctuated. It decreases again at 70°C, then increases slightly at 80°C, and finally decreases slightly at the highest temperature of 90°C. The increase in delay at temperatures above 50°C can be explained by premature vaporization (Ganjekhaviri et al., 2016). The lighter fractions may vaporize too early, creating a fuel-rich zone very close to the nozzle while leaving insufficient fuel for the downstream region, which can delay the formation of a stable flame front (Lefebvre & McDonell, 2017). Another possible explanation is the onset of flame stretch. As droplets become finer at higher temperatures, they are more easily entrained by the constant airflow, increasing the relative velocity between the fuel vapor and flame front, which can delay autoignition (Al-Abd & Masri, 2007; Lefebvre & McDonell, 2017).

At 90°C, the ignition delay remained lower than the initial value at 30°C, but it was not as low as the minimum observed at 50°C. Overall, preheating was beneficial for reducing the ignition delay, confirming that moderate preheating is beneficial for pure diesel in small-nozzle burner applications. However, the overall reduction in ignition delay from 30°C to 90°C was relatively small.

Ignition Delay of B50

B50 exhibited a stable ignition delay at various temperatures, as shown in Fig. 6. At 30°C, the ignition delay was slightly higher than that of B0 at the same temperature. This apparent difference can be explained by the higher viscosity of the B50 blend (3.299 mm^2/s at 40°C) compared to B0, which produces larger droplets and slower evaporation despite the beneficial cetane number. As shown in Table 1, B50 has a cetane number of approximately 56.8, compared to 51.2 for B0, but the viscosity effect appears to dominate at this temperature.

The presence of oxygenated compounds in biodiesel may also contribute to more reactive intermediate species during the pre-ignition period (Das et al., 2018; Xiao et al., 2023).

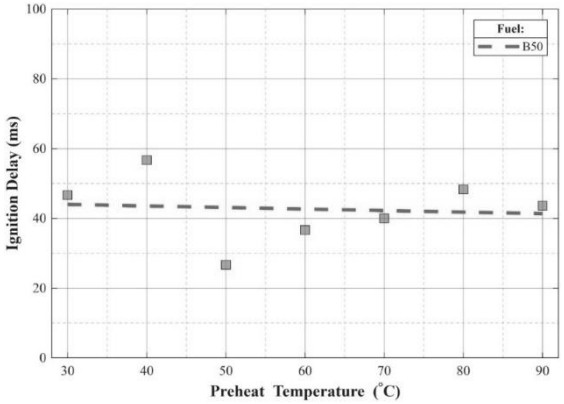


Figure 6. Effect of preheat on B50 ignition delay shows slight decline in ignition delay
Source: Gambar sebagaimana disajikan dalam naskah asli.

When preheated to 40°C, the ignition delay of B50 did not decrease; instead, it showed a notable increase, suggesting some instability in atomization owing to the uneven heating of the two fuel components. At 50°C, the delay decreased, resulting in the most significant reduction across all tested temperatures. At 60°C, the delay increased again, followed by moderate fluctuations at 70°C, 80°C, and 90°C. At the highest temperatures, the ignition delay remained close to 30°C at some points and slightly above at others. This inconsistent behavior is attributed to the competing effects of the diesel and biodiesel fractions: the diesel fraction may vaporize prematurely, whereas the biodiesel fraction remains less reactive, creating mixture heterogeneity that prolongs the time required to establish a self-sustaining flame (Hidegh et al., 2023; Kodate et al., 2020).

In comparison to B0, B50 exhibited a minimal net decline across various heating temperatures. This indicates that preheating consistently benefits B0 more than B50, which demonstrates reduced responsiveness to temperature variations due to its biodiesel content. The B50 mixture comprises both pure diesel and biodiesel, each possessing distinct properties. When subjected to specific temperatures, diesel tends to evaporate prior to biodiesel, resulting in localized evaporation cooling zones that decelerate the evaporation of biodiesel.

Ignition Delay of B100

In contrast to B0 and B50, preheating B100 in this particular setup provided the most substantial benefit in reducing ignition delay, as shown in Fig. 7. At 30°C, the ignition delay was relatively high. When the fuel was preheated, the delay decreased noticeably, with the shortest ignition delay occurring at the highest temperature of 90°C. Unlike B0, which shows an optimum at an intermediate temperature, and B50, which exhibits an almost flat response, B100 continues to improve as temperature increases, indicating that the heating of B100 reduces its viscosity.

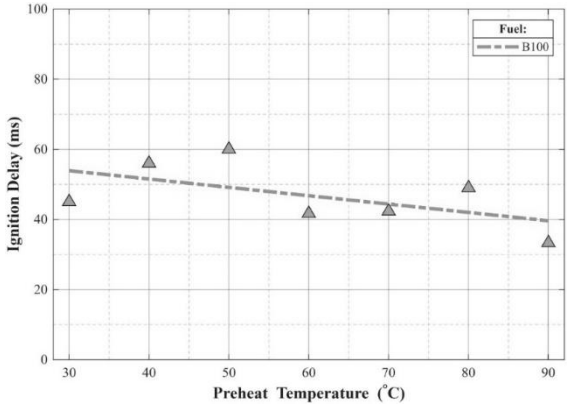


Figure 7. Effect of preheat on B100 ignition delay shows notable decline in ignition delay
Source: Gambar sebagaimana disajikan dalam naskah asli.

The improvement at higher temperatures is attributed to the significant reduction in biodiesel viscosity with preheating, leading to finer atomization, faster evaporation, and more rapid formation of a combustible mixture (Kodate et al., 2020; Reddy et al., 2020). Unlike the early vaporization effects seen in B0 and B50, B100 is less prone to creating overly rich or lean zones because its narrower boiling range results in more uniform vaporization behavior. Consequently, the detrimental effects of flame stretch or mixture heterogeneity were less pronounced for B100 at elevated temperatures.

Among the three fuels, B100 showed the largest overall reduction in ignition delay from 30 to 90°C. B0 showed a moderate but fluctuating improvement, whereas B50 responded only weakly with a nearly flat trend. Therefore, under the tested nozzle and airflow parameters, preheating was most beneficial for B100, and the highest preheating temperature tested (90°C) yielded the best performance.

CONCLUSION

This study experimentally investigated the effects of fuel preheating on ignition delay for three fuel compositions—conventional diesel (B0), a 50% biodiesel blend (B50), and pure biodiesel (B100)—using a laboratory-scale, open-ended swirl burner equipped with a 0.60-gallon-per-hour (GPH) nozzle operating at a constant air velocity. The findings demonstrated that the effects of preheating on ignition delay varied according to fuel composition. B0 exhibited its shortest ignition delay at approximately 50°C, although further temperature increases did not consistently improve ignition performance. B50 showed relatively limited sensitivity to preheating across the investigated temperature range, whereas B100 exhibited a progressive reduction in ignition delay, reaching its shortest recorded value at 90°C. These results indicated that a uniform preheating strategy was unlikely to provide optimal ignition performance across different fuel compositions. Instead, preheating conditions should be adjusted according to fuel characteristics and burner operating requirements. For practical applications, pure biodiesel may benefit from higher preheating temperatures, while diesel–biodiesel blends may require more carefully controlled temperature settings. However, these findings were specific to the experimental apparatus and operating conditions and require further validation before broader application. Future research should investigate additional

preheating temperatures, alternative nozzle capacities, and varying combustion air velocities to better understand their combined effects on ignition delay, fuel atomization, flame stability, and overall combustion performance in low-pressure swirl burners.

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