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EVAPORATION BEHAVIOR OF BIODIESEL FUEL DROPLETS UNDER VARYING BLEND RATIOS, SURFACE TEMPERATURES, AND TIP-TO-SURFACE DISTANCES

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ABSTRACT

Deposit formation inside combustion chambers can cause significant engine performance issues. A key factor influencing deposit formation is the evaporation behavior of fuel droplets. This study investigates the evaporation behavior of biodiesel fuel blends (B5, B10, B20), pure biodiesel (B100), and diesel fuel (DF) using high-speed photography. Surface temperatures of 250°C, 357°C, 450°C, and 600°C were examined. Fuel droplets were released from needle tips at 60 mm and 148 mm distances before impinging on a hot surface. Results indicate the dominant droplet evaporation behaviors under each condition. Droplets at 148 mm are smaller than those at 60 mm. At higher temperatures (450 °C and 600 °C), droplets evaporate predominantly in a single-droplet form, supported by a vapor film. These findings provide insight into early-stage fuel deposit formation mechanisms.

Keywords: bio-diesel, evaporation, droplet.

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INTRODUCTION

In combustion engines, fuel droplets vaporize as they absorb heat from surrounding hot gases in the combustion chamber. The evaporation rate is governed by chamber pressure, gas temperature, transport properties, droplet size and volatility, and its velocity relative to the surrounding gas (Barata, 2008; Liu *et al*., 2021; Sirignano, 2010). Unburned fuel droplets adhering to the combustion chamber wall absorb heat directly from the surface and eventually transform into fuel deposits. Thus, in this case, understanding droplet evaporation behavior is significant. Previous studies have extensively characterized droplet behavior for various fluids and explained the underlying mechanisms (Ladommatos & Fardad, 1999; Ghassemi *et al*., 2006; Watchers *et al*., 1966; Engel, 1955; Chandra & Avedisian, 1991; Makino & Michiyoshi, 1984; Yao *et al*., 2022; An *et al*., 2020). Evaporation research shows that droplets undergo nucleate, transition, and film boiling stages, which describe the behavior and lifetime of the droplet under varying Weber numbers (Bernardin *et al*., 1995; Bolle & Moureau, 1976; Akao *et al*., 1980; Ma *et al*., 2019). Studies on biodiesel and diesel fuels indicate that physical properties significantly influence droplet evaporation behavior on hot surfaces (Arifin *et al*., 2008; Arifin & Arai, 2009; Promvongsa *et al*., 2010; Mishra *et al*., 2018; Xu *et al*., 2020). This study examines biodiesel droplet evaporation at different surface temperatures and distances to clarify early-stage evaporation behavior. Investigating droplet–surface interactions is critical to understanding fuel deposition mechanisms. These findings help explain initial deposit formation mechanisms and may guide strategies for reducing deposits in engines.

METHODOLOGY

Experimental Set-up

The apparatus shown in Figure-1 was used to conduct the evaporation test by capturing the photograph of droplet evaporation behavior for biodiesel fuel (B5, B10, B20, and B100) and diesel fuel (DF) droplets when impinging on a hot surface. The apparatus consists of a droplet generator, heater, high-speed camera, and apparatus stand.

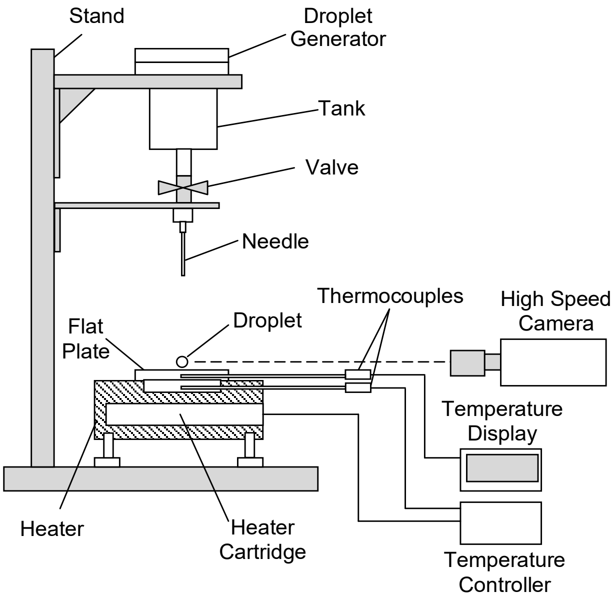

Figure-1. Schematic diagram for fuel droplet evaporation test apparatus.

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The droplet generator consists of a fuel tank, valve, needle, and tube. The needle used has a 0.65 mm outer diameter and is 1.5 inches long. The 4/3 valve and the needle are connected by using a modified 0.5 mL syringe. In order to make sure that the tested fuel flows through the needle, the valve was connected to the fuel tank by using a 10 mm diameter tube. The heater set consists of cartridge heaters, K-type thermocouples, and a flat aluminum alloy plate, which is connected to a temperature display and controller. One of the thermocouples is used to monitor the plate temperature, which is located beneath the hot plate surface. The other thermocouple was used to assist the temperature controller in maintaining the surface temperature of the plate at the desired temperature. Both temperature measurements are shown on the temperature display. In this study, tip-to-surface distance is the distance from the needle tip to the plate surface. The tip-to-surface distances for the experiment are 60 mm and 148 mm. The high-speed camera (Olympus i-speed 2) was used to capture the droplet evaporation behavior in this experiment. The capability of the high-speed camera is up to 33,000 frames per second (fps), and the resolution of this camera is 1,000 fps (800 x 600 pixels). The high-speed camera was used in conjunction with a high-intensity lighting source and a zoom lens.

Experimental Procedure

The droplet evaporation test began by setting the surface temperature using the controller to the desired value. Because the heater can reach up to 700 °C, the desired temperature was gradually achieved in 100 °C increments to maintain stability. Once the target temperature was reached, fuel droplets were released from the needle tip to impact the hot surface. At the same time, the photograph of the droplet evaporation behavior was captured by using a high-speed camera to observe the dominant behavior of the droplet during the evaporation on the hot surface. The high-speed camera was set at 600 fps with a zoom ratio of 1 to 1 and with a shutter speed of 1 μs. High-speed images were analyzed to determine fuel droplet evaporation behavior.

There are five types of fuel that are used for the evaporation test, which consist of the biodiesel blend (B5, B10, B20), pure biodiesel fuel (B100), and diesel fuel (DF). The densities and droplet sizes for each fuel are summarized in Table-1.

Table-1. Fuel's density and droplet diameter.

Fuel	Density (kg/m^3)	Droplet Diameter (mm)
DF	816.28	2.480
B5	835.11	2.432
B10	841.12	2.530
B20	845.06	2.622
B100	880.65	2.672

All types of fuel are tested to observe the evaporation behavior of fuel droplets when impinging on the hot surface. For this experiment, the surface temperatures at 250°C, 357°C, 450°C, and 600°C were set. The tip-to-surface distances used are 60 mm and 148 mm. The main result obtained from the experiment is the droplet behavior photograph during the evaporation process on the hot surface.

RESULTS AND DISCUSSIONS

Droplet Evaporation Behavior

Droplet evaporation behavior for B5, B10, B20, B100, and DF was obtained. The photographs captured were analyzed to determine the dominant evaporation behavior of fuel droplets for various surface temperatures and tip-to-surface distances. Images captured at 66.68 ms were selected to represent the dominant evaporation behavior of each droplet. Figure-2 and Figure-3 show the droplet evaporation behavior at surface distances of 60 mm and 148 mm for B5, B10, B20, B100, and DF, respectively.

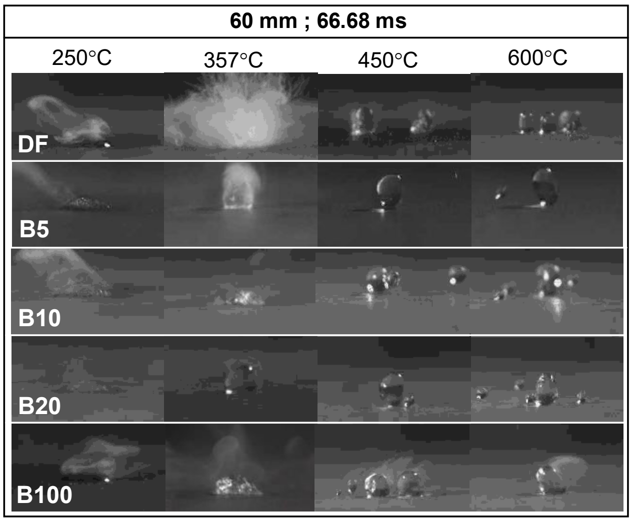

Figure-2. Droplet evaporation behaviors at a tip-to-surface distance of 60 mm.

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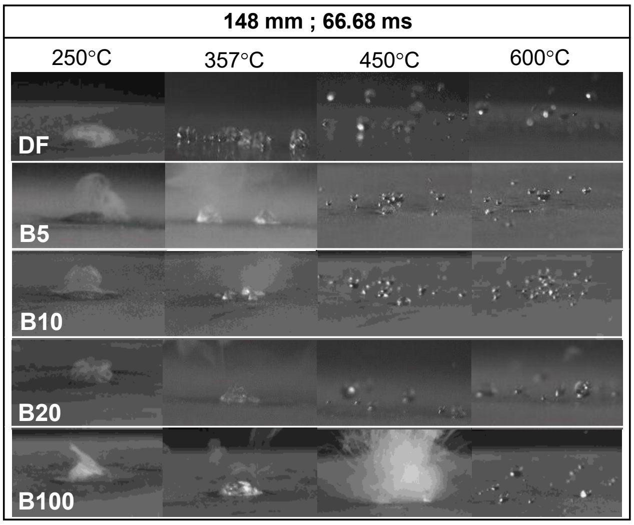

Figure-3. Droplet evaporation behaviors at a tip-to-surface distance of 140 mm.

These figures illustrate the dominant evaporation behavior observed at 66.68 ms, immediately after the droplet completely impinged on the hot surface, considering various surface temperatures and tip-to-surface distances.

However, Figure-4 and Figure-5 show the illustrations of Figure-2 and Figure-3, respectively, to simplify the observations. For a tip-to-surface distance of 60 mm with a surface temperature of 250°C, the impinged droplet was spread on the hot surface to form a lens-shaped fuel film. There were a few small bubbles formed during the evaporation for all tested fuels. As the surface temperature increased from 250°C to 357°C, vigorous boiling occurred for DF, B5, B10, and B100. These indicated that the evaporation occurred in the nucleate boiling regime of evaporation. For DF, the droplet immediately evaporates due to the temperature being the MEP (Maximum Evaporation Point) temperature for DF (Arifin *et al*., 2008). The smoke pattern produced was different from other fuels due to the vigorous boiling that occurred for several breakup droplets with smaller-sized droplets. The splashing of fine droplets occurred during this stage and disappeared after the evaporation was completed.

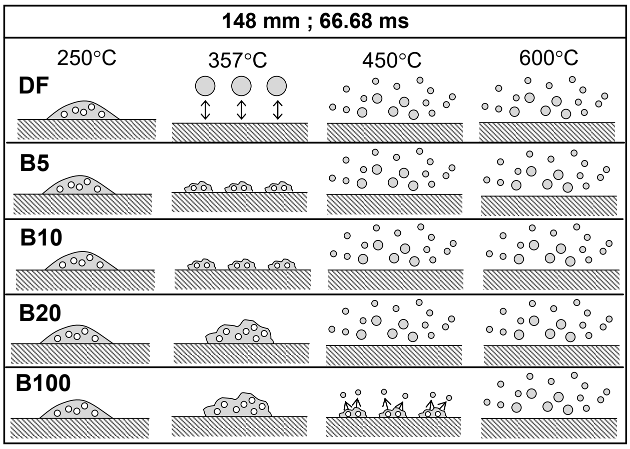

Figure-4. Illustrations of droplet evaporation behaviors at tip-to-surface distance of 60 mm.

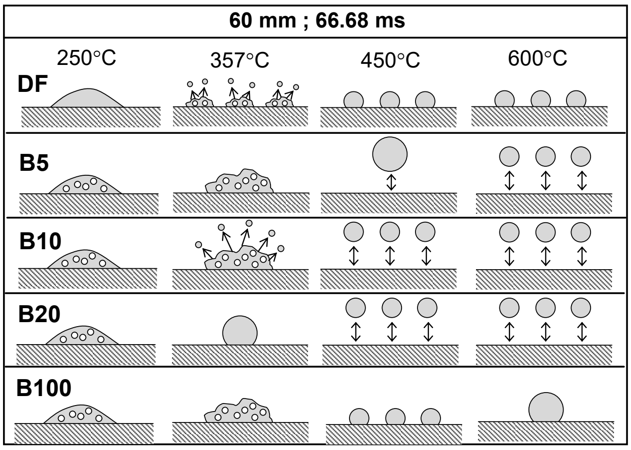

Figure-5. Illustrations of droplet evaporation behaviors at tip-to-surface distance of 140 mm.

B5 It is quite similar to DF in terms of fast, vigorous boiling evaporation, except that B5 evaporates more slowly and evaporates in a single droplet form. However, for B20, the droplet impingement forms a single droplet with a spherical shape during evaporation. When the surface temperature was increased to 450°C. All fuel droplets evaporate, with a few spherical droplets forming on the hot surface except for B5. B5 evaporation starts to appear as a single droplet with a spherical shape, slightly bouncing on the surface. When the surface temperature was set to 600°C, the droplet that impinged onto the hot surface broke up to form a greater number of droplets with smaller droplet sizes for DF, B5, B10, and B20. B5 droplet evaporation at 600°C still tends to show similar behavior to B5 droplet evaporation at a surface temperature of 450°C.

DF and B100 show slightly different behavior at the temperature. Although DF droplets also evaporate with a few smaller spherical droplets, the droplets still attach and stick to the hot surface during the evaporation, which is different from B5, B10, and B20, which bounce on the surface. However, the droplet of B100 formed a single

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droplet that attached to the surface as the surface temperature was at 600°C, as shown in Figure-2. In general, biodiesel blends exhibit breakup behavior, producing smaller droplets during evaporation.

For a tip-to-surface distance of 148 mm, during the evaporation at a surface temperature of 250°C, all tested fuel droplets that impinged on the hot surface were spread on the hot surface to form a fuel film with a bigger contact area with the surface compared with the result for a tip-to-surface distance of 60 mm. There were a few small bubbles formed during the evaporation, as shown in Figure-3, similar behavior to the tip-to-surface distances of 60 mm. For the B100 droplet, the lens shape of the droplet occurred during the initial stage of evaporation for a surface temperature of 250°C. At this point, the bubble didn’t accompany the droplet of B100. However, when the surface temperature increased from 250°C to 357°C, the bubble started to appear within the droplet fuel, indicating that the nucleate boiling regime occurred at this point. As the surface temperature increased to 357°C, B5, B10, and B20 had a broken film of the droplet. The nucleate boiling regime exists at the surface temperature of 357°C for B5, B10, and B20, for which vapor bubble nucleation and growth both cease as broken film. The B100 droplet experienced vigorous boiling without the broken film occurring. However, DF, the evaporation occurred with a few spherical droplets that attached to the surface.

Owing to its lower viscosity and density, diesel fuel droplets tend to break up into smaller droplets at 357 °C. DF droplet evaporation behavior was different from other fuels at the same temperature, where several breakup droplets with a constant smaller size of droplet bounced on the surface. Due to the force of surface tension, the big droplet is regrouping, but all the small droplets tend to break free. At a surface temperature of 450°C, all tested fuels produced smaller breakup droplets with an increased number of fine droplets, except for B100. At this temperature, B100 droplet behavior was similar to DF droplet evaporation behavior at a surface temperature of 357°C with a tip-to-surface distance of 60 mm. Probably at a surface temperature of 450°C, which is close to the MEP temperature for B100. All tested fuels show breakup droplets with a constant smaller size of droplet bouncing on the surface behavior at 600°C, including B100 droplet evaporation. The droplet evaporation for all types of fuels tested showed a similar pattern as mentioned by the research of Bernardin *et al*. (1995), who used water to observe the characteristics of the boiling regime when impinging on a polished surface.

The most obvious difference between the two tip-to-surface distances was the size of droplets formed during evaporation. For a tip-to-surface distance of 148 mm, the droplet size for the breakup droplet is smaller compared to the droplet size for a tip-to-surface distance of 60 mm. The droplet size during the evaporation becomes smaller as the tip-to-surface distance increases. From observation of the result, bio-blended diesel fuels (B5, B10, and B20) show the same droplet evaporation behavior due to the characteristics of biodiesel and diesel in this blend. However, B100 is different, especially from the result of droplet evaporation behavior for a tip-to-surface distance of 60 mm. B100 tends to form a single droplet due to higher viscosity, density, and surface tension than other fuels. However, the diesel fuel shows that the droplet tends to form a breakup droplet due to lower viscosity and density. This result is the same as mentioned in the Arifin *et al*. (2008) study, in which the droplet of both B100 and diesel fuel forms a single droplet and breakup droplets after MEP temperature.

Droplet Evaporation Behavior on Deposit Formation Possibility

In terms of fuel droplet evaporation behavior, there are four types of behavior observed, which are lens-shaped evaporation, vigorous boiling evaporation, single spherical droplet evaporation, and multi-spherical droplet evaporation. These behaviors affect the formation of fuel deposits on a hot surface or wall.

The deposit formation due to fuel droplet impingement on the wall depends on the evaporation period and droplet contact area with the hot surface. All behavior that was observed in this study had different evaporation periods and contact areas with the hot surface, which determined the amount of deposit formation on the surface. Figure-6 shows the possibility of deposit formation and droplet release to the surroundings if the same evaporation behavior occurs in a real engine.

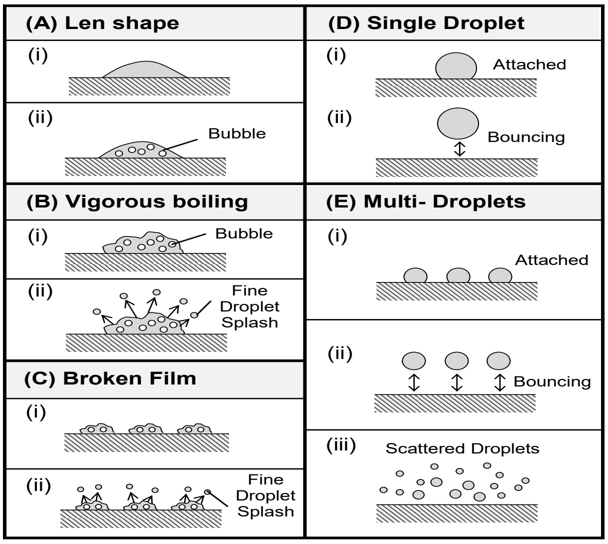

Figure-6. Deposit formation and deposit release to the surrounding environment.

CONCLUSIONS

Generally, at a surface temperature of 250°C, a lens-shaped droplet with a bubble was formed. As the surface temperature increased to 357°C, vigorous boiling with a distorted shape appeared, and it can be indicated as the nucleate boiling regime stage. Bouncing and rolling spherical droplets are formed at a surface temperature of

450°C. During surface temperature at 600°C, the droplet breaks up and forms smaller droplets. The droplet size during the breakup becomes smaller as the tip-to-surface distance increases. B5, B10, and B20 show similar droplet evaporation behavior. B100 tends to form a single droplet due to higher viscosity, density, and surface tension than other fuels. However, the diesel fuel shows that the droplet tends to form a breakup droplet due to lower viscosity and density.

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REFERENCES

Akao F., Araki K., Mori S. and Moriyama A. 1980. Deformation behavior of a liquid droplet impinging on a hot metal surface. Trans. Int. Steel Institute Japan. 20, 737-743.

An S., Kim J., and Lee C. 2020. Evaporation characteristics of diesel and biodiesel droplets on heated surfaces. Fuel. 275, 117936.

Arifin Y. M. and Arai M. 2009. Deposition characteristics of diesel and bio-diesel fuels. Fuel. 88, 2163-2170.

Arifin Y. M., Arai M., Furuhata T. and Masahiro S. 2008. Diesel and bio-diesel fuel deposits on a hot surface. Fuel. 87, 1601-1609.

Barata J. 2008. Modelling of biofuel droplets dispersion and evaporation. Journal of Renewable Energy. 33, 769-779.

Bernardin J. D., Stebbins C. J, and Mudawar I. 1995. Mapping of impact and heat transfer regimes of water drops impinging on a polishing surface. Heat mass transfer. 40(2): 247-267.

Bolle L. and Moureau J. C. 1976. Spray cooling of a hot surface. Multiphase Science and Technology. Hemisphere New York. pp. 1-92.

Chandra S. and Avedisian C. T. 1991. On the collision of a droplet with a solid surface. Proc. RSoc. Lond. 432, 13-41.

Engel O. G. 1955. Water drops collide with a solid surface. J. Res. NBS. 54, 281-298.

Ghassemi H., Baek S. W. and Khan Q. S. 2006. Experimental Study on Binary Droplet Evaporation at elevated pressures and temperatures. Combust.Sci and Tech. 178, 1031-1053.

Ladommatos N. and Fardad D. 1999. Evaporation of Hydrocarbon components, including gasoline and diesel fuel, on heated metal surfaces. Proc. Instn. Mech. Engrs. 213D, 625-645.

Liu B., Zhang Y., Yang L. and Zeng J. 2021. Droplet evaporation and combustion behavior: A comprehensive review. Fuel. 287, 119389.

Ma D., Lin L., Xu M. and Wang Y. 2019. Influence of Weber number on dynamic behaviors of impacting fuel droplets. International Journal of Heat and Mass Transfer. 131, 908-918.

Makino K. and Michiyoshi I. 1984. The behaviour of a water droplet on a heated surface. Int. J. Heat Mass Transfer. 27, 781-791

Mishra P. C., Murugan S., and Nagarajan G. 2018. Experimental studies on evaporation of biodiesel and diesel fuel droplets on hot surfaces. Energy Conversion and Management. 162, 141-150.

Promvongsa J., Vallikul, Fungtammasan, Grehan. 2010. On the evaporation constant of biodiesel-diesel blends: The effect of blending Ratio. J. Metal, Material and Mineral. 20, 43-45.

Sirignano W. A. 2010. Fluid dynamics and transport of droplets and sprays (2nd ed.). Cambridge University Press.

Wachters L. H. and Westerling N. A. J., 1966. The heat transfer from a hot wall to impinging water drops in the spheroidal state. Chem. Engineering Science. 21, 1047-1056.

Xu X., Zheng J., Yang H. and Yan Y. 2020. Influence of surface temperature and droplet size on the evaporation behavior of biodiesel and diesel. Renewable Energy. 145, 2027–2037.

Yao Z., Huang Z. and Hao B. 2022. Experimental investigation on single droplet evaporation behavior of multi-component fuels. Applied Thermal Engineering. 210, 118385.