



Evaporation Characteristics of Diesel and Biodiesel Fuel Droplets on Hot Surfaces

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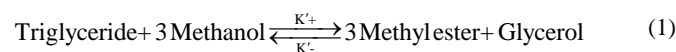
ABSTRACT

In CI engines, the evaporation rate of fuel on various hot surfaces, including the combustion chamber, has a significant effect on deposit formation and accumulation, the exhaust emissions of PM and NO_x, and their efficiency. Therefore, the evaporation of liquid fuel droplets impinging on hot surfaces has become an important subject of interest to engine designers, manufacturers, and researchers. The aim of this study is to investigate the evaporation characteristics based on droplet lifetime and critical surface temperature (the maximum heat transfer rate) of diesel and biodiesel fuel droplets on hot surfaces. In order to determine the effects of diesel fuel, canola oil biodiesel, and castor oil biodiesel, the droplets impinging on the hot surfaces of aluminum alloy (7075) and steel alloy (1.5920) and the evaporation lifetime of diesel and biodiesel fuels were measured. Statistical analysis (ANOVA and Duncan's multiple-range test) was carried out using SAS software. The results showed the maximum critical surface temperature of 450 °C for the castor oil biodiesel on steel 1.5920 surface and the minimum one for diesel fuel (350 °C). In this case, both surfaces had the same droplet lifetimes of approximately 2 s. The results of ANOVA showed the significant effect of the surface material and fuel type on the evaporation lifetime of fuel droplet at 1 % probability.

1. INTRODUCTION

The reduction of fuel resources and the environmental problems caused by the excessive use of fossil fuels have led to many environmental repercussions. In order to overcome these environmental problems and provide sustainable energy, various approaches have been developed, the most notable of which include increasing the fuel conversion efficiency and its replacement with renewable resources.

One of the renewable fuel types, which can be used as an alternative to fossil fuels in diesel engines, is biodiesel derived from vegetable oils and animal fats. It is worth mentioning that the invented engine by Rudolf Diesel was ignited using peanut oil for the first time [1]. Direct use of vegetable oils and animal fats has many disadvantages due to their high viscosity [2,3]. Therefore, many studies conducted so far have aimed to reduce the viscosity level of such renewable resources and optimize them to be applied as fuels for diesel engines. The methods used to reduce the viscosity include microemulsions, pyrolysis, and transesterification [3–5]. The most commonly used method, which is substantially significant in terms of both research and commerce, is transesterification. As represented in Equation 1, a mole of triglyceride with three moles of alcohol in the presence of a catalyst was converted to one mole of glycerol as a valuable byproduct and biodiesel, which is defined as the mono-alkyl esters of vegetable oils or animal fats [6].



The methyl ester produced through the transesterification reaction ought to meet the fuel standard requirements such as ASTM D6751 and EN14214 so as to be accepted as standard

biodiesel fuel. In addition to the aforementioned standards, there are other important characteristics, too. For instance, an important parameter is the fuel evaporation. The evaporation of liquid fuel droplets impinging on hot surfaces is the subject of interest to engine designers, manufacturers, and researchers. In compression ignition engines, the evaporation rate of fuel on various hot surfaces, including the combustion chamber, has an important effect on exhaust emissions, such as PM and NO_x, and their efficiency.

The literature review revealed a number of studies on the evaporation behavior of fuel droplets on hot surfaces. Mizomoto et al. (1978) investigated the evaporation process of n-cetane and n-heptane droplets with a diameter of 2 mm on a stainless steel hot surface. They found that the evaporation process could be divided into different regions. With an increase in the hot surface temperature (in the range of 300 °C to 600 °C), the modes of droplet evaporation including the film evaporation region, the boiling evaporation region, the transition region, and the spheroidal evaporation region will change [7]. Abu-Zaid (1994) studied the evaporation time durations of gasoline and diesel droplets impinging on different surfaces made of different materials (aluminum, stainless-steel, carbon-steel, ceramic MgO, and kaolin). He reported that, at the same surface temperature, the time required for the droplets to evaporate on the porous materials (MgO and Kaolin) was shorter than that on the metallic materials (aluminum, stainless-steel, and carbon-steel) [8]. In a research study, Fardad and Ladommatos (1999) studied the evaporation of various single- and multi-component hydrocarbon compounds on hot surfaces. The results revealed that the minimum amount of time required for droplet evaporation for gasoline, diesel fuel, and a hexane–octane mixture was the same (about 1 s). In addition, it was observed that increasing the surface roughness enhanced the evaporation rate [9]. Arifin et al. (2008) and Arifin and Arai

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(2009) studied the state of fuel evaporation on a hot surface made of aluminum alloy (JIS 2017S). In this study, the evaporation characteristics of dodecane, diesel, and palm oil methyl ester were investigated by defining the maximum evaporation rate point (equal to critical temperature point in this study), which is equal to the minimum lifetime of the droplet. The investigation of evaporation features close to the maximum evaporation rate point and beyond the maximum evaporation rate point showed no obvious differences between the diesel and palm oil ester features. However, some notable differences were observed in the features of dodecane, which could be attributed to multi- and mono-component structures of these fuels. Furthermore, in this study, the diesel fuel (DF), Philippines national standard diesel fuel (contains 1 % of coconut oil methyl ester) (DFP), palm oil methyl ester (B100P), and coconut oil methyl ester (B100C) were investigated in terms of evaporation characteristics. The obtained results revealed that DF and DFP showed a similar behavior in terms of the droplet lifetime profile before reaching the maximum evaporation rate point. Yet, DFP reached a slightly lower point than the maximum evaporation rate point and obtained a longer droplet lifetime at this point. Taking the behavior of B100C into consideration, one could notice a shorter droplet lifetime before the maximum evaporation rate point, compared to that of the B100P. Meanwhile, the maximum evaporation rate point for B100C was far lower than that for B100P, DF, and DFP [10,11].

The synthesized biodiesel's Physiochemical properties (viscosity, surface tension, and so on) are affected by the feedstocks used in the production process. These properties are significant in terms of the evaporation characteristics of the biofuel. To date, the examination of renewable fuels derived from different oils in terms of evaporation on hot surfaces has received scant attention. In addition, almost no such study has statistically analyzed the matter so far.

In the present study, the evaporation behavior of two renewable fuels (castor oil methyl ester and canola oil methyl ester) on aluminum alloy 7075 and steel 1.5920 surfaces is evaluated. The reason for choosing the methyl esters of these two vegetable oils is the significant difference in their viscosity, which can affect their behaviors. Aluminum alloy 7075 and steel 1.5920 were chosen due to their application in components related to the combustion chamber of internal combustion engines, especially in diesel engines.

2. MATERIALS AND METHODS

2.1. Materials

The oils used to produce biodiesel in the current study include canola oil and castor oil, which were purchased from the market. The fatty acid profiles of these oils were determined using Metcalfe method [12,13]. The alcohol required for producing biodiesel was the methanol made by Merck Company with 99.9 % purity. Moreover, the catalyst used was the hydroxide potassium produced by Merck Company with 99.99 % purity. The diesel fuel used was diesel No. 2, which was obtained from a gas station. Table 1 gives some of the important properties of the diesel fuel used in this research work.

2.2. The test equipments

The used experimental apparatus for droplet evaporation is shown in Figure 1. The hot surfaces were flat plates with a

raised edge to avoid jumping out of the droplet. The surfaces are made of aluminum alloy 7075 and steel 1.5920. The surface roughness of each plate was measured by MarSurf M300+RD 18, Mahr Co, Germany. The arithmetic average surface roughness (R_a) rates of the surfaces made of aluminum alloy 7075 and steel 1.5920 are 0.6 μm and 0.2 μm , respectively.

Table 1. Important properties of the test diesel fuel (measured).

Item	Unit	Amount
Density	kg/m ³ at 15 °C	830
Kinematic viscosity	mm ² /s at 40 °C	2.88
Flash point	°C	77
Final boiling point	°C	350

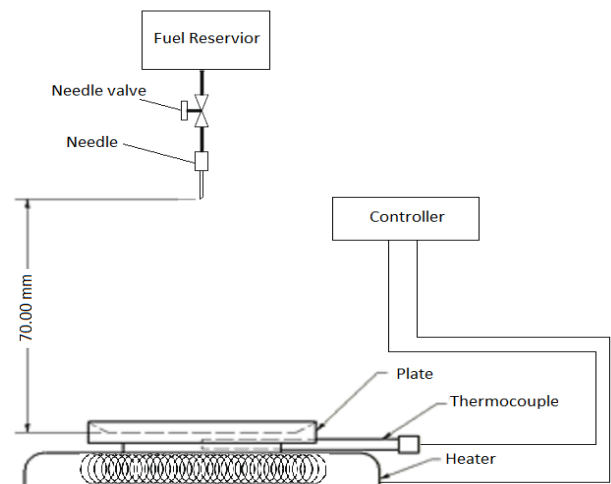


Figure 1. Schematic of an experimental apparatus used in this study.

A radius hole was considered for each surface for the temperature measurement by a thermocouple (J type, ± 2.5 °C accuracy, JUMO, Germany). The hole was placed because the tip of the thermocouple must be 2 mm below the surface. Using the thermocouple, a controller (TZ4ST, ± 0.3 % F.S. accuracy, Autonics, South Korea), and an electric heater, the plate temperature was set to the desired temperature.

A stainless steel needle (G20- 1,1/4") and a needle valve were used as droplet generators. The distance between surface of plate and needle tip was set at 70 mm (trial and error) to avoid the splash loss of impinged droplet and minimize preheating. The average mass of a droplet for diesel fuel, biodiesel of canola, and castor is calculated from the weighing of 100 droplets. The measured values were 5.77 gr, 6.12 gr, and 6.8 gr respectively.

2.3. The tests procedure

To run the experiments, the surface temperature was set to the desired value. To maintain a uniform surface temperature and prevent temperature fluctuations occurred by the surrounding air, a portable transparent insulation chamber was used around the heater and plate in all experiments. Moreover, before starting each experiment, enough time (around 5 min) was given to experimental setup in order to improve the uniformity of the surface temperature. A droplet of the fuel impinged on the center of surface. The lifetime of evaporation droplet is defined either as the duration of droplet hitting the total evaporation (specifically for the mono-component

hydrocarbons) or the case in which no other evaporation occurs. Since the studied fuels in this research were of the multi-component type, the lifetime of droplet for these fuels was considered as the duration of droplet hitting the hot surface until no other evaporation occurred. The lifetime of the droplet was measured using two stopwatches, and the average values were recorded. After conducting each experiment, the surface was cleaned and prepared for further experiments. The temperature ranged from 300 °C to 500 °C at an interval of 25 °C.

2.4. Statistical analysis

All the experiments were repeated three times. The data was statistically analyzed using three completely randomized factors designed to determine the effects of hot surface materials, fuel types, and temperature of surfaces (independent parameters) on the droplet lifetime as the dependent parameter. Moreover, Duncan's multiple range tests were used to compare whether the mean values of the droplet lifetime varied significantly or not when the hot surface materials and fuel types changed. Common letters were used to show no significant difference at a probability level of 5 % between the mean values. Spreadsheet software of Microsoft EXCEL 2007 and SAS 9.2 software were used to analyze the data.

3. RESULTS AND DISCUSSION

3.1. Characteristics of produced biodiesel

The fatty profile of biodiesel base oils is given in Table 2. Moreover, some of the physical characteristics of the biodiesel produced from these oils are given in Table 3.

Table 2. Fatty acid composition (wt %) of the used oils.

Fatty acid	Canola oil	Castor oil
Palmitic acid	6.1	1.1
Stearic acid	2.2	0.9
Oleic acid	60.5	3.2
Linoleic acid	19.5	4.6
Linolenic acid	9.1	-
Ricinoleic acid	-	88.2
Others	2.6	2

Table 3. Some properties of synthesized Canola and Castor biodiesel fuels.

Item	Unit	Accuracy	Amount	
			Canola oil biodiesel	Castor oil biodiesel
Methyl ester content	% mass		97.2	96.6
Density	kg/m ³ at 15 °C	1 kg/m ³	867	909.6
Kinematic viscosity	mm ² /s at 40 °C	±0.1 mm ² /s	4.63	14.9
Flash point	°C	±1 °C	175	196

The properties of the vegetable oils and their biodiesels, given in tables 2 and 3, were measured at Renewable Energy Research Institute of Tarbiat Modares University laboratories. The data of fatty acids given in Table 2 were measured by a

Perkin-Elmer Clarus 580 gas chromatograph (GC) instrument, operating under conditions of the EN 14103 standard. The methyl ester content of biodiesels given in Table 3 was also measured by the GC under conditions of the EN 14103 standard. The density and kinematic viscosity were measured by an Anton Paar-SVM 3000 viscometer. The flash point was measured by an MINIFLASH FLP/H/L Grabner Instrument according to the methods described in ASTM D 93.

3.2. The effects of temperature on the droplet lifetime

Figure 2 illustrates the trend of evaporation related to diesel fuel droplets on hot surfaces. As shown in this figure, an increase in surface temperature results in a sudden reduction in droplet lifetime; therefore, an increase in the temperature from 300 °C to 350 °C leads to a reduction in droplet lifetime by about 5 times (i.e., reducing 9.8 seconds to 1.81 seconds). The 350 °C temperature is called the "critical temperature point", because it is at this point where the minimum droplet lifetime occurs. By increasing the temperature at this point, the evaporation rate decreases and the droplet lifetime increases to some degrees. This occurs as a result of the evaporation regime change from nucleate boiling to transition regime [14,15].

According to this figure, for both aluminum and steel surfaces, the diesel fuel evaporation is similar. At a temperature of 350 °C, the critical temperature points (equal to the droplet's minimum lifetime or the maximum evaporation point) for diesel fuel on aluminum and steel surfaces were 1.81 s and 1.97 s, respectively. As expected, since the critical temperature points on both surfaces were equal, it could be concluded that the critical temperature point was independent of the surface material.

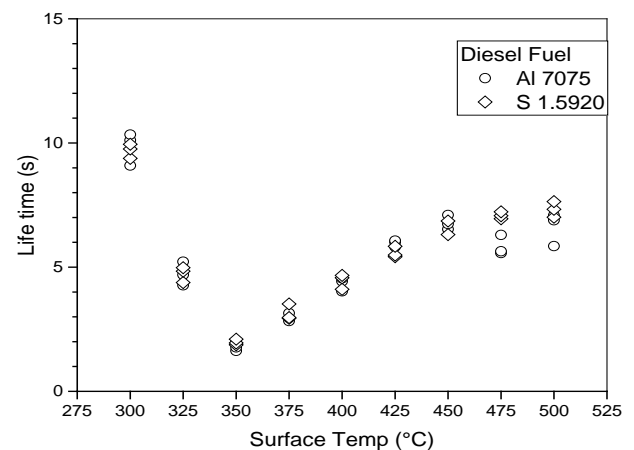


Figure 2. Droplet evaporation lifetime for diesel fuel.

Arifin and Aray (2010) examined the diesel fuel evaporation on the aluminum surface (JIS 2017S). They found that the vapor bubble and splash droplets occurred at temperatures lower than the critical temperature point, and the vigorous boiling occurred at temperatures close to the critical temperature point. In addition, the evaporation was identified to be of vapor layer type at temperatures greater than the critical temperature point. Accordingly, the formation of a thin layer of vapor between the hot surface and the evaporating liquid phase resulted in a relative increase in droplet lifetime [16]. The results reported by Fardad and Ladomatou (1999) and Revankar (2017) indicated a similar evaporation trend for diesel fuel on the surfaces of aluminum and stainless steel materials [9, 15]. Moreover, Abu-zaid (2004) reported the

critical temperature point of diesel fuel on the aluminum surface at 345 °C [17]. The findings of the present study are in accordance with those reported by the aforementioned studies.

Figure 3 shows the evaporation characteristics of the canola oil biodiesel fuel. At temperatures ranging from 300 °C to 350 °C, the evaporation of canola oil biodiesel fuel on the steel surface occurred at a level greater than that of the aluminum surface. Additionally, by increasing the temperature from 300 °C to 325 °C, the fuel droplet lifetime on the aluminum and steel surfaces reduced 3 times (reduction from 20.1 s to 6.74 s) and 1.7 times (from 26.58 s to 15.6 s), respectively. When the temperature increased up to 375 °C, the evaporation of canola oil biodiesel fuel droplets occurred on both surfaces nearly to the same degree. The critical temperature points observed on the aluminum and steel surfaces are 2.25 s and 1.14 s, respectively, at 400 °C.

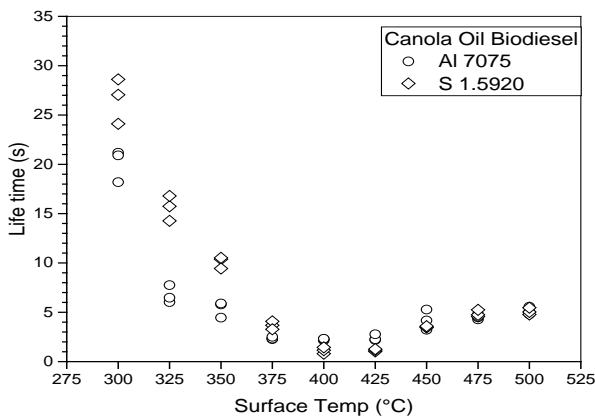


Figure 3. Droplet evaporation lifetime for canola oil biodiesel.

The comparison of evaporation trends of diesel fuel and the canola oil biodiesel fuel reveals that the droplet evaporation of these two fuels on both aluminum and steel surfaces follows a similar trend. The only difference is that the critical temperature point for the canola biodiesel fuel is about 50 °C greater than that of the diesel fuel.

In the present study, as reported by Arifin and Aray (2009), the evaporation trend of canola oil biodiesel on steel surfaces was similar to that of the coconut biodiesel fuel on aluminum surfaces.

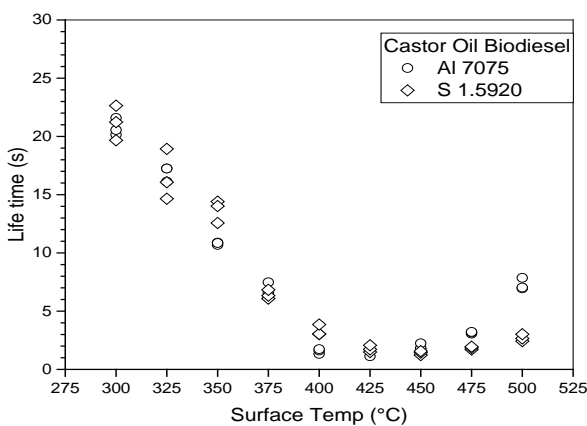


Figure 4. Droplet evaporation lifetime for the castor oil biodiesel.

The evaporation characteristics of the castor oil biodiesel fuel are represented in Figure 4. Although the critical temperature point was reached at the same temperature on both surfaces for the two previously mentioned fuels, the critical temperature point for the castor oil biodiesel fuel was

reached at 425 °C and 450 °C on aluminum and steel surfaces, respectively. As depicted in this figure, the evaporation of castor oil biodiesel fuel occurred at temperatures greater than those of the canola biodiesel fuel, which could be attributed to the greater boiling point of fatty acid methyl ester as castor oil biodiesel (ricinoleate ca. 412 °C at 760.00 mm Hg) than that of the fatty acid methyl ester as canola biodiesel (methyl oleate ca. 352 °C at 760.00 mm Hg).

To gain a better understanding, the values of the critical temperature point for the fuels used on different surfaces are given in Table 4. According to the table, the critical temperature point of biodiesel fuels, compared with diesel fuel, is reached at higher temperatures. In an engine using diesel fuel blended with biodiesel fuel, there might be wall wetting. To prevent this undesirable effect, engine designers should take this issue into consideration.

Table 4. The critical temperature point of diesel and biodiesel fuels on the hot surfaces.

Fuel Type	Surface material	
	Al 7075	Steel 1.5920
Diesel	350 °C	350 °C
Canola oil biodiesel	400 °C	400 °C
Castor oil biodiesel	425 °C	450 °C

3.3. Results of the statistical analysis

The results of the analysis of variance (ANOVA) with respect to the type of surface material, fuel type, and surface temperature (independent parameters) on the evaporation time (dependent parameter) are given in Table 5. As shown in the table, the simple effects of the independent parameters and their interaction on the evaporation time are significant.

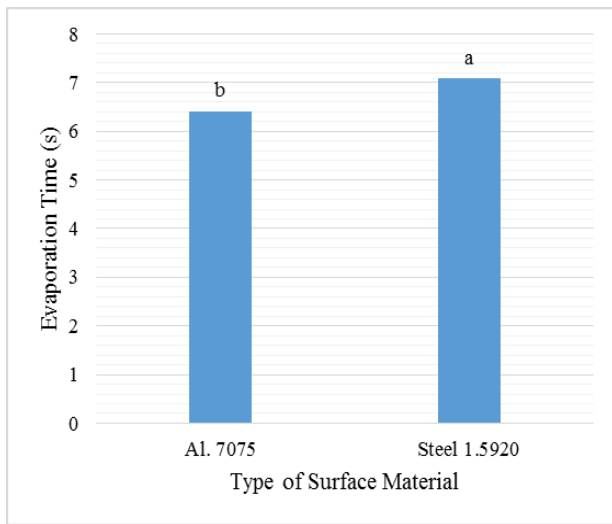
Table 5. Analysis of variance (ANOVA) of parameters effective in the time of evaporation.

Source	Degree of freedom	Mean sum of squares
Type of surface material	1	19.15**
Fuel type	2	67.86**
Temperature of surface	8	433.7**
Type of surface material × Fuel type	2	19.67**
Type of surface material × Temperature of surface	8	10.10**
Fuel type × Temperature of surface	16	95.5**
Type of surface material × Fuel type × Temperature of surface	16	8.65**
Error	106	

**stands for significant at 1 % probability level.

Figure 5 indicates the results of Duncan’s multiple range test to compare the mean values of the evaporation time with the type of surface material. As illustrated in this figure, the type of the surface material had a significant effect (at a 5 % probability level) on the fuel evaporation time. The evaporation time on the steel surface has a greater mean than that on the aluminum surface, indicating that the evaporation of fuels from the aluminum surface occurs faster. Abu Zeid (1994) stated that the droplet evaporation from a hot surface

was strongly dependent upon thermal diffusivity of surface material. He also proposed that, with an increase in the thermal diffusivity of the material, the evaporation time decreased, or vice versa.

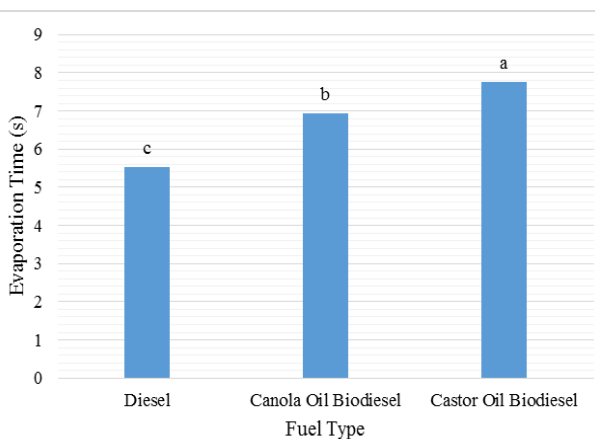


Un-common letters imply that there are significant differences between means at a 5 % probability level.

Figure 5. The effects of type of surface material on the evaporation time.

In the present study, the thermal diffusivities of aluminum and steel are 4.83×10^{-5} and 4.53×10^{-6} m²/s, respectively; therefore, it could be concluded that this is the main reason for the higher evaporation rate on aluminum surface than that on steel surface.

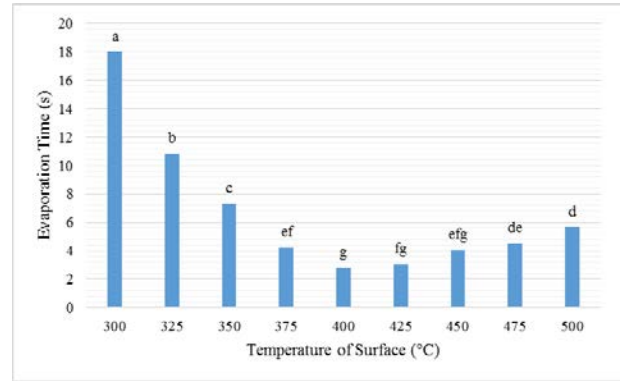
The results of comparing the means through Duncan's method for different fuels are depicted in Figure 6. According to the findings, the fuel type has a significant effect (at a 5 % probability level) on the fuel evaporation on the hot surface. The maximum and minimum evaporation time durations were measured for the castor oil biodiesel fuel and diesel fuel, respectively. The evaporation time of canola oil biodiesel fuel has a mean ranging between two categories of the tested fuels.



Un-common letters mean that there are significant differences between means at a 5 % probability level.

Figure 6. The effects of fuels type on the evaporation time.

The results of Duncan's multiple range tests to compare the mean values of the evaporation time versus surface temperature are given in Figure 7.



Un-common letters mean that there are significant differences between means at a 5% probability level.

Figure 7. The effects of the surface temperature on the evaporation time.

According to the results, increasing the surface temperature in the range of 300 °C to 400 °C significantly decreases the evaporation time ($P < 0.05$) from 18 s to 5.7 s. However, the evaporation time increases significantly if the surface temperature increases.

The interaction effects of the surface type by fuel type on the evaporation time are given in Table 6. Although canola oil biodiesel on the steel surface experienced the maximum evaporation time (7.97 s), it can be observed that the evaporation time for castor oil biodiesel on both surfaces was not insignificantly different through this treatment. On the other hand, the evaporation time of diesel fuel on the aluminum surface was the minimum one (5.43 s). Additionally, the evaporation time for the steel diesel fuel and canola oil biodiesel on the aluminum surface was not significantly different.

Table 6. Interaction effects of fuel type × surface type on the evaporation time of fuel droplets.

Type of surface material	Fuel type		
	Diesel	Canola biodiesel	Castor biodiesel
Al. 7075	5.43 ^b	5.91 ^b	7.84 ^a
St. 1.5920	5.63 ^b	7.97 ^a	7.65 ^a

Un-common letters mean that there are significant differences between means at a 5 % probability level.

Table 7 shows the interaction effects of the surface temperature by surface material type on the evaporation time. The maximum evaporation time (19.15 s) was related to the surface temperature of 300 °C on the steel surface, and the minimum evaporation time (2.72 s) was observed at a surface temperature of 400 °C on the surface with aluminum material. Increasing the surface temperature from 300 °C to 350 °C on the aluminum surface and increasing the surface temperature from 300 °C to 375 °C on the steel surface caused a significant decrease in the evaporation time.

As given in Table 7, in the temperature range of 300 °C to 350 °C, the evaporation time of steel surface was significantly ($P < 0.05$) longer than that of the aluminum surface at each temperature level; in other words, the droplet lifetime varies on the surface materials at low surface temperatures. The difference of droplet lifetime on different surface materials at lower temperatures could be attributed to some physical

phenomena such as spreading and so on. In the temperature range of 375 °C to 500 °C, there were no significant differences between the evaporation times of aluminum and steel surfaces at each level of temperature; in other words, at high surface temperatures, the lifetime is independent of surface materials. At high temperatures, the wettability of the fuel droplet on the hot surfaces decreased.

Table 7. Interaction effect of surface temperature × surface type on the evaporation time of fuel droplets.

Surface temperature (°C)	Type of surface material	
	Al. 7075	St. 1.5920
300	16.9 ^b	19.15 ^a
325	9.45 ^d	12.29 ^c
350	5.99 ^{ef}	8.58 ^d
375	4.04 ^{fgh}	4.41 ^{efgh}
400	2.72 ^h	2.97 ^h
425	3.28 ^{gh}	2.83 ^h
450	4.32 ^{fgh}	3.87 ^{gh}
475	4.51 ^{efgh}	4.59 ^{efgh}
500	6.35 ^e	5.04 ^{efg}

Un-common letters mean that there are significant differences between means at a 5 % probability level.

The interaction effects of the surface temperature by fuel types on the evaporation time are given in Table 8.

Table 8. Interaction effects of surface temperature × fuel type on the evaporation time of fuel.

Surface temperature (°C)	Fuel type		
	Diesel	Canola biodiesel	Castor biodiesel
300	9.77 ^{cd}	23.34 ^a	20.97 ^a
325	4.73 ^{fghi}	11.18 ^c	16.71 ^b
350	1.89 ^{jk}	7.74 ^{de}	12.24 ^c
375	3.06 ^{hijk}	3.03 ^{hijk}	6.58 ^{ef}
400	4.39 ^{fghij}	1.69 ^k	2.44 ^{ijk}
425	5.78 ^{efg}	1.79 ^{jk}	1.61 ^k
450	6.73 ^{ef}	3.88 ^{ghijk}	1.68 ^k
475	6.46 ^{efg}	4.69 ^{fghi}	2.49 ^{ijk}
500	6.97 ^{ef}	5.13 ^{efgh}	4.99 ^{fghi}

Un-common letters mean that there are significant differences between means at a 5 % probability level.

For the castor biodiesel, by increasing the surface temperature from 300 °C to 400 °C, the evaporation time decreased significantly ($P < 0.05$). The further increment of the surface temperature to 500 °C caused an insignificant increase in the evaporation time. For the canola oil biodiesel, the increment of the surface temperature in the range of 300

°C to 375 °C reduced the evaporation time significantly ($P < 0.05$). For diesel fuel, increasing the surface temperature from 300 °C to 350 °C caused a significant ($P < 0.05$) decrease in the evaporation time, while the evaporation time increased significantly due to the further increment of the surface temperature.

4. CONCLUSIONS

The conclusions drawn from this research work are as follows:

1. The simple effects of surface material, fuel type, and surface temperature parameters and their interaction effects were significant on the evaporation lifetime of fuel droplets.
2. For the steel surface, the evaporation time of biodiesel fuels was significantly greater than that of the diesel fuel, while, on the aluminum surface, the evaporation time of castor oil biodiesel was significantly greater than that of the canola biodiesel and diesel fuels.
3. The droplet lifetime at high temperatures was not dependent on the surface materials.
4. The value of the critical temperature point for the diesel fuel on both surfaces was 350 °C. In this temperature, the fuel droplet lifetime was about 2 s.
5. The canola oil biodiesel fuel droplet lifetimes on the aluminum and steel surfaces at a temperature of 400 °C were 2.25 s and 1.14 s, respectively.
6. The critical temperature point for the castor oil biodiesel on the steel surface (450 °C) was higher than that on the aluminum surface (425 °C).

5. ACKNOWLEDGEMENT

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