Isolated Droplet Combustion Study of Malaysian Palm Biodiesel-Diesel Blends

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Isolated Droplet Combustion Study of Malaysian Palm Biodiesel-Diesel Blends

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Abstract. Malaysian palm biodiesel is one of the attractive biofuels for petroleum diesel due to its zero-sulphur content (i.e., non-toxic), renewable capability, and similar physicochemical properties. Recent studies have reported significant improvement in the performance and emission characteristics of diesel engines by leveraging the blending composition between palm biodiesel and diesel. However, the fundamental aspects of combustion performance due to the blending effects of Malaysian palm biodiesel remain unexplored. This study aims to investigate the isolated droplet combustion behaviour of palm biodiesel-diesel blends at various blending compositions through a time-based image capturing method. Experimental results show that palm biodiesel-diesel blend with 60% palm biodiesel content (B60) and above produce a more prominent blue flame, which indicates cleaner and more complete combustion. The ignition delay (ID) increased when the palm biodiesel content is increased. Similarly, the burn rate constant for palm biodiesel-diesel blends increased with increasing palm biodiesel content. The combustion duration of palm biodiesel-diesel blends increased slightly when the palm biodiesel content is raised to 40% (B40) but decreased significantly when the palm biodiesel content is at 60% and above. Overall results suggest B60 is the optimum blend, which could potentially improve the performance and emissions of diesel-powered vehicles.

1. Introduction

Diesel engines are commonly used in automobile, marine transport, and generators owing to their high durability and economical operation. Over several decades, fossil diesel has been heavily relied on to power diesel-operated vehicles because it is relatively low cost and easily available. However, serious concerns over elevating greenhouse gases and depletion of fossil fuels have motivated research efforts for renewable fuels. Palm biodiesel is one of the potential sustainable fuel candidates to be used in diesel engines. Compared to other biodiesel derived from vegetable oils, palm biodiesel is non-toxic (i.e., zero-sulphur content), less expensive, and economically beneficial by its energy yield [1]. Palm biodiesel also exhibits better oxidation stability and greater lubricity than diesel. Palm biodiesel also promotes shorter ignition delay and more complete combustion compared to that of fossil diesel owing to the presence of oxygen molecules and greater cetane number. This results in relatively lower unburned hydrocarbons, carbon monoxide, and soot, but higher nitrogen oxides (NO_x) [2]. Besides, the energy content of palm biodiesel is lower than that of fossil diesel, which contribute to higher specific fuel consumption.

Recent studies on the blending effects between palm biodiesel and diesel on the performance and emission characteristics of diesel engines show that the two major disadvantages of palm biodiesel could be mitigated. Gad et al. [3] reported that the thermal efficiency, brake specific fuel consumption and NO_x emissions of B20 (20% palm biodiesel and 80% fossil diesel) is lower than that of B100 when tested on a single cylinder, four-stroke, air cooled, direct injection, naturally aspirated diesel engine. Their findings also show carbon monoxide and unburned hydrocarbon emissions for B20 are lower than that of B100. Similarly, Ali et al. [4] found that the heating value of B10, B20, B30, B40, and B50 is significantly higher compared to B100, which contributed to significantly lower brake specific fuel consumption on the naturally aspirated, water-cooled, four-cylinder diesel engine. Although there have been research studies focusing in exploring the effects of palm biodiesel-diesel blends on the performance and emission characteristics of diesel engines, their results are greatly influenced by the types of diesel engine used because the in-cylinder combustion is a very complex process. For instance, the mode of fuel injection and injection pressures, type of engine air intake (i.e., naturally aspirated or turbocharged), and different air swirl ratio in a cylinder could significantly affect the combustion performance of the fuel blends [5].

In this study, single droplet combustion experiment was used to investigate the combustion behavior of palm biodiesel-diesel blends so that the fuel's combustion performance can be examined in detail without the interference of the abovementioned effects [6, 7]. An isolated droplet was suspended on a wire and contained in an enclosed chamber under atmospheric conditions. This setup was done to isolate the complex processes involved in a diesel engine (e.g., rapid air-fuel mixing and liquid-gas phase interaction) and hence, to ascertain the blending effects of palm biodiesel on the combustion behavior of diesel. The temporal evolution of the burning droplet was analyzed by a high-speed camera to analyze the droplet burning behavior in detail [8]. The flame appearance, ignition delay, burn-rate, and combustion duration of diesel, B20, B40, B60, and B100 were examined. This study provides a comprehensive insight on the droplet combustion characteristics of Malaysian palm biodiesel-diesel blends at different concentrations. This work also discusses how the droplet combustion performance of biodiesel-diesel blends could affect the performance and emission characteristics of a diesel engine.

2. Methodology

2.1. Experimental setup

A schematic diagram of the single droplet combustion experiment setup is shown in **Figure 1**. The combustion chamber was partially enclosed with three opening ports required for the backlight illumination, camera, and insertion of glow plug. A 100 W standard halogen light bulb was used as a backlight for the droplet so that a shadowgraph image can be obtained. A fuel droplet of approximately 2 mm in diameter was set on the intersected horizontal wires using a micro-syringe and the droplet is auto-ignite using a glow plug. The vertical distance between the droplet and glow plug was set approximately 3 mm. A CMOS camera was used to capture the whole burning event of a droplet at a resolution of 3968 × 2976.

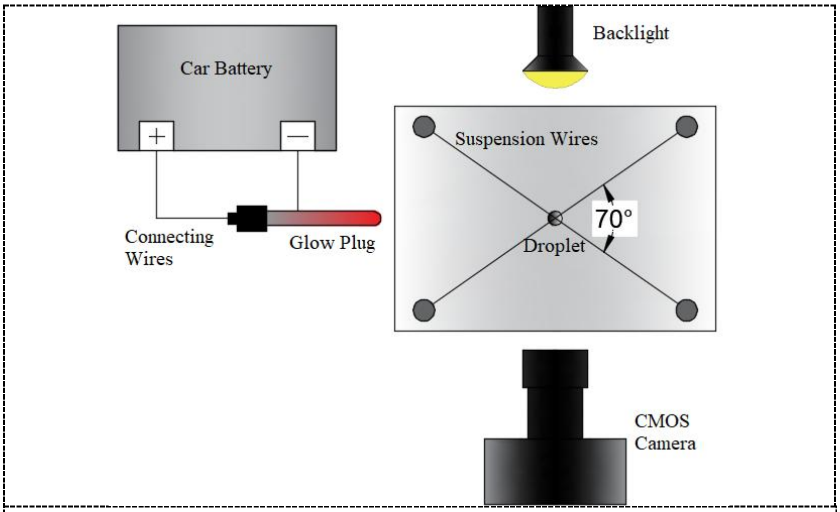

Figure 1. Schematic diagram of the single droplet combustion setup (Top view).

2.2. Fuel preparation
The fuel properties of diesel and palm biodiesel are summarized in **Table 1**. Diesel, B20, B40, B60, and B100 are the test fuels used for the experiments. Each fuel blends were prepared by mixing palm biodiesel into diesel based on volume to volume ratio. Before running the experiments, all test fuels were agitated vigorously and then bath sonicated to ensure the fuel is well-mixed.

Table 1. The pertinent properties of diesel and palm biodiesel

Parameters	Palm biodiesel	Diesel
Density @ 25 °C (kg/m^3)	860 – 900	860
Kinematic viscosity @ 40 °C (mm^2/s)	3.5 – 5.0	2.0 – 5.8
Cetane number	51	47

2.3. Image capturing and processing
Color and monochrome images were captured for each test fuels to analyze the flame color of the burning droplet and droplet shape, respectively. Monochrome images captured were converted into binary images and filtered. Next, MATLAB image processing software was used to calculate the number of pixels contained within the droplet boundary for each image captured. Then, the droplet area was calculated based on the number of pixels.

3. Results and Discussion

3.1. Progression of droplet burning
The combustion behaviour of all the test fuels were examined based on the normalised droplet area versus time throughout the entire droplet burning, as illustrated in **Figure 2**. The progression of the droplet burning for all the test fuels were found to be similar and can be generalized in the following. During the preheating phase, all droplets experienced a slight expansion (e.g., slight increase droplet area), as evident in **Figure 2**. This may be attributed to the heat transfer from the glow plug and the heat conduction from the wires [9]. Upon ignition, the droplets experienced a gradual decrease in size, which it is regarded as a quasi-linear burning process [10]. Diesel and B20 showed relatively high fluctuations compared to other test fuels. These fluctuations are mainly caused by the cavitation built-

up within the droplet thereby causing the droplet to expand and distorts, as shown in **Figures 3** and **4**. Near the end droplet burning, bubble formations on the droplet surface and droplet fluctuations became more apparent before the droplet and flame diminishes.

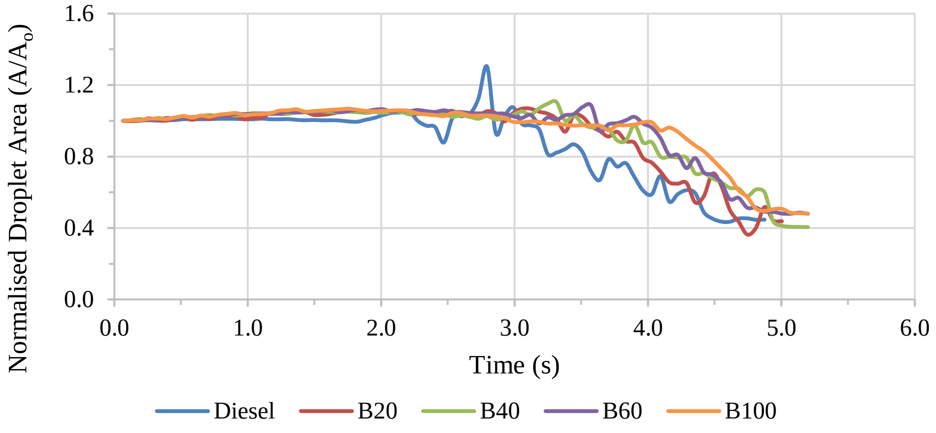

Figure 2. Normalised droplet area against time for all the test fuels.

Figure 3. Large cavitation occurred for the diesel droplet.

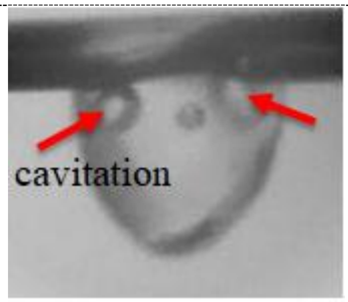

Figure 4. Cavitation starts to form within the B20 droplet.

3.2. Flame analysis

The flame colour and appearance of burning droplet for diesel, B20, B40, B60, and B100 are illustrated in **Figure 5.** Diesel showed a more orange sooty flame however a brighter and more yellowish flame is more prominent for the B40 and B60 droplets. The transition of yellowish flame to a brighter flame with blue streaks as the proportion of palm biodiesel increases. In contrast, a bright and bluish flame visible near the burning droplet can be seen for the B100 droplet, as shown in **Figure 5**. This bluish flame is attributed to the presence of oxygenated content found in palm biodiesel which facilitated a more complete combustion process, emitting less soot when burning [11]. Additionally, Botero et al. [12] also confirmed that the blue flame of biodiesel has lower tendency to soot due to the lack of aromatics and presence of oxygenated functional groups. It can be concluded that fuel blends with higher palm biodiesel content burn cleaner with a less sooty flame.

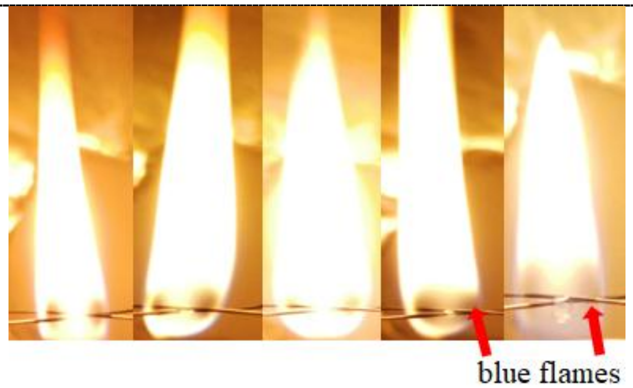

Figure 5. Coloured images of flame produced by test fuels (Left to Right: Diesel, B20, B40, B60, and B100).

3.3. Ignition delay

Ignition delay is a crucial combustion characteristic which affects diesel engine performance and exhaust emissions. A short ignition delay period produces more diffusion burning than premixed burning over the burning process thereby resulting in less engine knock/noise, low NO_x emissions, and high soot level, whereas a long ignition delay period causes more engine knock, high NO_x emissions and less soot [13]. Blending between diesel and palm biodiesel could balance these two extremes to control diesel emissions. In this study, the ignition delay is obtained by measuring the period between the introduction of heat from glow plug and point of ignition of droplet. The ignition delay results for all the test fuels are shown in **Figure 6**. It is observed that increasing the palm biodiesel composition prolonged the ignition delay period. Diesel fuel show the shortest ignition delay of 2.405 s, whereas the longest ignition delay of 3.640 s is found for B100. In comparison to diesel, B20, B40, and B60 has greater ignition delay by 5.41%, 16.22%, and 27.03%, respectively. This trend is counterintuitive to that of the assumed higher cetane number for the fuel blends with higher palm biodiesel composition. However, this correlation between the cetane number and ignition delay is not valid because cetane number magnitude is determined using a varying compression-ignition engine, which is not the case for this investigation of single droplet combustion test [5].

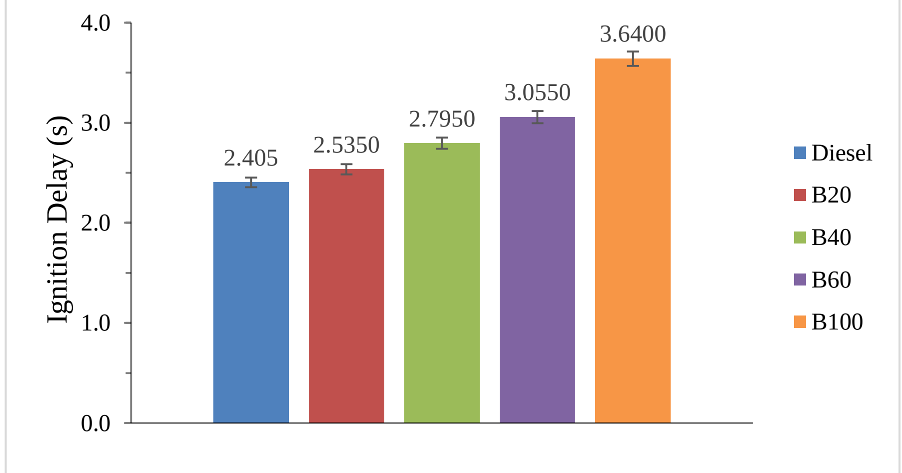

Figure 6. Ignition delay of diesel, B20, B40, B60, and B100.

The contributing factors for the prolonged ignition delay in fuel blends with greater palm biodiesel composition is most likely due to the lower volatility and higher boiling point of biodiesel [14]. Palm biodiesel requires a longer time to produce combustible mixture of fuel vapor and air when subjected to the same amount of heat. The presence of double bonds in biodiesel molecules may also contribute to the increase in ignition delay [15]. A longer ignition delay is generally not preferred as it leads to a greater increase in temperature gradient once the droplet achieved ignition [16]. The high combustion temperature would contribute to the formation of NO_x. However, due to the higher cetane number of palm biodiesel, combusting fuel blends in an actual engine may provide a shorter ignition delay [17]. In comparison among the fuel blends, B20 has the shortest ignition delay.

3.4. Burn-rate

Burn-rate is one of the crucial parameters in diesel engines as it determines how fast the fuel burn. Generally, high burn rate reduce the fuel's combustion duration, thus significantly limiting heat dissipation through the engine in-cylinder wall and improving engine's thermal efficiency [9]. In addition, high burn-rate is also attributed to clean diesel emissions (e.g., less carbon monoxide and smoke emissions) [13]. The burn-rate constant of a burning droplet was calculated using the D^2 law equation; $D^2 = D_o^2 - kt$, in which, k represents the burn-rate constant, D_o is the original diameter of the droplet, and D is the droplet current diameter. The burn-rate constant of all the test fuels are depicted in **Figure 7**. An increasing trend of burn-rate is observed for fuel with higher palm biodiesel content. Diesel show the lowest burn rate constant of 2.136 mm^2/s, whereas B100 achieve the highest burn-rate constant of 4.551 mm^2/s. The improvement by percentage in comparison to diesel for B20, B40, B60 and B100 were found to be 2.11%, 4.21%, 56.27%, and 113.06% respectively, with B60 achieving the greatest burn-rate among the fuel blends. The increasing burn-rate with the addition of palm biodiesel in the fuel blends can be attributed to the high oxygen content of palm biodiesel [15].

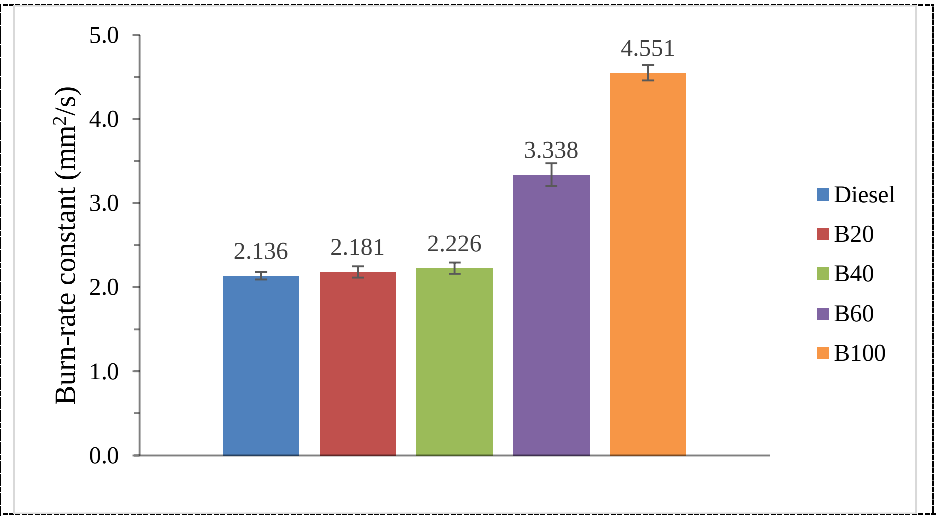

Figure 7. Droplet burn-rate comparison among diesel, B20, B40, B60 and B100.

3.5. Combustion duration

Combustion duration is attributed to the thermal efficiency of a diesel engine. A short combustion duration is favoured as it minimizes heat losses through the engine cylinder walls thereby resulting in high thermal efficiency [13]. In this study, the combustion duration of a burning droplet is measured between the start of ignition and the end of burning droplet. The combustion duration of diesel, B20, B40, B60, and B100 is presented in **Figure 8**. It is observed that the combustion duration decreases when the palm biodiesel content of the test fuels increase. Among the test fuels, B100 exhibits the shortest combustion duration of 1.235 s. However, the combustion duration for B20 and B40 are found to be the same, achieving 2.275 s, which is slightly higher than that of diesel by 2.94%. Among the fuel blends, the combustion duration of B60 is the shortest (1.820 seconds) and achieving a reduction of 17.65% compared to that of diesel. The shorter combustion duration found for B60 and B100 may be attributed to their much greater burn-rate (see **Figure 7**). Additionally, the higher ignition delay for B60 and B100 may also contribute to their shorter combustion duration since more fuels are rapidly used up after droplet ignition [5].

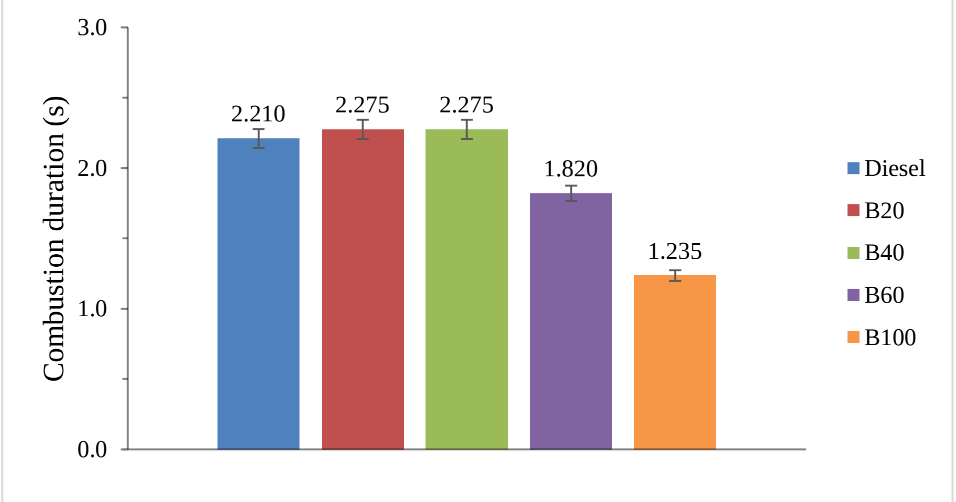

Figure 8. Combustion duration of diesel, B20, B40, B60 and B100 droplet.

4. Conclusion

The combustion behaviour of diesel, B20, B40, B60 and B100 were investigated using a single droplet combustion experiment. From the flame colour analysis, a more bluish flame was observed when the composition of palm biodiesel in diesel is increased, which indicates a clean and complete combustion. The ignition delay was found to be associated to the content of palm biodiesel, where higher composition of palm biodiesel resulted in more prolonged ignition delay. The prolonged ignition delay with the palm biodiesel addition is likely attributed to the relatively higher boiling point and lower volatility of palm biodiesel. Palm biodiesel was also found to be the contributing factor in improving the burn-rate and shortening combustion duration because of its high oxygen content. In comparison among the B20, B40, and B60 blends, B60 achieved the greatest burn-rate (+56.27% compared to diesel) and the shortest combustion duration (-17.65% compared to diesel). Overall, this study suggest that B60 could be the optimum fuel blend for diesel engine applications.

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