INVESTIGATION OF THE EFFECTS OF PREHEATING TEMPERATURE OF BIODIESEL-DIESEL FUEL BLENDS ON SPRAY CHARACTERISTICS AND INJECTION PUMP PERFORMANCES

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Abstract

The use of high viscosity biodiesel resulted in poor fuel injection pump performance, leading to a decrease in diesel engine performance. This problem is expected to be solved by preheating high-viscosity fuel. This study aims to investigate effect of preheating temperature of biodiesel-diesel fuel blends on fuel spray characteristic and injection pump performance. The study was conducted by using a fuel injection system apparatus in which the fuel was supplied into an injector using a single-plunger fuel injection pump. Several biodiesel-diesel blends were tested at preheating temperatures of 30ºC to 70ºC. Fuel spray pattern was taken using a high speed camera. The result showed that preheating temperature highly influenced fuel spray characteristic and injection pump performance. The higher the biodiesel-diesel fuel blends, the higher the preheating temperatures were needed. Injection pump and injector required different fuel preheating temperatures for obtaining better performance. For B100, the best conditions were obtained at 50ºC for injection pump and 70ºC for fuel injector that produce almost similar pump efficiency and fuel spray cone angle to diesel fuel. As a whole, a new option of fuel supply system for biodiesel and blends was proposed in order to overcome the transport difficulty of high viscosity fuels.

Keywords: Preheating temperature, biodiesel-diesel fuel blends, spray characteristic, injection pump performance

1. Introduction

The non-renewable energy of fossil fuel supply is diminishing in the world and will eventually run out. This is because energy consumption is dominated by fuel oils such as gasoline, diesel oil, kerosene, and aviation fuel. By 2015, Indonesia has proven petroleum reserves of 3.7 billion barrels, natural gas 100.3 TSCF and coal reserves of 32.27 billion tons which will be exhausted in 11 years, 36 years and 70 years for petroleum, natural gas and coal, respectively, if it is assumed that no new reserves are found. The use of renewable alternative energy is very important in order to reduce dependence on fossil energy sources. There are abundant sources of renewable energy, one of which is biofuel. Biofuels can be produced directly from plants or indirectly from industrial, commercial, domestic or agricultural wastes. Biodiesel is mainly produced from oil or fat through trans-esterification process and its composition is similar to that of diesel. Besides being produced from plants, biodiesel can also be produced from waste cooking oil. Biodiesel has a lower calorific value than diesel, but has a higher cetane number.

Several studies on the use of biodiesel from waste cooking oil have been conducted to assess diesel engine performance. These literature indicate that engine performance and emission are affected by various factors such as sources of cooking oil waste, fuel blend ratio, fuel injection system, engine load and speed conditions. As with biodiesel from other feedstock's, engine performance using biodiesel from waste cooking oil can be improved by adjusting injection time and pressure. The differences in the nature and strategy of the injection affect the spray characteristics, process of atomization and evaporation which ultimately lead to differences in performance, combustion characteristics and emissions.

In general, biodiesel has a higher viscosity than diesel thus making better lubrication of the injection pump. Good lubrication can reduce the wear rate of materials due to direct contact between moving metal surfaces. However, to some extent, higher viscosity even inhibits fuel injection processes. If diesel is mixed with biodiesel, there will be a viscosity change which tends to be higher so the fuel mixture does not flow easily to the pump and injector. It can increase dynamic load such as peak pressure and low frequency vibration on fuel injection pump components. Moreover, the higher the viscosity of the liquid, the greater the need for energy to drive the pump.

Beside injection pump, the injector/nozzle performance, especially the fuel spray angle and pattern, is also strongly influenced by viscosity and density of the fuel, where biodiesel-diesel fuel blends typically have a worse atomization than diesel fuel. The difficulty of separating the fuel particles during the injection process causes only a small amount of air can enter in the mist. The literatures show that fuel explosion, longer spray tip penetration, larger Sauter mean diameter, narrow spray, and smaller spray volume increased with the increase of biodiesel-diesel fuel blends ratio due to its high viscosity and surface tension. Biodiesel requires higher injection pressure to achieve the same level of injection as conventional diesel. Stronger superheated conditions also greatly affects the spray atomization quality. It was found that preheating of biodiesel fuel up to 60ºC can produce better diesel engine efficiency and reduce fuel consumption.

Based on the above literatures, although studies on the use of biodiesel as well as effect of some parameters including injection pressure and temperature have been done, the works mainly focus on the performance and characteristic of certain parts, i.e. the engines, the injection pumps, or the injectors only. It should be noted that for fuel supply system, it is possible that each component in particular injection pump and injector requires different treatments when using high-viscosity fuel. This encourages the important of research on pump performance and injector characteristics to be done simultaneously to obtain better understanding in delivering high-viscosity fuel. Therefore, the purpose of this study was to investigate the effect of fuel preheating temperature on injector spray characteristics and injection pump performance at various biodiesel-diesel blends. Several previous studies showed that macroscopic spray characteristics of diesel, biodiesel, and their blends produce similar trends although the magnitude is different for various ambient pressures. So, to get a new insight about the injection pump and injector condition in delivering high-viscosity fuel as the effect of preheating temperatures, this research was carried out under atmospheric pressure condition.

2. Material and Methods

2.1. Material

Biodiesel produced from waste cooking oil and diesel fuels were used in this study. The biodiesel was obtained from CV. Klaten Energy whereas diesel fuel was obtained from PT. Pertamina. Both types of fuels were used as received. The fuels were then mixed to prepare biodiesel-diesel blends with composition of B0, B10, B20, B30, B50, and B100. In this work, B0 and B100 refer to 100% of diesel and biodiesel, respectively while B10 means the fuel contained 10% of biodiesel in diesel fuel. Table 1 shows major properties of biodiesel, diesel and their blends used in this study.

2.2. Experimental Setup

A schematic representation of the experimental setup is shown in Fig. 1. It mainly composed of four units namely fuel tank, injection pump, injector, and data acquisition units. Fuel tank unit was equipped with a mechanical stirrer to accommodate the fuel mixture in the tank, electric heater to increase the fuel temperature, fuel filter, and a thermocouple with temperature controller. Injection pump unit consisted of a single phase electric motor of 0.5 HP with camshaft to drive the injection pump, vacuum gauge (-1 to 3 bar) to measure the pressure in the suction line, and a pressure gauge (0 to 245 bar) to measure the pressure in the discharge line. In this study, a single-plunger fuel injection pump of diesel was used.

Injector unit comprised of a transparent atmospheric pressure chamber, a flow meter to measure the fluid capacity, and a high-speed camera with white LED light as a source of illumination for spray visualization. To allow spray characterization, the chamber was made of acrylic material with a 10 cm inner diameter and 70 cm pipe length. A single hole pintle injector was employed in this work.

2.3. Spray Characteristic and Injection Pump Performance

The effect of fuel preheating temperature and biodiesel-diesel blends on spray characteristic and injection pump performance were investigated. Fuel preheating temperature in this work was conducted from 30ºC to 70ºC, whereas biodiesel-diesel fuel blend was operated from B0 to B100. For each experiment, the fuel blend was heated at a predetermined temperature. It was filtered and then supplied into the injector and transparent chamber by using a diesel injection pump at a fix injection pressure of 120 bar and at a constant camshaft speed of the injection pump of 2500 rpm.

In the case of spray characteristic studies, the visualized spray patterns within transparent chamber were taken using a high speed camera with a frame rate of 30 fps with a resolution of 1280 × 720 pixel. The captured images of spray pattern were then processed by using *ImageJ* software for quantification of spray characteristics including spray cone angle and spray area. In the image processing procedure, the color images were first converted to the gray scale style, then a preset threshold value was chosen to extract the spray contour as shown in Fig. 2. The spray cone angle is defined as the largest angle formed by two straight lines from the tip of the nozzle to the spray boundary at the position of 1/3 distance from the nozzle tip.

In the case of injection pump performance studies, capacity and head-capacity curve are the main used parameters in defining pump performance. For this purpose, the suction and discharge pressures of injection pump were measured using a vacuum and a pressure gauges, respectively for pump head evaluation. Fluid pump capacities were measured by passing the accumulated fuel blend in the chamber into a microcontroller-operated flow meter sensor. The data were displayed and recorded on a computer using *Arduino* software. Three samples were taken to obtain the average. The obtained data were then used to calculate injection pump head (H) and volumetric efficiency (ηv) as follows:

where $\Delta \boldsymbol{P}$ is the difference of discharge and suction pressures of injection pump (N/m^2), γ is the specific gravity of the fuel (N/m^3), $\Delta \boldsymbol{v}$ is the difference of discharge and suction velocities of fluid (m/s), $\Delta \boldsymbol{Z}$ is the difference of discharge and suction elevation of fluid (m), $\boldsymbol{H_L}$ is the major and minor head losses (m), $\boldsymbol{Q_a}$ is the actual pump capacity (m^3/s), and $\boldsymbol{Q_t}$ is the theoretical pump capacity (m^3/s).

3. Results and Discussion

3.1. Spray Characteristics

3.1.1. Spray cone angle and pattern

High resolution photography system was applied to capture the image for fuel spray macroscopic features evaluation. The images are given in Figs. 3 and 4. Figure 3 shows comparison of fuel spray pattern at 30ºC for diesel (B0), biodiesel (B100), and their blends (B10, B20, B30, and B50) under the investigated condition. As shown, diesel had the widest spray pattern. Among biodiesel-diesel fuel blends, B10 and B20 had almost the same spray pattern as diesel. Study by Chen et al. also found that in atmospheric conditions, 20% biodiesel blended diesel (B20) had similar characteristics to diesel with slightly larger droplet size and shorter tip penetration. The fuel spray pattern became narrow with the increase of fuel blend ratio. This condition occurred due to physical properties change in which kinematic viscosity increases with increasing biodiesel-diesel fuel blends fraction. It means that higher viscosity fuels provided a narrower spray pattern. When the experiment continued at B100, there was no spray image. This was because of the failure of fuel supply system due to the large workload in which the plunger load and the pressure exceeded the rated values.

Figure 4 shows comparison of spray pattern for biodiesel-diesel fuel blends particularly B30, B50, and B100 at different preheating temperatures under the investigated condition. The figure shows that fuel spray pattern became wider with the increase of preheating temperature for all investigated biodiesel-diesel fuel blends. It was found that fuel preheating temperatures for B30, B50, and B100, which approached the diesel spray pattern were obtained at temperatures of 50°C, 60°C, and 70°C, respectively. The result indicated that higher biodiesel-diesel fuel blend needed higher fuel preheating temperature for better atomization during injection process. It has been discussed that although viscosity of biodiesel-diesel fuel blends increased with the increase of biodiesel fraction, viscosity of each blend decreased with the increase in temperature.

Figure 5 shows the average spray cone angle from three repeated experiments as a function of fuel preheating temperature for biodiesel and blends compared to diesel under the same experimental conditions. Biodiesel (B100) produced the smallest spray cone angle because it has the highest viscosity. It can be observed from the research results that increasing biodiesel-diesel fuel blends fraction reduces the fuel spray cone angle due to the increase of fuel viscosity. The higher viscosity and density of biodiesel leads to a worse atomization than that of diesel.

Figure 5 also reveals the variation of spray cone angle with fuel preheating temperature. For given fuel mixture, it is very sensitive to change fuel preheating temperature. The spray cone angle increased as the increase of fuel preheating temperature. This is due to changes in fuel viscosity and density in which kinematic viscosity and density decreased with increasing fuel preheating temperature. Under investigated conditions, at 70°C, B30 provided the highest spray cone angle, as can also be observed in Fig. 4. Higher fuel preheating temperatures cause higher kinetic energy in the sprays and smaller fuel droplets are formed, which are more likely to atomize and scatter in the chamber. This is consistent with previous studies in which lower fuel viscosity led to higher spray cone angle and higher level of air entrainment.

3.1.2. Spray area

The spray area of biodiesel and its blends with respect to diesel spray area under the same experimental conditions is shown in Fig. 6. The spray area is an important indicator of fuel-air mixing process characteristic in which a higher spray area characterizes a more widely distributed of fuel droplets. The figure shows that as the biodiesel-diesel fuel blends ratio increases, the spray area decreases. The main reason is the change in fuel viscosity as explained earlier in the previous section. Compared to biodiesel and blends, diesel has the highest spray area due to its relatively low density and viscosity. This is consistent with previous studies that higher density and viscosity of biodiesel leads to the formation of larger droplets, resulting in poor atomization compared to diesel.

Figure 6 also shows the effect of preheating temperature on fuel spray area. A generally linear trend as a function of fuel temperature can be observed particularly for B30, B50, and B100. In general, the spray area becomes larger as the fuel temperature increases. This indicated that as the fuel preheating temperature rises, the smaller the fog particle and the larger the spray area. At 70°C, B30 provided the highest spray area under the investigated conditions as can be observed in Fig. 4.

3.2. Pump Performance

3.2.1. Pump capacity

Pump capacity is defined as the amount of fluid volume that the pump generates continuously in each unit of time. Pump capacity for biodiesel fuel and mixtures under the same experimental conditions is shown in Fig. 7. The result showed that under certain conditions, excessive addition of biodiesel to diesel fuels tends to cause the decrease of pump capacity. This is possible because of the high viscosity of fuel. Viscosity is a fluid property that shows the ability of a fluid to flow. In common, high viscosity liquids are more difficult to flow because of the large flow resistance. Thus, the use of high viscosity fuel will cause fuel to be difficult to flow in the pump and injection system.

Figure 7 also shows that as the fuel preheating temperature rose, the pump capacity rose. At high temperatures, the liquid viscosity was smaller as can be seen in Table 2, thus the liquid was more easily pumped. Hot fluids flow more readily than cold fluids. However, the subsequent increase in fuel temperature causes a decrease in the pump capacity. When the temperature is too high, the fluid viscosity drops significantly causing the pump suffers of lubrication deterioration. This condition makes the friction between the plunger and the cylinder becomes larger, leading to the reduction of pump capacity. In addition, lower viscosity fluid is easier to slip back from the discharge side to the suction side of the pump through the clearance in a pump. In this study, the use of B30 at temperatures of 50ºC-70ºC caused the pump experienced an excessive vibration phenomenon. If the pump is operated for a long time, there is a possibility of plunger and pump cylinder damage in the form of scratches that cause leakage. It is therefore fuel viscosity should always be given at a specified temperature. In this study, the best pump capacity for B0 (Diesel), B10, B20, and B30 was obtained at 30ºC whereas for B50 at 40ºC and B100 at 50ºC.

3.2.2. Head-capacity relation

Figure 8 shows the relation between volume flow and total head at a constant speed of the pump crank. The injection pump head was calculated by using Equation 1. The pump curve is typically very steep reveals that a more or less constant capacity is produced with a range of heads. The result showed that the difference of pump capacity was about 6% only.

Although injection pumps are theoretically capable of moving a wide range of fluids like high viscous fluids, in this work, there were two main areas that described the relationship of pump head with capacity as a result of differences in fluid viscosity. The first area was fuels with viscosity of more than 3.5 mm^2/s. It can be seen that as the viscosity rose, the pump head decreased due to the increase of fluid friction to vessel walls thereby more time will be needed to fill the cylinder and that the pump must run slower. In this condition, the capacity of the pump falls correspondingly.

The second area was fuels with viscosity of less than 3.5 mm^2/s. On the one hand, it can be observed that as the viscosity decreased, the pump head increased because of the decrease in fluid friction. Moreover, the pump head is also affected by specific gravity or density of the fuel as given in Equation 1. Addition of biodiesel fraction leads to the increase in fuel density. The lower the fuel density, the higher the pump head will be generated. In this condition, the liquid could be pumped easily. On the other hand, the capacity of pump decreases with viscosity decrease. This occurred due to slip phenomenon that is the recirculation of the pumped fluid from the discharge side of the pump back to the pump suction side. The slip amount is determined by the discharge pressure requirement and the fluid viscosity. The increase of discharge pressure will force more fluid from the discharge to the pump suction side, whereas the increase of fluid viscosity causes slip amount decrease due to the fact that it is more difficult for a high viscosity fluid to slip back through the clearance in a pump than a thin fluid.

3.2.3. Volumetric efficiency

Figure 9 shows the comparison of volumetric efficiency for diesel, biodiesel and their blends at each optimum fuel preheating temperatures. The pump volumetric efficiency was calculated by using Equation 2. Volumetric efficiency refers to the percentage of actual fluid flow out of the pump compared to the flow out of the pump without leakage. The loss of volumetric efficiency is induced by slippage through valves, ratio of liquid chamber volume at end of stroke to plunger/piston displacement volume, and liquid compressibility. In general, injection pumps maintain high efficiencies throughout the viscosity range.

Figure 9 indicated that the pump volumetric efficiencies are relatively comparable for diesel, biodiesel and their blends in the range of 70%-72%. As in the case of pump capacity, the best volumetric efficiency of the injection pump was obtained at 30ºC for B0 (Diesel), B10, B20, and B30, whereas at 40ºC and 50ºC for B50 and B100, respectively. Among them, B30 has relatively lower pump volumetric efficiency. It is assumed that to obtain optimal volumetric efficiency, the initial heating temperature of B30 should be between 30ºC-40ºC.

3.3. New Option of Fuel Supply System for Biodiesel

The fuel supply system has an important role in compression ignition engines or diesel engines which supply fuel from the tank to the combustion chamber. To obtain a good engine performance, it is necessary to have a good fuel supply system which mainly depends on the performance of the injection pump and the injector/nozzle. The results of this study indicated that the best performance of the injection pump and the injector occurs at different preheating temperatures when supplying high-viscosity biodiesel fuel. For waste cooking oil biodiesel (B100) used in this work, it was found that the best injection pump performance and fuel injector spray were obtained at biodiesel preheating temperatures of 50ºC and 70ºC, respectively under atmospheric pressure condition. These conditions are almost the same as the performance of injection pump and injector when using diesel fuel.

Based on the above description, a new option of fuel supply system for biodiesel and biodiesel-diesel blends is proposed in order to obtain a more efficient performance of diesel engines as shown in Fig. 10. This new option of biodiesel fuel supply system uses two fuel heaters, before and after injection pump. The heaters can be placed in the fuel tank or wrapped along the suction and discharge lines of the injection pump. The first heater (before the pump) is set to serve the needs of the injection pump, while the second heater (after the pump/before the injector) is used to serve the injector needs. Nevertheless, scientific verification of this separate heating system concept for delivering high-viscosity biodiesel fuel into the combustion chamber is very important to study further. Several aspects of research and development in this area need to be explored that might affect overall system performance including biodiesel sources, heating mechanisms and technologies, types of injection pump and fuel injector, ignition and combustion characteristics, engine performances, etc.

4. Conclusions

The effect of fuel preheating temperature on injector spray characteristics and injection pump performance at various biodiesel-diesel blends under atmospheric pressure conditions was successfully investigated. Fuel preheating temperature plays a crucial role in the biodiesel fuel supply system under the investigated conditions. Biodiesel and biodiesel-diesel fuel blends need to be heated at specific temperatures to properly pump and spray the fuel. The result also showed that the requirement of biodiesel fuel preheating temperature for the injection pump and the injector is different. In this work, the best conditions of biodiesel (B100) from waste cooking oil that generated almost identical pump efficiency and fuel spray with diesel fuel were 50^{o}C for injection pump and 70^{o}C for fuel injector. Based on the obtained results, a new option of fuel supply system was proposed to handle high-viscosity biodiesel fuel.

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