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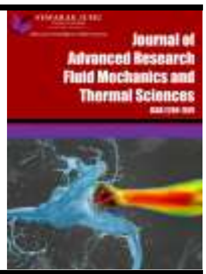

Analyzing the Impact of Droplet Impingement Interval on Biodiesel Deposition Characteristics

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ABSTRACT

The purpose of this work is to investigate the effect of droplet impingement interval on deposition characteristics of diesel fuel (DF) and palm oil biodiesel with different blending ratios (B10-B50) by applying the hot surface deposition test (HSDT). Generally, HSDT method is a simplified method to simulate fuel deposition in diesel engines by impinging fuel droplets on a heated aluminum alloy plate surface. The mass of accumulated deposits after droplets N_D=16000 for impingement interval of t_{imp}=7 seconds (dry condition) M_R=3.7mg (DF), M_R=3.9mg (B10), M_R=17.1mg (B20), M_R=24.0mg (B30), M_R=25.1mg (B40), and M_R=28.8mg (B50). For impingement interval of t_{imp}=3 seconds (wet condition), the deposit mass was M_R=4.4mg (DF), M_R=8.9mg (B10), M_R=20.4mg (B20), M_R=31.1mg (B30), M_R=62.4mg (B40), and M_R=58.2mg (B50). In terms of deposit surface temperature, the recorded average minimum and maximum deposit surface temperatures were between T_d=295°C to T_d=325°C (t_{imp}=7 seconds) and T_d=200°C to T_d=300°C (t_{imp}=3 seconds) for DF. For B10-B50, the deposit surface temperatures were around T_d=290°C to T_d=350°C (t_{imp}=7 seconds) and below T_d=200°C for impingement interval of t_{imp}=3 seconds.

1. Introduction

Biodiesel has gained popularity as a replacement for diesel fuel for having comparable performance without the need for engine modification when used in diesel engines [1]. In Malaysia, palm oil biodiesel is the most utilized biodiesel owing to its easy access to feedstock and abundant resources of crude palm oil [2,3]. However, in our previous work, we found out that one of the main disadvantages when using biodiesel is the deposit development inside the combustion chamber, which could cause negative impacts on the engine such as on the emissions and mechanical performance [4]. Furthermore, severe issues such as combustion chamber part problems and engine damage could occur especially for long-term operation involving biodiesel applications [5]. Apart from that, biodiesel deposit development on diesel engine parts was considered a complex occurrence [6]. Moreover, it is inevitable to prevent the presence of deposits within the engine's

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combustion chamber [7]. Therefore, to address this concern, it is more advantageous to blend biodiesel with conventional diesel or other additives [8].

The performance of a diesel engine is notably influenced by both the properties of the fuel and the characteristics of the fuel injection system, as emphasized by Abdelrazek *et al.,* [9]. However, the primary challenge with pure biodiesel lies in its exceptionally high viscosity, which is 10 to 20 times greater compared to ordinary diesel fuel. In addition, when used in the engine, diesel fuel displays a well-developed spray, whereas biodiesel exhibits poor atomization with a fast-travelling spray and slow dispersion [10,11]. When compared to diesel fuel, biodiesel typically exhibits characteristics such as a lower heating value, higher density, higher kinematic viscosity, and a higher flash point. These properties can lead to poor atomization and combustion performance in engines [12,13]. This is a result of the fuel droplets growing larger in the engine during fuel atomization. Larger fuel droplets will take longer to ignite. Fuels with a higher viscosity will ignite more slowly than those with a lower viscosity. As a result, deposit formation rates may likely to rise. In addition, increased viscosity and reduced volatility of the fuel can result in poor fuel atomization and air-fuel mixing, primarily due to larger fuel droplets during the atomization process within the engine. Larger fuel droplets contribute to a longer ignition delay, and fuels with higher viscosity tend to exhibit a greater ignition delay compared to fuels with lower viscosity. Consequently, this extended ignition delay can lead to an increased propensity for deposit formation [14]. Other than that, ignition delay is one of the most influential parameters affecting both the engine's heat release rate and its emissions, where partially reacted carbon of the fuel hydrocarbon and the incomplete burning of the liquid fuel leads to the formation of soot [15]. Furthermore, the ignition delay is also a crucial parameter for determining an engine's knocking characteristics, as mentioned by Bui *et al.,* [16].

Faik *et al.,* [17] found that the proportion of biodiesel in blended fuels affects the evaporation characteristics of biodiesel-diesel mixtures, including the evaporation lifetime. The proportion of biodiesel in a blend can also influence the size of spray droplets in the combustion process. A higher proportion of biodiesel can result in larger droplet sizes, which can negatively impact the quality of spray characteristics in a diesel engine, leading to suboptimal performance [12,18]. Researchers, engine manufacturers, and designers are particularly interested in how liquid fuel droplets evaporate when they come into contact with heated surfaces, such as the combustion chamber. When a fuel droplet interacts with a surface, multiple factors come into play, influencing the droplet's behaviour and resulting in various outcomes. Mahulkar *et al.,* [19] observed that different applications require distinct behaviours from droplets when they contact a heated solid surface. Reis [20] explained that several factors, including droplet diameter, impact velocity, saturation temperature, viscosity, and surface tension, all closely related to the liquid's properties, determine the forces acting on a droplet during the impingement process, which subsequently affect the deposition mechanism. However, quantifying the exact forces acting on an impinged single fuel droplet, especially in numerical terms, is a challenging task. Furthermore, Liang and Mudawar [21] suggested that the characteristics of the solid surface, including diffusivity, wettability, surface roughness, and surface temperature, have a significant impact on the dynamics of impinged droplets during the impact process.

The rate at which fuel evaporates on heated surfaces directly impacts exhaust emissions, including particulate matter (PM) and nitrogen oxides (NOx), as well as the efficiency of compression ignition engines [22]. According to Wang *et al.,* [23], one of the primary reasons for studying the evaporation properties of individual fuel droplets is to better understand spray vaporization and combustion. The author also emphasized that various factors, such as temperature, pressure, fuel volatility, spray droplet diameter, and droplet velocity relative to the surrounding gas, all contribute to the overall rate of fuel evaporation. This finding aligns with the conclusions of Mariani *et al.,* [24], who emphasized that fuel characteristics, including droplet size and momentum, are pivotal in improving effective fuel mixing while reducing the interaction of droplets with the chamber walls. By employing the HSDT method, this study focuses on understanding the impact of droplet impingement interval (dry and wet conditions) and fuel properties, such as density and kinematic viscosity, on the deposition characteristics of a blend of diesel fuel (DF) and Malaysian palm oil biodiesel (B10-B50). In addition, this research aims to investigate how different droplet impingement intervals affect the deposition process during the droplet repetitions test. The findings in this study are important in identifying the conditions in which deposits are more likely to be produced at a higher rate.

2. Methodology

The fuels used in this study were DF and Malaysian palm oil biodiesel with a blending ratio of 10% (B10), 20% (B20), 30% (B30), 40% (B40), and 50% (B50) by volume of biodiesel content blended with diesel fuel. The properties of these fuels are presented in Table 1.

Table 1
Fuel properties of diesel fuel and palm oil biodiesel blend [25]

Properties	Fuel					
	DF	B10	B20	B30	B40	B50
Density (kg/m^3)	847	850	853	857	860	863
Kinematic viscosity (mm^2/s)	3.8	3.86	3.91	3.95	3.97	4.00
Heating value (MJ/kg)	45.21	44.23	44.12	43.13	42.95	42.74
Acid value (mg KOH/g)	0.16	0.18	0.22	0.26	0.30	0.33

To simulate the deposit formation inside the combustion chamber, the Hot Surface Deposition Test (HSDT) method was utilized. The HSDT method is a simplified method to investigate the evaporation characteristics of fuel droplets and fuel deposition on a heated aluminum alloy surface. Our earlier research revealed that the aluminium alloy plate's centre region produced the most heat [26,27]. Since the centre of the plate is the hottest place, it is where the fuel will be applied during the experiment. Since aluminium alloys are typically used to make pistons for internal combustion (IC) engines, the circular plate was constructed out of aluminium to resemble a piston [28,29]. Moreover, in earlier research on deposit formation on a hot surface, the HSDT experimental approach was used [30,31]. The schematic diagram of the HSDT experimental setup is illustrated in Figure 1.

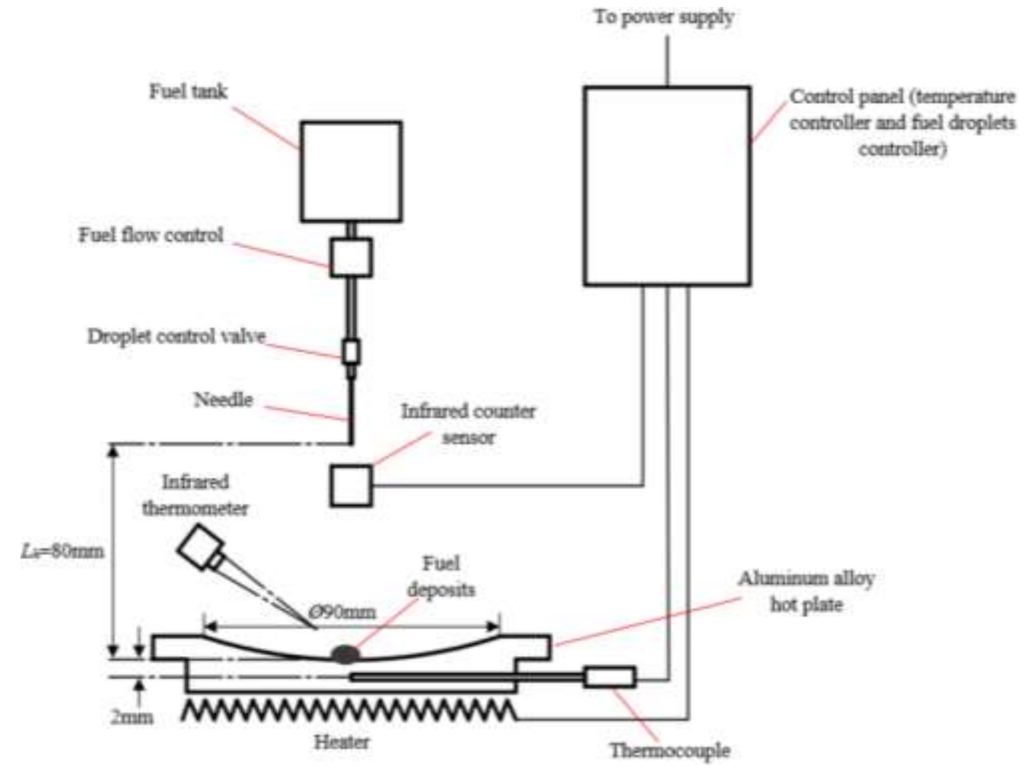

Fig. 1. Schematic diagram of HSDT experimental setup

In terms of the hot plate temperature (T_s), it was set at T_s=315°C for DF and T_s=340°C for B10-B50 These temperatures were determined based on the maximum evaporation point (MEP) of each fuel which were obtained from separate evaporation characteristic test. Furthermore, at a hot plate temperature of T_s=315°C, the droplet's lifetime (t_{life}) of DF is around t_{life}=4 seconds. Similarly, at T_s=340°C, the droplet's lifetime for B10-B50 is also around t_{life}=4 seconds. Thus, to create dry and wet conditions during the deposition test, the droplet impingement interval (t_{imp}) was set accordingly. For all test fuels, the droplet impingement interval (t_{imp}), was set to t_{imp}=7 seconds (dry condition) and t_{imp}=3 seconds (wet condition). The dry condition means that the droplet impingement interval was set higher than the droplet's lifetime (t_{life}) and lower for wet conditions.

The mass of deposits produced on the heated plate was recorded at every 1000 droplet repetitions (N_D) until the repetitions reached N_D=16000 by using a micro-balance. On the other hand, the deposit surface temperature (T_d) was also measured at every 1000 droplet intervals by using an infrared thermometer. The deposit's minimum surface temperature was recorded immediately following an impingement, and its highest temperature was recorded just before the next droplet. To obtain a more accurate reading, the minimum and highest deposit surface temperatures were recorded at least three times to obtain the average readings.

3. Results and Discussion

As can be seen in Figure 2, the mass of accumulated deposits for both dry and wet conditions was less than M_R=1.0mg at the early stage (N_D≤5000) of the DF deposition test, which indicates that deposits development of DF was very slow even at lower heated plate surface temperature (T_S=315°C). After the droplet repetitions reached N_D=16000, only small amounts of deposits were generated on the hot surface. The accumulated deposits at N_D=16000 were M_R=3.7mg for dry condition and M_R=4.4mg for wet condition tests, which the difference was only around M_R=0.7mg more deposits produced when the impingement interval is shorter than the droplet evaporation lifetime compared to that of longer impingement interval. This shows that impingement interval has minimal impact on DF deposition for droplet repetitions N_D≤16000.

In terms of deposit surface temperature, the recorded average minimum and maximum deposit surface temperature were between T_d=295°C to T_d=325°C for DF during the dry condition test. Furthermore, there was a slight decrease in the deposit surface temperature at the later stage of the experiment (N_D≥10000). For the wet condition test, the average minimum and maximum deposit surface temperature for DF was the most inconsistent (T_d=200°C - T_d=300°C) and this was probably affected by the significantly thin layer of the DF deposit produced corresponding to its low accumulated mass.

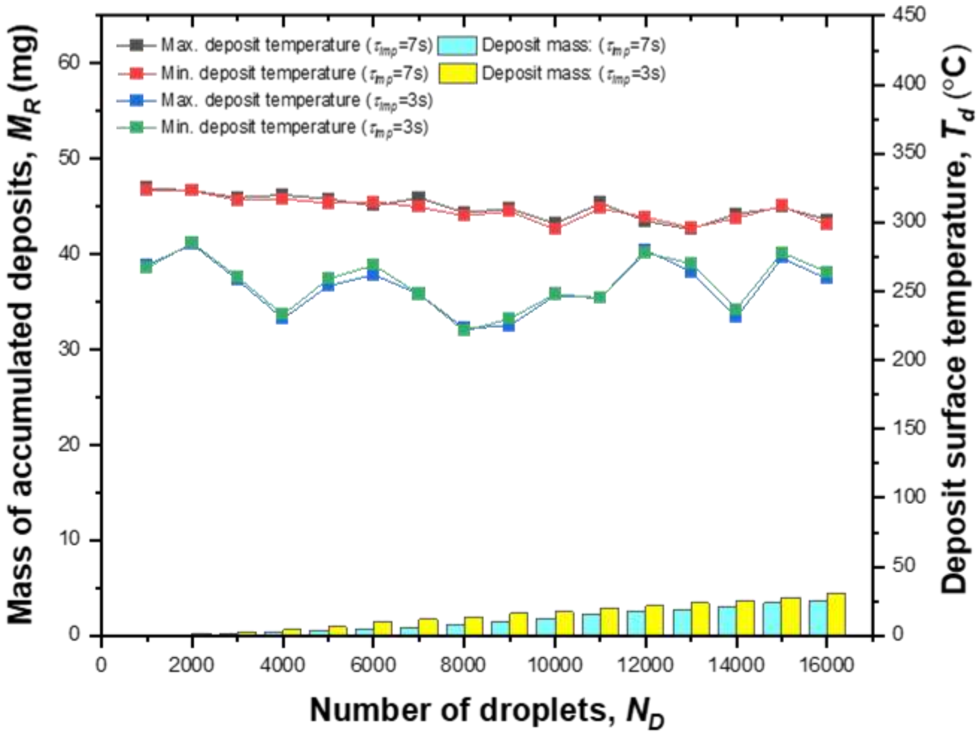

Fig. 2. Deposition characteristics of DF

For B10 fuel, the hot plate surface temperature was set higher at T_S=340°C. During the early stage (N_D≤5000) of the B10 deposition test, the mass of accumulated deposits for the dry condition test was higher (M_R=1.6mg) than that of the wet condition test (M_R=1.0mg) as presented in Figure 3. However, at droplet repetitions N_D=16000, the mass of deposit generated were M_R=8.9mg and M_R=3.9mg for wet condition and dry condition tests, respectively. The difference between the accumulated masses was around M_R=5.0mg, which indicates that at the later stage of the experiment (N_D≥10000), the deposition was more influenced by the impingement interval. In addition, for t_{imp}=3 seconds, B10 fuel produced around 2 times more deposits than DF, which accounted for the biodiesel content in B10 fuel.

The recorded deposit surface temperatures for the wet condition test (T_d=157°C - T_d=184°C) were lower than those for the dry condition test (T_d=296°C - T_d=345°C). Furthermore, there was a slight decrease in the deposit surface temperature at the later stage of the experiment (N_D≥10000) for both test conditions. This was mostly caused by the accumulation of deposits that were thicker and more massive during the wet condition test. Because of the deposits' low thermal conductivity, the surface temperature of the generated deposits decreased more slowly than the temperature of the heated plate [30,32].

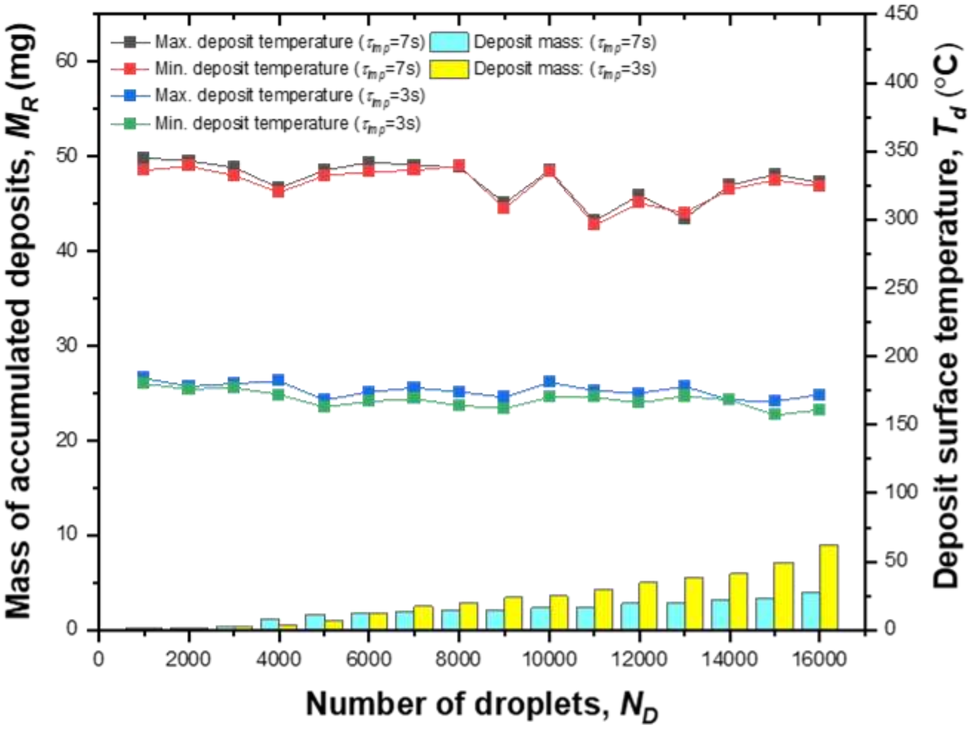

Fig. 3. Deposition characteristics of B10

In Figure 4, the amounts of accumulated deposits for B20 fuel increased gradually for both dry and wet conditions. The deposits generated on the hot surface at N_D=16000 were M_R=17.1mg for dry condition and M_R=20.4mg for wet condition, which the difference came to around M_R=3.3mg, respectively. This shows that the impingement interval has a noticeable effect on the deposition characteristics of the B20 fuel. Moreover, these amounts exceeded the mass of produced deposits generated by DF and B10 fuel at the same droplet repetitions, which resulted from the higher biodiesel content of B20 fuel.

In terms of deposit surface temperature, the recorded average minimum and maximum deposit surface temperature were between T_d=291°C to T_d=343°C during the dry condition test. As the deposit becomes thicker (N_D≥10000) its surface temperature become more inconsistent. On the other hand, for the wet condition test, the recorded deposit surface temperature was ranging from T_d=156°C to T_d=184°C. There was also a noticeable decrease in the deposit surface temperature at the later stage of the experiment (N_D≥10000) for both test conditions.

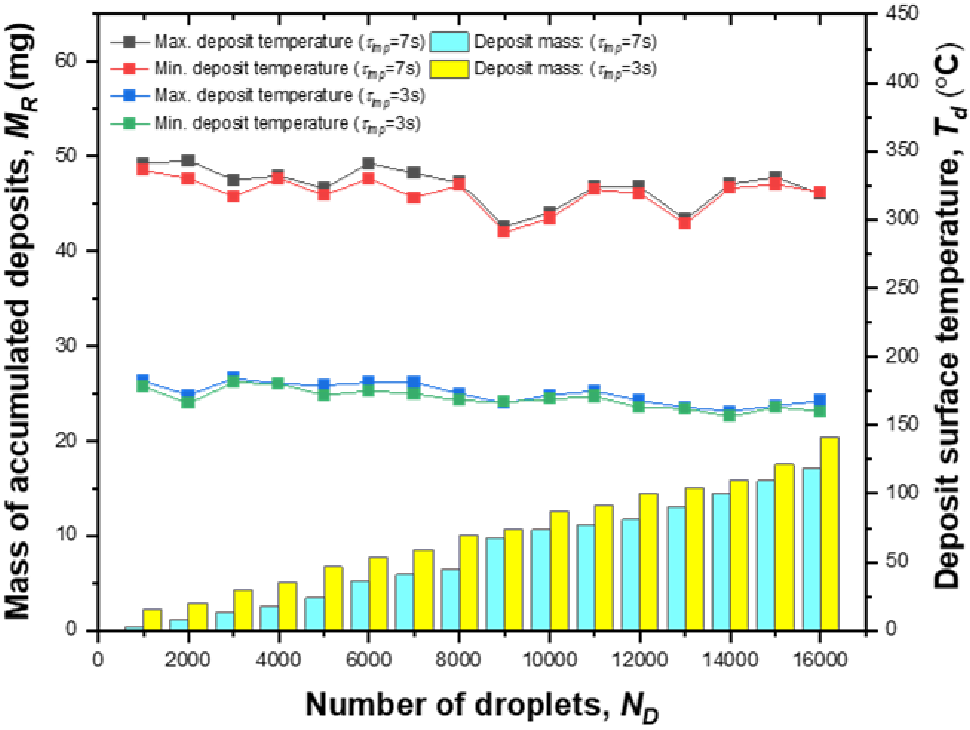

Fig. 4. Deposition characteristics of B20

In Figure 5, for an impingement interval of t_{imp}=3 seconds, the deposits accumulated by B30 fuel (M_R=31.1mg) were approximately M_R=7.1mg greater compared to an impingement interval of t_{imp}=7 seconds (M_R=24.0mg) for the same droplet repetitions at N_D=16000. Therefore, this indicates that the impingement interval has a greater impact on the deposition of B30 fuel.

The recorded average minimum and maximum deposit surface temperature for the B30 fuel were between T_d=294°C to T_d=350°C during the dry condition test. Meanwhile, for the wet condition test, the recorded deposit surface temperature was ranging from T_d=152°C to T_d=185°C. At the later stage of the experiment (N_D≥10000), for the dry and wet conditions, there was a slight decrease in the deposit surface temperature.

Based on the data in Figure 6, B40 fuel deposit formation for wet conditions was the highest among all tested fuels, which was about M_R=62.4mg for N_D=16000. This value is around twice the mass of the deposit produced by B30 fuel M_R=4.2mg more than B50 fuel for the same impingement interval. This shows that the impingement interval has a greater effect on the deposition of the B40 fuel. However, for the dry condition test at N_D=16000, B40 fuel only generated M_R=25.1mg of deposits, which is only around M_R=1.1mg more than that produced by B30 for a similar impingement interval.

In terms of deposit surface temperature, there was a slight decrease in the deposit surface temperature at the later stage of the experiment (N_D≥10000). The recorded average minimum and maximum deposit surface temperature were between T_d=295°C to T_d=345°C for an impingement interval of t_{imp}=7 seconds. On the other hand, for the impingement interval of t_{imp}=3 seconds, the recorded deposit surface temperature was ranging from T_d=156°C to T_d=186°C.

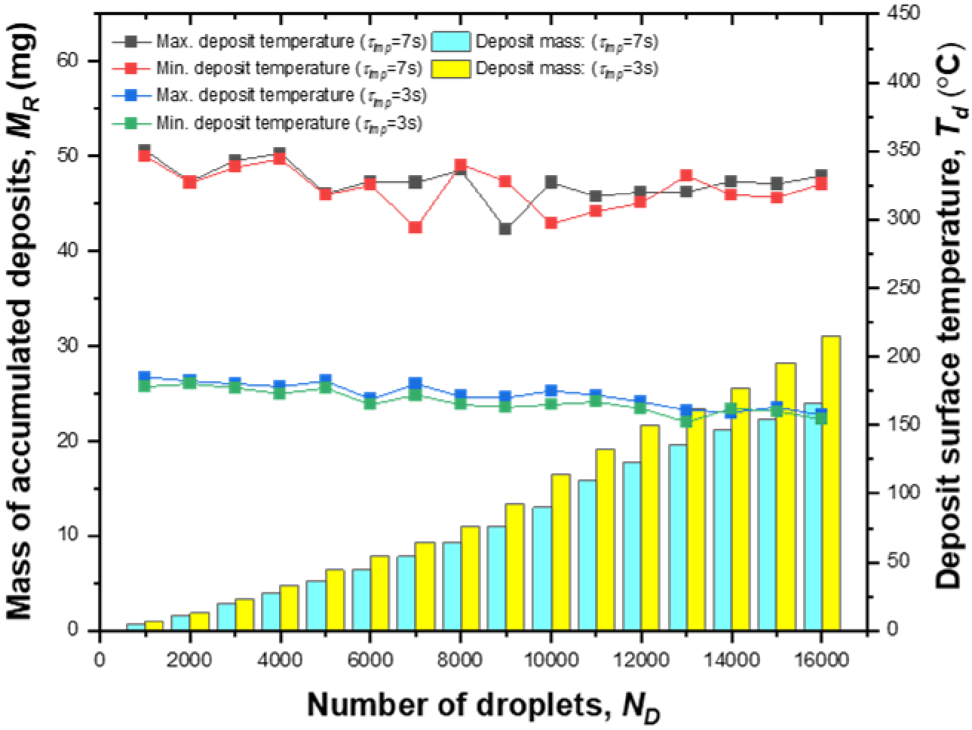

Fig. 5. Deposition characteristics of B30

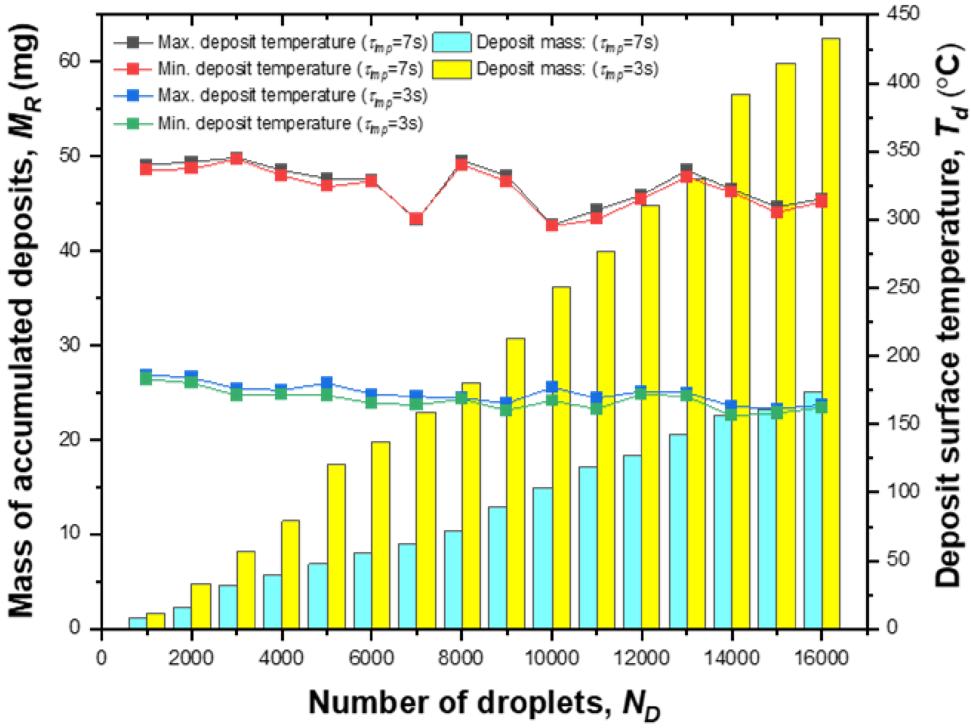

Fig. 6. Deposition characteristics of B40

In Figure 7, the obtained deposits for B50 fuel (M_R=28.8mg) for the dry condition test were approximately M_R=3.7mg greater compared to that of B40 fuel for the same test condition at droplet repetitions of N_D=16000. However, for the wet condition test, B50 fuel produced only M_R=58.2mg of deposits, which is approximately M_R=4.2mg fewer than the deposits produced by B40 fuel (M_R=62.4mg) for similar test condition even though B50 fuel has a higher palm oil biodiesel mixture in its blends. This indicates that the deposition of B40 fuel for the wet condition test was more affected by the impingement interval rather than the fuel properties itself.

The average minimum and maximum temperatures recorded were ranging from T_d=293°C to T_d=335°C for the dry condition test. On the other hand, for the wet condition test, the temperatures were between T_d=151°C to T_d=177°C. As explained by Pham [30], and Kalam and Masjuki [32], the surface temperature of deposits decreases below the heated surface temperature due to the low thermal conductivity of deposits. However, several factors such as engine specifications, speed and load, and environmental conditions could influence the surface temperature of deposits in an actual engine. In addition, a thick deposit makes it more difficult for subsequent fuel droplets to vaporize, causing more unburned fuel to convert into deposits. Additionally, compared to petroleum diesel, biodiesel undergoes more extensive auto-oxidation, which aids in the production of thicker deposits [33].

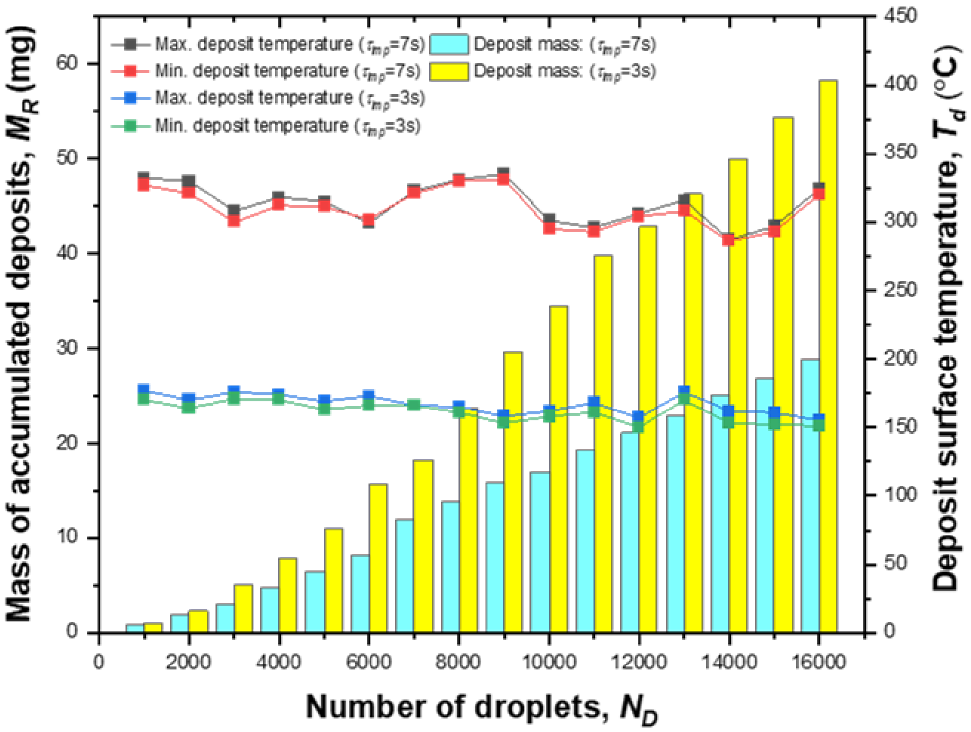

Fig. 7. Deposition characteristics of B50

4. Conclusions

The effect of droplet impingement interval on the deposition characteristics of diesel fuel and Malaysian palm oil biodiesel (B10-B50) was studied using the HSDT method. The outcomes were analyzed and compared to each other. The following is a summary of the main findings

i. The mass of accumulated deposits after droplets N_D=16000 for impingement interval of t_{imp}=7 seconds (dry condition) M_R=3.7mg (DF), M_R=3.9mg (B10), M_R=17.1mg (B20), M_R=24.0mg (B30), M_R=25.1mg (B40), and M_R=28.8mg (B50).
ii. For impingement interval of t_{imp}=3 seconds (wet condition), the deposit mass was M_R=4.4mg (DF), M_R=8.9mg (B10), M_R=20.4mg (B20), M_R=31.1mg (B30), M_R=62.4mg (B40), and M_R=58.2mg (B50).
iii. DF generated the least amount of deposit among other fuels for both wet and dry condition deposition tests, and this was primarily contributed by the absence of other fuel components in DF content. Furthermore, the droplet impingement interval which is shorter than the

droplet's lifetime causes more deposits to be formed on the heated plate. Thus, it is better to have a dry condition in the combustion chamber to minimize deposit formation.

iv. Deposit surface temperatures were lower for the wet condition test (t_{imp}=3 seconds) compared to that of the dry condition test (t_{imp}=7 seconds). This was mostly caused by the accumulation of deposits that were thicker and more massive during the wet condition test. Moreover, because of the deposits' low thermal conductivity, the surface temperature of the generated deposits decreased more slowly than the temperature of the heated plate.

v. During the dry condition test (t_{imp}=7 seconds), the recorded average minimum and maximum deposit surface temperature were between T_d=295°C to T_d=325°C for DF. For the wet condition test (t_{imp}=3 seconds), the deposit surface temperature for DF was the most inconsistent, which was between T_d=200°C to T_d=300°C, and this was probably caused by the significantly thin layer of the DF deposit compared to the other fuels.

vi. For the dry condition test for B10-B50 fuel, the recorded average minimum and maximum deposit surface temperatures were between T_d=290°C to T_d=350°C. For the wet condition test, the average minimum and maximum deposit surface temperature were recorded below T_d=200°C, even though the set temperature of the hot plate for the B10-B50 fuel deposition test (T_s=340°C) was higher compared to that of the DF deposition test (T_s=315°C).

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