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Analysis of Straight Vegetable Oil (SVO) Spray Characteristics at End of Injection (EOI)

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Abstract—**The depletion source and the increasing demand of fossil fuel have prompted scientists and researchers to search new alternative fuels for diesel engine. Biodiesel is seen a promising alternative fuel to reduce dependent on conventional diesel fuel. Advantages of biodiesel compared to petroleum-based diesel include high biodegradability, excellent lubricity, higher flash point, no sulfur content and produces less air pollutants. Although biodiesel has many advantages on the fuel properties, the fuel consumption rate or lower horsepower output are still need to be improved. This is due to the differences in fuel properties especially the kinematic viscosity between diesel fuel (GO), biodiesel fuel (BDF) and straight vegetable oil (SVO). In this study, the effect of kinematic viscosity of SVO on the spray behavior at End of Injection (EOI) were investigated. High kinematic viscosity of fuel highly affects the spray characteristics at EOI. In additional, high injection pressure and high kinematic viscosity of SVO apply resistance at nozzle inner hole caused needle lift cannot completely close the nozzle at EOI signal. At the EOI in which the combustion temperature inside chamber reduces promptly, many fuel droplets could not undergo a complete atomization process especially for large size of diameter fuel droplets. This phenomenon result the development of carbon deposition around the nozzle tip area and it will cover the nozzle hole. The development of carbon deposition will affect the fuel flow from nozzle. This study indicates that fuel injection pressure show no effect on SVO spray characteristics at the end of injection. Furthermore, high ambient temperature spray will reduce the kinematic viscosity value of SVO and could improve SVO spray atomization at end of injection.**

Index Terms—**Biodiesel, kinematic viscosity, spray characteristic, straight vegetable oil**

I. Introduction

Biofuel is a renewable resource that are mainly derived from biomass or bio waste such as a vegetable oil or animal fat-based diesel fuel. The use of biofuel fuel may be the solution to the increasing transportation energy crisis. Biofuel fuels perform just as well as regular diesel fuels and can be used with diesel engine with less modification needed. Laboratory tests, as well as road tests, have proven that biofuel fuels have equally horsepower and torque as diesel engines. With the continued rise of fuel prices, biofuel is set to become much more popular as a fuel option in the transportation industries.

Some advantages of biofuel application are engines will last longer when using biofuels. Traditional diesel engines have a much higher rate of engine wear due to oil lubricant problem. Using biofuel could improve lubricity levels inside the engine thus lengthen the engine durability. New regulations require diesel engines to lower sulfur emissions considerably, making biofuel blends much more attractive as a practical fuel to use since it produce less emission compared to fossil fuel [1]-[2]. On the other hand, some disadvantages of biofuel application are biofuel contains less energy value than diesel, leading to reduction of engine power output. Biofuel has yet shown no significant effect on the energy efficiency of any test engine. The energy content per gallon of biofuel is approximately 10% lower than that of petroleum diesel. Vehicles running on biofuel are therefore expected to achieve about 10% fewer miles per gallon of fuel than diesel[3-4]. Other problems include limited oxidation and storage stability, a tendency to form deposits, corrosion issues, cold flow problems and questionable stability from diverse feedstock.

In addition to this research, experiment on spray characteristics of biofuel was done in order to analyze the effect of biofuel kinematic viscosity on fuel spray. Hossainpour et. al [5] conclude that the knowledge of the fuel spray atomization mechanism can be a key issue or a successful simulation of all the subsequent process of mixture formation and eventually combustion and pollutant formation. While Adam et. al. [6]-[7] reported that the characteristics of fuel spray can be obtained using the nano-spark shadowgraph photography technique.

Many know that biofuel fuel has high potential of replacing the usage of diesel. However, biofuel is well known for its high level of the kinematic viscosity. The high level of kinematic viscosity could cause some sort of resistance of fuel flow during fuel injection, effect the spray geometry thus affects the atomization process[8].

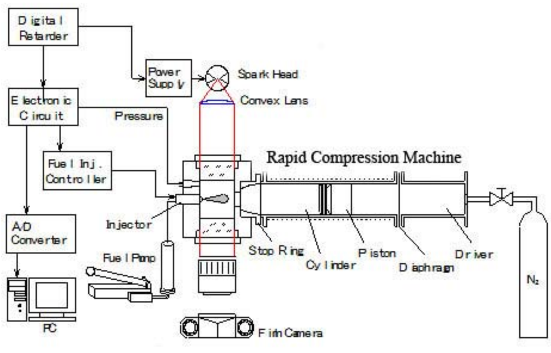

Fig. 1. Schematic diagram of single spark method.

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II. Experimental Setup

In this experiment, the diesel engine atmosphere was created by a rapid compression machine. The diesel spray was injected in a constant volume chamber. The one-shot spray behavior was optically visualized. The experimental apparatus shown in Fig. 1 consists of a spray chamber, a single shot common rail injection system, a rapid compression machine, and a nano-spark photography system.

A. Spray Chamber

Fig. 2 shows a schematic cross-section diagram of a spray chamber. The spray chamber has a diameter of 60mm and a width of 20mm. The spray chamber has upper access for the fuel injector unit and two accesses sized 60mm in diameter. Both accesses were sealed with optical windows which were made of quartz. One side of window was used for the nano spark access and the other side was used for the still camera photography access.

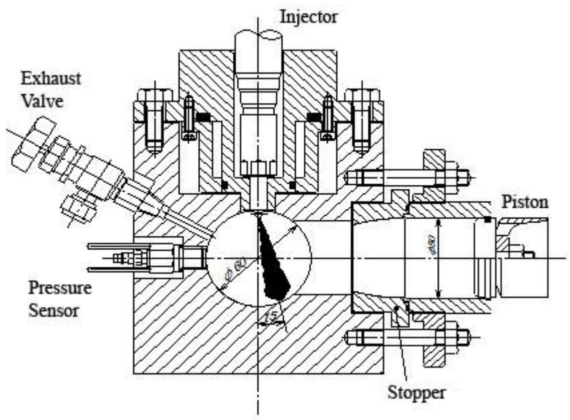

Fig. 2. Cross section of spray chamber.

B. Fuel Injection System

A single-shot common rail fuel injection system was used to inject the fuel into the spray chamber through a single-hole nozzle with hole diameter of d_n=0.18mm at an orientation of 15^o. The injection period was fixed constant at 2.0ms. Fuel used was JIS#2 diesel fuel, biodiesel fuel (BDF) and Solid Vegetable Oil (SVO). By using this system, the injection pressure can be varied in the range of P_{inj}=20~150MPa.

C. Rapid Compression Machine

A rapid compression machine was used to simulate the diesel spray in a constant volume over a wide range of ambient temperatures and pressures conditions, close to actual diesel engines[9]. High pressure N_2 gas in the driver reservoir breaks the diaphragm and drives the piston inside the cylinder section. Then the piston stops at stopper section generating desired ambient condition inside the chamber thus simulating the actual condition inside diesel engine. When the ambient condition reached the required parameter value, a single-shot common rail injection system will inject the fuel into the spray chamber.

D. Nano-spark Shadowgraph Photography Technique

In this setting, Nikon D60 DSLR and prime lens: Nikon 105mm f/2.8 was used and convex lens f=200mm was used to widen the angle of light spark emitted by spark head. ND filter was used in order to reduce by 30% the brightness of light spark emitted by spark head.

III. Test Fuel Properties

Properties of straight vegetable oil (SVO) used in this experiment are shown in Table I. Referring to TableI, kinematic viscosity value measured for SVO fuel at 303K is 47.78mm^2/s compared to 3.3mm^2/s for diesel (GO) fuel. Kinematic viscosity for SVO is almost 14.5 times higher than GO fuel.

TABLE I: Properties Of Diesel Fuel (GO) And Straight Vegetable Oil (SVO)

Fuel and Notation		GO	SVO
Density	g/cm^3	0.827	0.911
Kinematic viscosity	mm^2/s	3.3	47.78
Carbon	wt-	0.86	0.78
Hydrogen	wt-	0.14	0.11
Oxygen	wt-	0	0.11
Lower heating value		42.70	38.14

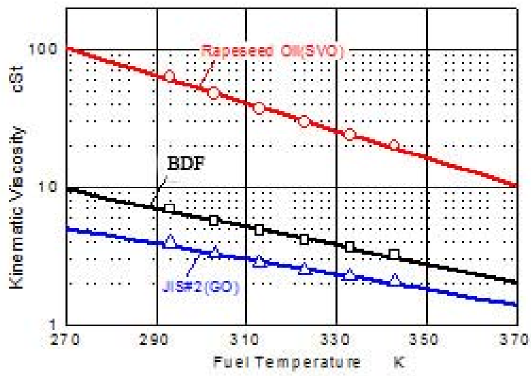

Fig. 3. The effect of fuel temperature on kinematic viscosity.

Pre-experiment was done to analyze the effect of fuel temperature on kinematic viscosity. Referring to Fig. 3, same pattern can be seen in all the test fuel samples of GO, biodiesel fuel (BDF) and SVO where its kinematic viscosity value are declining with the increasing of the fuel temperature.

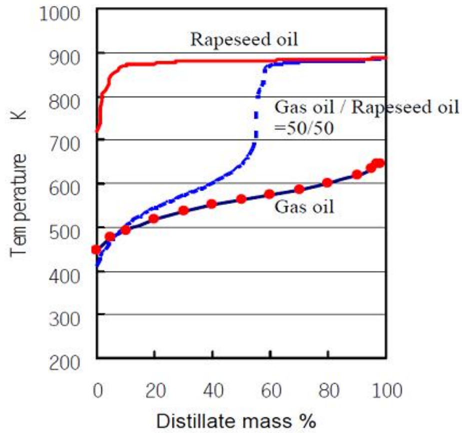

Fig. 4. Distillation characteristic of test fuels.

Fig. 4 shows distillation characteristics of the test fuels. The measurement was strictly done following the JIS K2254 which is Japan Standard Measurement Method for fuel distillation test. The result shows that BDF has 95% high-end distillation component compared to GO. Meanwhile, SVO shows highest distillation measurement among others test fuels. Pre experiments results shows that SVO has highest kinematic viscosity and highest distillation among others test fuels which will affect spray characteristic when injected into engine. Furthermore, Fig. 4 shows that fuel properties change significantly with the temperature, which will affects the spray development and spray penetration.

IV. Results and Discussions

A. Spray Comparison of SVO, BDF and GO

Fig. 5 shows spray images of SVO, BDF and GO fuel taken at ambient temperature T_i=298K, fuel injection pressure P_{inj}=40MPa and time after start of injection t=0.5ms. Referring to the images, SVO spray penetration was obviously shorter than BDF and GO spray. Moreover, narrow spray cone angle can be seen from SVO spray from nozzle tip until spray tip area. No structures like branches formed along SVO spray boundary as can be seen in BDF and GO spray. This is due to the high value of kinematic viscosity for SVO fuel as shown in Table 1. Meanwhile, BDF has similar value of kinematic viscosity compared with GO thus its spray behavior shows similar characteristics with GO spray.

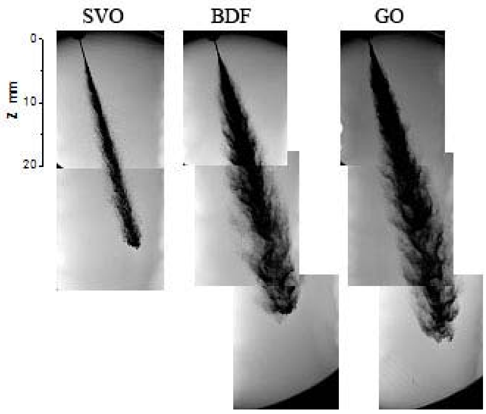

Fig. 5. Comparison of spray structures between SVO, BDF and GO spray (T_i=298K, P_{inj}=40MPa, t=0.5ms).

B. Analysis of Spray Behavior at End of Injection (EOI)

Figure 6 and Figure 7 shows spray images taken at end of injection (EOI) at t_{EOI}=3ms. End of Injection (EOI) t_{EOI} is considered as time start to count as soon as the signal for fuel injection ended. In this research, t_{EOI} starts after 2.0ms from start of injection (SOI). Fig. 6 and Fig. 7 show EOI of both sac volume nozzle 0.28mm^3 and 0.57mm^3 at different injection pressure of 40MPa and 70MPa respectively.

Referring to Fig. 6, t_{EOI}=3ms, P_{inj}=40MPa, GO fuel spray was at state of mist condition while SVO fuel spray shows completely different characteristic where its spray still in form of fuel containing large size of fuel droplets. At the end of injection where temperature inside chamber reduced rapidly, large size of fuel droplets have difficulty to atomize completely thus leading to the development of carbon deposits around the nozzle hole. Low ambient temperature will caused the fuel droplets inside the combustion chamber remain unburnt and incomplete combustion could promotes the formation of solid residuals [10]. This problem become more significant in case of SVO fuel since its kinematic viscosity and distillation characteristics is much higher than GO fuel. From observation, both sac volume nozzle shows same spray characteristic of SVO but sac volume 0.28mm3 nozzle has less number of droplets due to less quantity of fuel remain inside small size of sac volume. Small size sac volume nozzle will improve the atomization process when compared to large size sac volume nozzles due to less number of droplets exist inside combustion chamber at the end of injection. Referring to Fig. 7, at higher injection pressure of P_{inj}=70MPa, same phenomena occurs for SVO fuel where large size of droplets still can be observed. This concludes that increment of injection pressure has no affect for improving end of injection spray condition. Meanwhile, GO fuel spray shows narrower cone angle at higher injection pressure.

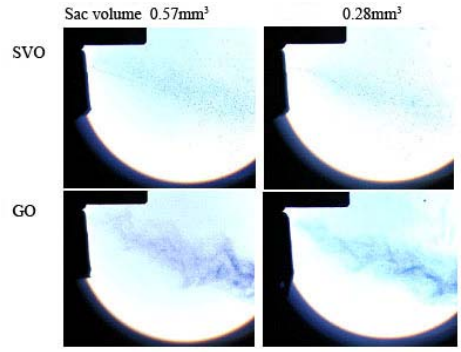

Fig. 6. End of Injection(EOI) spray at t_{EOI}=3ms, P_{inj}=40MPa.

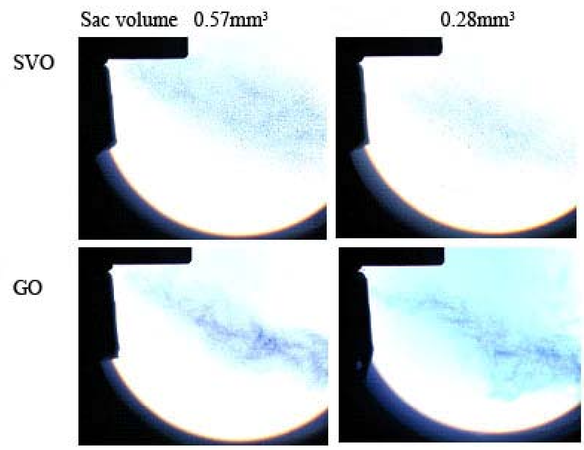

Fig. 7. End of Injection(EOI) spray at t_{EOI}=3ms, P_{inj}=70MPa.

Fig. 8 and Fig. 9 shows images taken at t_{EOI}=2ms and t_{EOI}=3ms. Ambient temperature was set at normal room temperature of T_i=298K (Fig. 8) and high ambient temperature of T_i=700K (Fig. 9) for real engine room temperature condition simulation. Figure 8 shows that SVO fuel spray like “straight thread” can be seen injected from nozzle even as late as t_{EOI}=3ms, P_{inj}=40MPa. At the same time, GO spray was already at mist condition. The observation proof that needle lift inside injector unit which controlled by solenoid valve and spring could not completely close the inner nozzle hole opening due to the high kinematic viscosity of SVO compared to GO which caused high resistance toward being deformed by either shear stress or tensile stress[11]. Meanwhile, observation on P_{inj}=20MPa, SVO spray shows thinner and "dotted thread" spray compared to P_{inj}=40MPa. This can be concludes that low fuel pressure at end of injection could improve the needle lift closing accuracy.

Fig. 9 shows end of injection spray characteristics at high ambient temperature of T_i=700K. The images shows mist condition for SVO spray at P_{inj}=20MPa, t_{EOI}=2ms and 3ms. Furthermore, "dotted thread" spray could be visualize at P_{inj}=40MPa, t_{EOI}=3ms. As shown in Fig. 9, high temperature can decreased kinematic viscosity level of SVO cause a significant improvement on the needle lift closing accuracy.

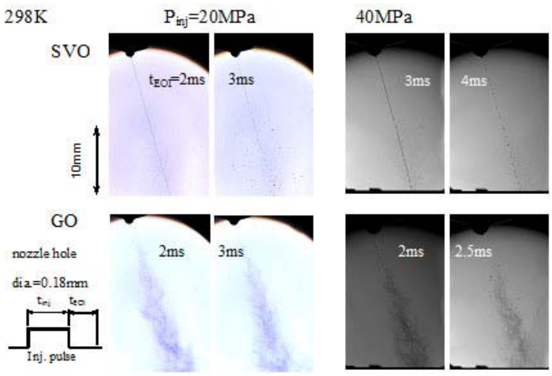

Fig. 8. Effect of low injection pressure on spray at EOI (T_i=298K).

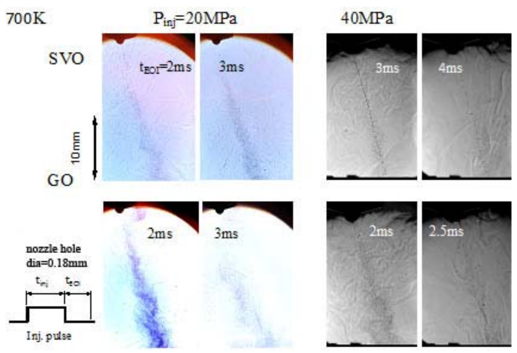

Fig. 9. Effect of low injection pressure on spray at EOI (T_i=700K).

V. Conclusions

Improvement of SVO spray by various control strategies have been done and reported in this paper. The conclusions of the results are shown as follows:

1) Kinematic viscosity value highly effect spray geometry such as penetration and cone angle. SVO spray penetration measured shortest and narrow cone angle compared with BDF and GO spray in Ti=298K. These are due to the high level of kinematic viscosity inside SVO compared to BDF and GO fuel.
2) According to the large discrepancy of kinematic viscosity value between GO and SVO fuel, both fuels show different spray characteristics where GO fuel spray at haze state while SVO in the condition of fuel surrounds with droplets in the big size.
3) The number of droplets depends on the size of the sac volume nozzle where the smaller sac volume turn out less droplets caused by a lesser amount of fuel stay within.
4) SVO fuel shows the same phenomena of droplets at high and low injection pressure. This concludes that the increasing of injection pressure did not affect the improving of end of injection spray condition.
5) Low injection pressure spray could improve spray atomization at end of injection by ease the needle lift to completely close the inner nozzle hole. High injection pressure with combination of high kinematic viscosity of SVO apply resistance at nozzle inner hole caused the needle lift cannot completely close the nozzle hole at end of injection signal. In addition, high ambient temperature spray will reduce the kinematic viscosity value of SVO and could improve SVO spray atomization at end of injection

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