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# Analysis on Evaporation Characteristics of Palm Oil Biodiesel using a HSDT Method

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**ABSTRACT**

The purpose of this study is to investigate the evaporation characteristics of different types of fuels by applying the hot surface deposition test (HSDT). Generally, HSDT method is a simplified method to simulate fuel deposition in diesel engines. In this study, diesel fuel (DF) and palm oil biodiesel with different blend ratios (B10-B50) were used to evaluate the fuel droplet evaporation behavior on a heated aluminum alloy plate surface. Single fuel droplet was impinged on the heated plate at various surface temperatures ($T_s$). Important data from the evaporation characteristics was the maximum evaporation point (MEP), which is the temperature point where a droplet evaporates in the shortest lifetime ($t_{life}$). MEP is referred to identify the surface temperature range in which fewer deposits will be produced by the test fuel. Furthermore, MEP is also used to determine the appropriate droplet interval to create wet and dry conditions in the fuel deposition test. The obtained MEP was 360°C (DF), 365°C (B10, B50), 375°C (B20, B40), and 385°C (B30).

## 1. Introduction

Two types of internal combustion engines that are globally used for transportation purposes are the diesel engine and gasoline engine, which are power-driven by petroleum diesel for the former and petrol for the latter [1]. These engines have their advantages that are commonly influenced by fuel use. Gasoline engine, usually runs on fuel with lower density compared to diesel fuel such as gasoline, ethanol, methanol, or mixtures between two types of fuels [2,3]. Due to its lower density, gasoline fuel possesses a higher evaporation rate than diesel fuel [4]. Furthermore, gasoline engines typically function with lower compression ratios, leading to reduced engine efficiencies. However, a notable benefit is the capability to achieve exceptionally low emissions, making them environmentally favourable [1]. Moreover, gasoline fuel with a high-octane number also has better resistance to auto-ignition, which makes its combustion rate more controllable and helps to avoid early ignition that can cause knocking in the engine [5]. However, in terms of thermal efficiency,

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diesel engines are superior compared to gasoline engines. Biodiesel is commonly applied in diesel engines, especially in the transportation sector and it has gained popularity as a substitute for diesel fuel for having comparable performance such as thermal efficiency without the need for engine modification when used in diesel engines [6,7]. Although the widespread adoption of 100% biodiesel in commercial vehicles hasn't occurred yet, diesel-biodiesel blends, varying from 5% to 30% biodiesel mixed with pure diesel, are globally accepted and used in diesel engines with either no or minimal modifications [8,9]. In Malaysia, palm oil biodiesel is the most utilized biodiesel [10]. Furthermore, there are also abundant feedstock and resources of crude palm oil in this country [11,12]. However, one of the primary drawbacks 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 as documented in our previous work [13]. The main challenge with pure biodiesel lies in its exceptionally elevated viscosity, which is 10 to 20 times greater than that of conventional diesel. Consequently, it is more favorable to blend it with regular diesel or other additives to address this concern [14]. In contrast to pure diesel, biodiesel exhibits increased carbon residues owing to differences in its chemical composition and molecular structure, thereby increasing the likelihood of carbon buildup within the combustion chamber [15]. Moreover, biodiesel application may result in severe engine problems and could damage the engine, especially for long-term operation [16]. As discovered by Arifin *et al.,* [17], biodiesel deposit development on diesel engine parts was considered a complex occurrence. Apart from that, deposits existing inside the combustion chamber of an engine are impossible to be avoided [18].

The wall temperature, the design of the fuel injector nozzle, the use of lubricants, and the kind of fuel itself are just a few of the variables that may have a significant impact on deposit development inside the combustion chamber of real engines. Other than that, Faik *et al.,* [19] also stated that the amount of biodiesel in the blended mixture affects the biodiesel-neat diesel blend fuel evaporation characteristics, such as the evaporation lifetime. This suggests that because biodiesel burns more quickly than base diesel, adding it will result in greater fuel usage. Additionally, it is essential to understand single droplet evaporation characteristics since it shares many physical and chemical processes with spray characteristics [20]. Thus, researchers, engine makers, and designers are interested in the evaporation of liquid fuel droplets impinging on heated surfaces. The interest in this subject has been simulated by several researchers via the heated wall surface method in the early studies on the evaporation characteristics of fuel droplets [21-25]. The rate at which fuel evaporates on various hot surfaces, such as the combustion chamber, affects exhaust emissions, including PM and NOx, and its efficiency in compression ignition engines [25]. As indicated by Wang *et al.,* [26], one of the most crucial reasons to research the evaporation properties of a single fuel droplet is to characterize spray vaporization and combustion. The author also noted that factors such as temperature, pressure, volatility, spray drop diameter, and drop velocity concerning the surrounding gas all affect the total rate of fuel evaporation. This is in agreement with Jadidbonab *et al.,* [27], who investigated the diesel droplets impacting a heated aluminum substrate. The author discovered that several parameters such as ambient pressure, wall-surface temperature, surface conditions, and the liquid physical properties itself are influential towards the droplet evaporation characteristics. Other than that, Marlina *et al.,* [28] studied the ignition and boiling of vegetable oil droplets. The author found that the long molecular structure in biodiesel, characterized by numerous unsaturated double bonds, results in elevated surface tension. This high surface tension hinders droplet formation, leading to a slow evaporation rate of the droplets and an inefficient atomization process. In her other work, Marlina *et al.,* [29] also discovered that adding other types of oil could alter the molecular chain of triglyceride of a biodiesel, hence, affecting the evaporation characteristics of its droplet.

Mahulkar *et al.,* [30], in their research, noted that specific applications necessitate distinct desired behaviors of droplets when they make contact with a heated solid surface. The author explained that, in the context of spray cooling, the expectation is for the entire droplet mass to be deposited onto the surface, minimizing splashing and rebound. Conversely, in fuel injection systems, a lower level of droplet adhesion to the surface is preferable because it enhances the efficiency of the evaporation process. In another investigation by Segawa *et al.,* [31], the author claimed that it is evident that one of the crucial aspects of the overall processes involved in the combustion chamber is the evaporation process of fuel droplets on a heated surface. This also aligns with the findings of Mariani *et al.,* [32], who noted that fuel characteristics like the size of fuel droplets and their momentum play a vital role in improving effective fuel blending while also decreasing the interaction of droplets with the walls of the combustion chamber. During the interaction between a droplet and a surface, various factors influence the behavior of a single fuel droplet, leading to different outcomes. In the literature, another parametric investigation on evaporation characteristics is the effect of surface roughness and inclination angle. As experimentally studied by Deendarlianto *et al.,* [33], the authors discovered that a heated substrate with various inclined angles and surface roughness significantly affects the droplet evaporation behavior. Chakaneh *et al.,* [34] also found that a heated solid surface with high surface roughness reduces the maximum spreading diameter of a droplet, which could accelerate the rate of evaporation and increase the formation of non-single droplet evaporation. Additionally, when a droplet impinges on an inclined surface, it will go through five stages, which are the kinetic stage, the spreading stage, the sliding stage, the retraction stage, and the stable wetting stage [35,36]. Other than that, the Weber number could also dictate the evaporation behavior of fuel droplets. Fujimoto *et al.,* [37] explained that for high Weber numbers, inertial forces become more significant, and the droplet is more likely to break up into smaller droplets, leading to splash. On the other hand, for a lower Weber number, the droplet is more likely to spread, recede, and rebound from the surface after impact due to relatively small kinetic energy [38].

In this study, the effect of wall surface temperature and fuel properties (density and kinematic viscosity) on the evaporation characteristics of DF and Malaysian palm oil biodiesel (B10-B50) were examined. There was not enough research done on the evaporation behavior of fuel droplets on a heated surface. Therefore, this research intends to explore how droplets of a blend of Malaysian palm oil biodiesel and diesel evaporate on a heated aluminum surface, specifically using the HSDT method. The findings will be contrasted with those of pure diesel fuel to understand how the properties of the droplets affect their evaporation at specific temperatures. Moreover, the findings will be used to determine the parameter in the droplet repetition test (deposition test). In addition, the results from this test are important in identifying the temperature range in which fuel droplets for each test fuel evaporate faster, thus, decreasing the rate of deposit development.

## 2. Methodology

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

**Table 1**
Fuel properties of diesel fuel and palm oil biodiesel blend [39]

| 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 |
| Diameter of droplet (mm) | 2.2 | 2.3 | 2.2 | 2.2 | 2.2 | 2.2 |

The method that was utilized in this study was the Hot Surface Deposition Test (HSDT) method and the experimental setup schematic diagram is shown in Figure 1. This method is a simplified method to simulate and investigate the deposit formation inside the combustion chamber of an engine. The concept of this method is to investigate the evaporation characteristics of fuel droplets and fuel deposition on a heated aluminum alloy surface. In the previous studies by Jikol *et al.,* [40,41], they found out that the maximum heat was generated on the center region of the aluminum alloy plate. Hence, when conducting the experiment, the fuel is being impinged on the center area as that is the hottest spot on the plate. The circular plate was fabricated from aluminum to simulate a piston, as pistons within internal combustion (IC) engines are primarily made from aluminum alloys [42,43]. Furthermore, the HSDT experimental concept has been applied in previous work regarding deposit formation on a hot surface [24,44].

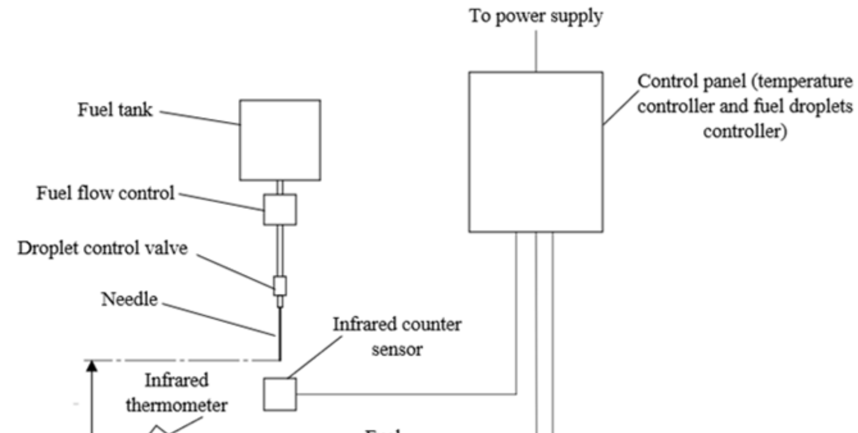

**Fig. 1.** Schematic diagram of HSDT experimental setup

In this experiment, the initial plate temperature was set to 250°C, and it was gradually increased in 5°C increments until reaching 430°C. The 5°C increment was chosen to carefully monitor even minor changes in droplet evaporation behavior. Furthermore, the temperature was raised to 430°C to ensure the occurrence of a non-single droplet evaporation state. In the case of diesel fuel, the time interval from when the droplet first makes contact with the hot plate surface until the completion of the evaporation process is defined as the droplet's lifetime. However, in the context of multi-component fuels like a blend of palm oil biodiesel and diesel fuel, the droplet's lifetime is measured until the remaining fuel is challenging to vaporize, and no further vapor is produced during the evaporation. To determine a more precise average evaporation time for each set of surface temperatures, three evaporation times of a single fuel droplet were recorded. The behavior of the fuel droplets during the evaporation test was observed and noted appropriately.

## 3. Results and Discussion

Two evaporation states occurred during the evaporation process, which were identified as single droplet and non-single droplet evaporation states as illustrated in Figure 2. The main difference between the non-single droplet and single droplet during the evaporation process is non-single droplet involves fuel splashes while the latter does not.

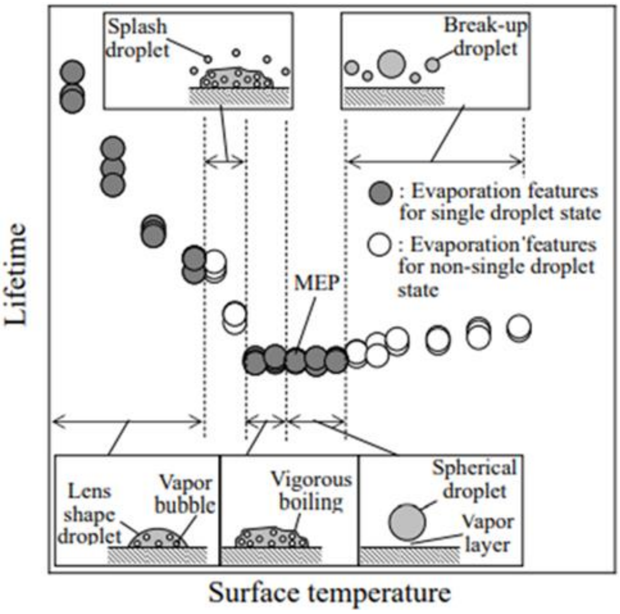

**Fig. 2.** General feature of evaporation characteristics [45]

The droplet evaporation behavior for all test fuels was observed and recorded in Table 2. Meanwhile, the evaporation characteristics profile for each test fuel obtained from this test is presented in Figure 3 to Figure 8 and their comparison is illustrated in Figure 9. In Table 2, the droplet evaporation behavior of all test fuels is explained. Generally, all test fuels produced a single droplet evaporation state at the early stage of the experiment. However, when the plate temperature was raised above *Ts*=350°C, a non-single droplet evaporation state was more likely to occur. Moreover, more smoke and droplet splashes were produced at higher plate temperatures. In addition, when the plate temperature was increased to *Ts*=380°C, DF produced more smokes, more obvious non-single droplet evaporation state, and more droplet splashes compared to B10-B50 fuel. This shows that without a biodiesel component in DF fuel, the droplet can evaporate completely at a faster rate.

**Table 2**
Droplet evaporation behavior comparison

| Surface temperature, $T_s$ (°C) | Evaporation characteristics | | | | | |
|---|---|---|---|---|---|---|
| | DF | B10 | B20 | B30 | B40 | B50 |
| 250 | Single droplet, evaporates completely, moderate boiling | Single droplet, boiling vigorously, left visible deposit | Single droplet, moderate boiling, | Single-droplet, moderate boiling, left small spot of deposit, more smoke | Single droplet, some droplets evaporate completely, moderate boiling, left tiny spots of deposit | Single droplet, evaporates completely, moderate boiling |
| 260 | | | | | | |
| 270 | | | | | | |
| 280 | | | | | | |
| 290 | | | | | | |
| 300 | | | | | | |
| 310 | | | Almost evaporated completely, small spot left | | | |
| 320 | | | | | | More smoke, boiling vigorously, still single droplet |
| 330 | | | Evaporate completely, more smoke, but still moderate boiling | Almost evaporated completely, vigorously boiling, left a more visible small spot of deposit, more smoke | Still single droplet, more smoke, boiling vigorously, evaporates completely | |
| 340 | Droplet spreads (non-single droplet lookalike) but no splash, boiling vigorously | | | | | |
| 350 | | Non-single droplet, a lot of smoke, a lot of splashes, completely dry deposit/tiny deposit | Evaporate completely, boiling vigorously, more smoke, still single droplet | | | Droplet spreads (non-single droplet lookalike), no splash, evaporates completely |
| 360 | | | | Non-single droplet but not so obvious | Droplet spreads and evaporates like non-single droplet but without splash | |
| 370 | Non-single droplet but not obvious | | Non-single droplet and single droplet appear, vigorously boiling, less splash compared to B10 | Completely evaporate, non-single droplet, big bubble boiling | | Boiling vigorously (bubble), a lot of smoke, evaporates completely |
| 380 | More obvious non-single droplet, more splash compared to B10-B50, more smoke, evaporates completely | | | | Non-single droplet | |
| 390 | | | | More obvious non-single droplet | More obvious non-single droplet, more non-single droplet compared to B30, more smoke | Non-single droplet but not too obvious |
| 400 | | | | Non-single droplet, more splash | | |
| 410 | | | More obvious non-single droplet, more splash | | | More obvious non-single droplet and splash |
| 420 | | | | | | |
| 430 | | | | | | |

As can be seen from the evaporation characteristics profile in Figure 3, the droplet lifetime of all test fuels decreased as the heated plate surface temperature was raised. For DF evaporation, its average evaporation lifetime which was around $t_{life}$=40 seconds was the shortest among other test fuels at $T_s$=250°C. Moreover, the MEP obtained for DF was also the lowest at MEP=360°C. When the hot surface temperature was increased approaching $T_s$=300°C, the average evaporation lifetime of DF became lower than $t_{life}$=10 seconds. However, at a hot plate surface temperature of $T_s$=350°C, a non-single droplet evaporation state occurred and in terms of droplet splashes and smoke produced, DF was greater compared to other fuels.

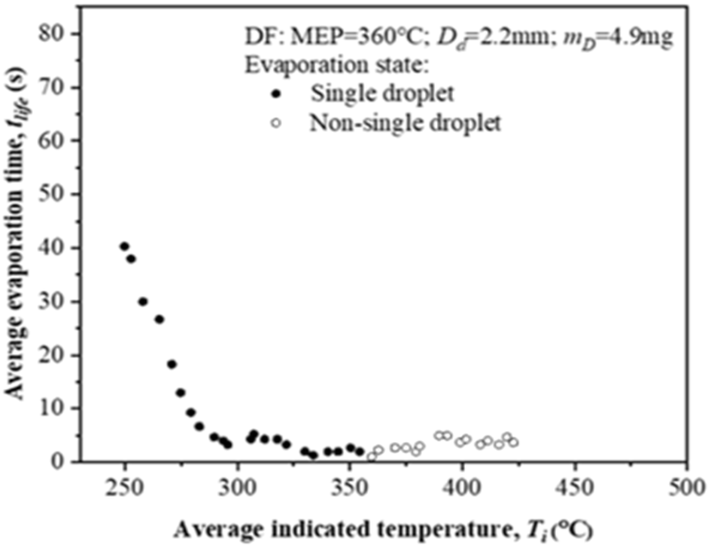

**Fig. 3.** Evaporation characteristics profile of DF

As for B10 fuel in Figure 4, its average droplet lifetime declined gradually with the increase of hot plate surface temperature. The longest droplet lifetime for B10 fuel was around $t_{life}$=61 seconds at a hot plate temperature of $T_s$=250°C. Moreover, the non-single droplet evaporation state occurred below the hot plate surface temperature of $T_s$=350°C. The MEP obtained for B10 fuel was MEP=365°C, which is higher compared to that of DF. In addition, the plate surface temperature in which the non-single droplet evaporation state occurred was also lower than the MEP for B10 fuel. In terms of deposit splashes and smoke produced, these occurrences were significantly visible after the hot plate surface temperature exceeded $T_s$=350°C.

At plate surface temperature of $T_s$=250°C, the droplet lifetime of B20 fuel was around $t_{life}$=61 seconds, which was longer than that of DF and B10 fuel. This is clearly shown in Figure 5. The MEP obtained for B20 fuel was MEP=375°C, which was higher than DF and B10 fuel. As can be seen in the figure, the non-single droplet evaporation state existed after the hot plate surface temperature exceeded $T_s$=350°C, however, still less than the obtained MEP for B20 fuel. As for B10 fuel, deposit splashes and smoke were also more visible after the hot plate surface temperature exceeded $T_s$=350°C.

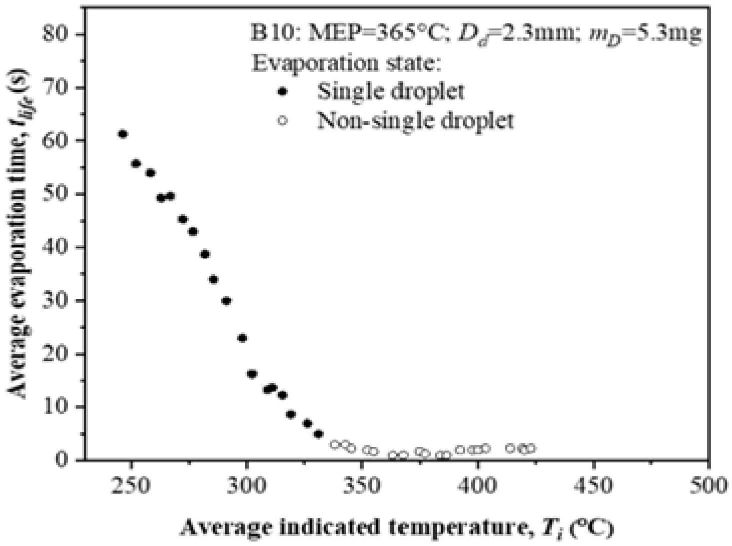

**Fig. 4.** Evaporation characteristics profile of B10

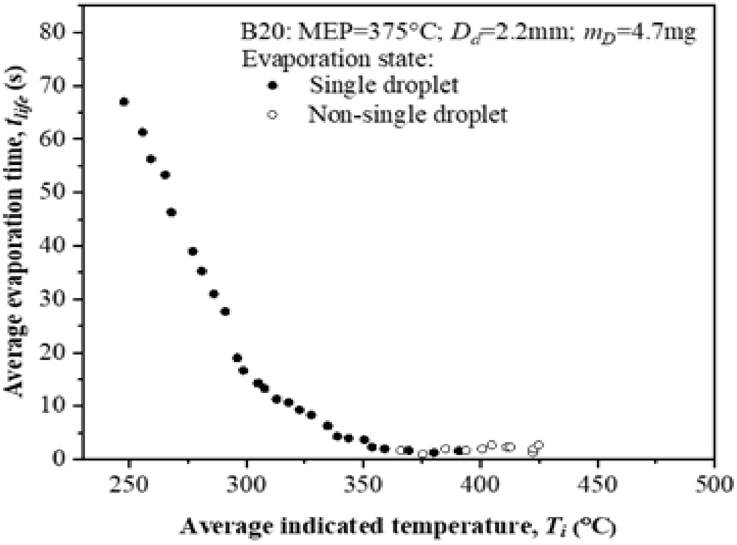

**Fig. 5.** Evaporation characteristics profile of B20

In Figure 6, the MEP obtained for B30 fuel was MEP=385°C, which was the highest among the test fuels, and a non-single droplet evaporation state was observed after the hot plate surface temperature reached around $T_s$=350°C, which is significantly lower than the obtained MEP. Additionally, when compared to fuel with a higher blend ratio (B40 and B50), the longest droplet lifetime was recorded for B30 fuel which was around $t_{life}$=75 seconds at hot plate surface temperature $T_s$=250°C. This shows that biodiesel content in B30 fuel has a greater influence on its evaporation profile than that of its DF component at a lower wall temperature before the MEP region. Furthermore, at a hot plate surface temperature around $T_s$=350°C, more smokes were produced. Meanwhile, deposit splashes became more obvious at hot plate surface temperature around $T_s$=400°C.

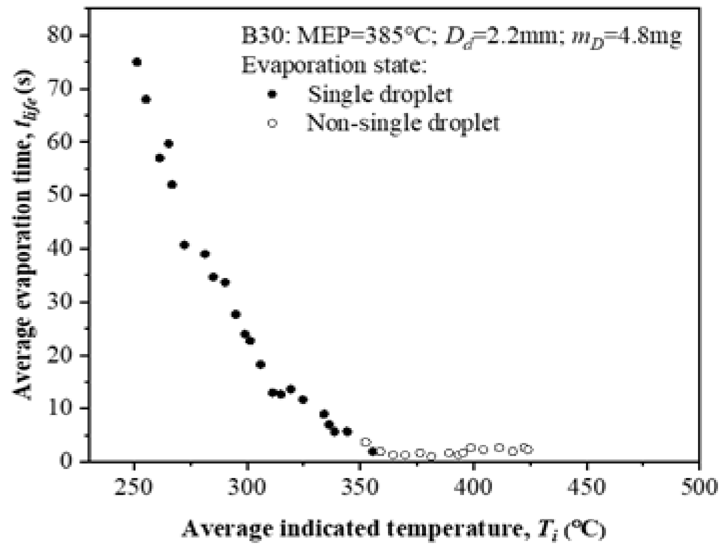

**Fig. 6.** Evaporation characteristics profile of B30

As for B40 fuel in Figure 7, the obtained MEP was MEP=375°C, which is lower compared to that of B30 fuel, even though B40 contains a higher percentage of biodiesel in its mixture. In addition, the non-single droplet evaporation state only existed after the hot plate surface temperature reached around $T_s$=375°C, which is similar to the obtained MEP of B40 fuel. The obtained droplet lifetime was around $t_{life}$=69 seconds at hot plate surface temperature $T_s$=250°C. Furthermore, the evaporation lifetime of B40 fuel decreased the fastest, which was around $t_{life}$=58 seconds at $T_s$=280°C to around $t_{life}$=16 seconds at $T_s$=300°C. This indicates that B40 fuel was mainly affected by its DF component rather than its pure biodiesel content before the MEP region. In terms of smokes and deposit splashes produced, the occurrences were almost identical to that of B30 fuel, in which more smokes were visible at hot plate surface temperature around $T_s$=350°C and deposit splashes became more obvious at hot plate surface temperature around $T_s$=400°C.

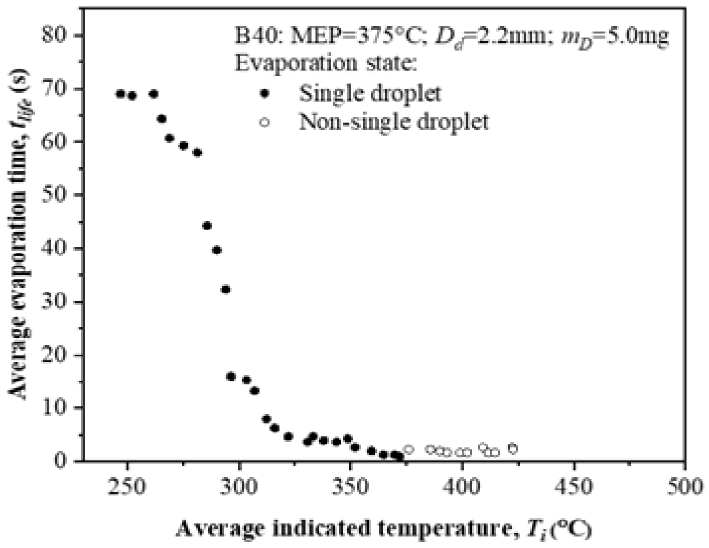

**Fig. 7.** Evaporation characteristics profile of B40

In terms of smoke produced, more smoke was visible after the hot plate surface temperature reached $T_s$=320°C. On the other hand, deposit splashes became more obvious at hot plate surface temperature around $T_s$=400°C. At plate surface temperature of $T_s$=250°C, the droplet lifetime of B50 fuel was around $t_{life}$=67 seconds. In Figure 8, the non-single droplet evaporation state for B50 fuel also occurred at plate surface temperature higher than $T_s$=350°C. Interestingly, the MEP for B50 fuel was MEP=365°C, which was less than that of B20 fuel and B40 fuel, and significantly lower compared to the MEP obtained for B30 fuel. Theoretically, the MEP value should be higher for biodiesel fuel with a higher blend ratio as the density and kinematic viscosity are greater. Despite the effort of storing the fuels in proper containers that were secured firmly and kept away from sources of high temperature, the auto-oxidation process in an atmospheric condition during storage of the fuels may have slightly altered the physicochemical properties of some fuels. Nevertheless, it can be concluded that the evaporation lifetime of fuels decreases as the surface temperature of the heated plate increases [21]. The droplet interval to create wet and dry conditions in the fuel deposition test can also be determined by referring to the MEP value for each fuel. Furthermore, the temperature region in which fewer deposits will develop can be referred from the MEP obtained for each test fuel.

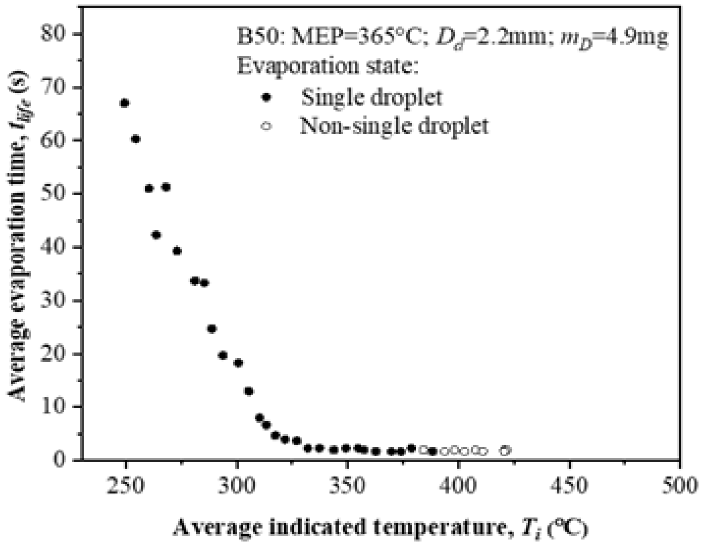

**Fig. 8.** Evaporation characteristics profile of B50

As can be seen from the comparison in Figure 9, the gap between the evaporation profile for B10-B50 fuel is narrower. However, if compared to that of DF, there is a wider gap in DF evaporation profile from other fuels. Furthermore, DF has the shortest evaporation lifetime at $T_s$=250°C. This indicates that the absence of other fuel components in DF makes it evaporate faster than that of fuels with biodiesel components. Other than that, above $T_s$=400°C, the evaporation state for all test fuels is non-single droplet evaporation, which means that more droplet splashes will be produced.

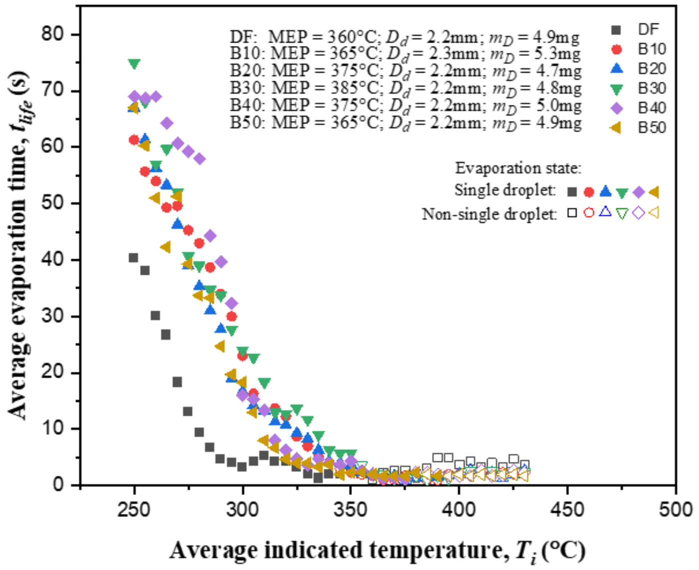

**Fig. 9.** Evaporation characteristics profile comparison

## 4. Conclusions

It was figured out that during the test, there was single and non-single droplet evaporation behavior that was influenced by the hot plate temperature and the type of fuel itself. The temperature region in which the non-single droplet evaporation occurs is important to be identified as it is the region where deposit splashes are produced. Based on the observation of the evaporation behavior, DF droplet evaporation stands out for generating heightened droplet splashes and smoke, potentially leading to increased fuel adhesion on surfaces and augmented deposit formation. The insights into fuel evaporation characteristics offer a valuable understanding of initial wetting, droplet-surface interaction, and droplet lifetime prediction, contributing to explanations of deposit buildup on heated surfaces. Furthermore, based on the evaporation characteristics test, the obtained MEP was 360°C (DF), 365°C (B10, B50), 375°C (B20, B40), and 385°C (B30). In theory, the MEP value should be higher for fuel with higher biodiesel content as the density and kinematic viscosity are greater. This intricate interplay of temperature, droplet behavior, and fuel type provides valuable insights into the combustion characteristics and performance variations. Additionally, these MEP values are used in determining the suitable experiment parameters (hot plate temperature and droplet interval) of the fuel deposition test.

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