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Spray Characteristics Comparison of Different Fuels Injected from a Diesel Injector

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Abstract

Fuel spray and atomization characteristics play an important role in the performance of internal combustion engines. As the reserves of petroleum fuel are expected to be depleted within a few decades, finding alternative fuels that are economically viable and sustainable to replace the petroleum fuel has attracted much research attention. In this work, the spray and atomization characteristics were investigated for commercial diesel fuel and biodiesel derived from Canola seeds oil (B100). The spray tip penetrations and cone angles were acquired using a high speed imaging technique. Also, spray volume and Sauter mean diameter (SMD) are determined by experimental correlations.
The experimental results showed that biodiesel had different features compared with diesel. Longer spray tip penetration and larger droplet diameters were observed for B100. The smaller droplet size of the diesel were believed to be caused by its relatively lower viscosity and surface tension. High-pressure injection helps to optimize the trade-off of spray volume and droplet sizes. Furthermore, it was observed that the smallest droplets were within a region near the injector nozzle tip and grew larger along the axial and radial direction. The variation of droplet diameters became smaller with increasing injection pressure.

1. Introduction

The conversion of bulk liquid into a dispersion of small droplets ranging in size from submicron to several hundred microns (micrometers) in diameter is of importance in many industrial processes such as spray combustion, spray drying, evaporation cooling, spray coating, and drop spraying; and has many other applications in medicine, meteorology, and printing. Breakup of fluids can be described as the procedure when bulk liquid disintegrates into droplets by the action of forces both internal and external.

In most combustion systems, fuel atomization performance leads to a wider combustion range and low pollutant exhaust emissions. Park et al. conducted a study on fuel atomization to modify combustion systems [1]. Combustion engines are used as an essential source of mechanical energy in direct injection diesel engine. Spray shape and atomization quality strongly affect fuel performance and outlet

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emissions. Mohammadi et al. [2] reported that if the spray leads to smaller droplets, combustion becomes finer and quicker, performance and torque increase, and outlet emissions decrease. Jianfang et al. [3] reported that the spray cone angle and spray tip penetration of biodiesel increases, the atomization of spray improves, the ignition delay and duration of combustion becomes shorter. Delacourt et al. [4] studied the effect of injection pressure on macroscopic spray characteristics, such as spray tip penetration and spray cone angle, for a wide pressure range of up to 2500 bar and developed a measurement technique to extract these characteristics quickly and reliably. Shao et al. [5] found that diesel engine combustion and emission characteristics are greatly influenced by atomization quality, particularly the fuel-air mixture in the combustion chamber. Injection pressure is one of the most important parameters influencing pulverization. The spray characteristics of diesel and biodiesel (derived from palm and used cooking oil) under ultra-high injection pressure of up to 3000 bar were studied by Xiangang et al. [6], who showed that biodiesel has longer spray tip penetrations than diesel fuel because of the higher density and viscosity of biodiesel; however, these differences become smaller at higher ambient pressures (greater than 30 bar). The spray cone of the biodiesel is smaller than that of the diesel fuel, thereby generating smaller spray areas and volumes. Kegl and Pehan [7] reported that high biodiesel viscosity affects atomization by increasing the mean droplet size, which in turn increases the spray tip penetration. Thus, mixture formation and combustion worsen when biodiesel is used instead of diesel fuel. However, this problem can be solved by blending diesel with biodiesel to reduce viscosity. Another method to improve atomization involves injecting biodiesel at higher pressures, which increases the atomization process by increasing the dispersion of biodiesel spray. Ainul et al. [8] conducted experiments to examine the effects of injection pressure and fuel type on the spray tip penetration and angle of spray injected into atmospheric chamber and formulate an empirical correlation of the spray tip penetration and spray cone angle for non-evaporative conditions. Ethan et al. [9] studied diesel fuel spray development using high speed imaging of a high pressure common rail direct injection mounted in a spherical constant volume combustion chamber. The fuels were injected at injection pressures of 1000, 1500, and 2000 bar into a nitrogen environment at chamber densities of 17.5, 24.2, and 32.7 kg/m3 and temperature of 298 K. Jitendra et al. [10] found that the fatty acids in vegetable oils include stearic, palmite, oleic, and lonolenic acids. The viscosity and density of straight vegetable oil are much higher than those of conventional petro-fuels because the former includes long fatty acid structures. Given these properties, the spray cone angle of straight vegetable oil is relatively small but its liquid penetration is high when sprayed through a nozzle. Pin-Chia Chen et al. [11] investigated spray and atomization of diesel fuel and its alternatives from a single-hole injector using a common rail fuel injection system. Raghu Palani et al. [12] studied spray characteristics of diesel and derivatives in direct injection diesel engines with varying injection pressures.

Liquid fuel combustion requires atomization of the fuel in the form of a spray using spray atomizers. High-quality atomization, an important prerequisite for good combustion, can be achieved using various injectors. The atomizers inject the fuel in the form of a spray, which then undergoes breakup because of instabilities at the spray surface, resulting in multitude of droplets. Atomization quality is characterized by the spray cone angle, liquid distribution in the spray pattern, spray penetration, and drop size distribution. In this research, spray atomization in a diesel engine cylinder was investigated near the nozzle tip to examine the effects of injection pressure on various spray characteristics, including spray cone angle, spray tip penetration, and spray area, under non-evaporating conditions.

2. Experimental setup

The fuel injection system is illustrated in Figure 1. Diesel and Biodiesel (Canola oil) are chosen as operating fuels. The chosen injection pressures were 150, 200, 250, 300 and 500 bar. The fuels were stored in room temperature at 25 °C and also injected into air at room temperature and pressure. The injector orifice diameter is 0.1 mm (shown in Figure 2).

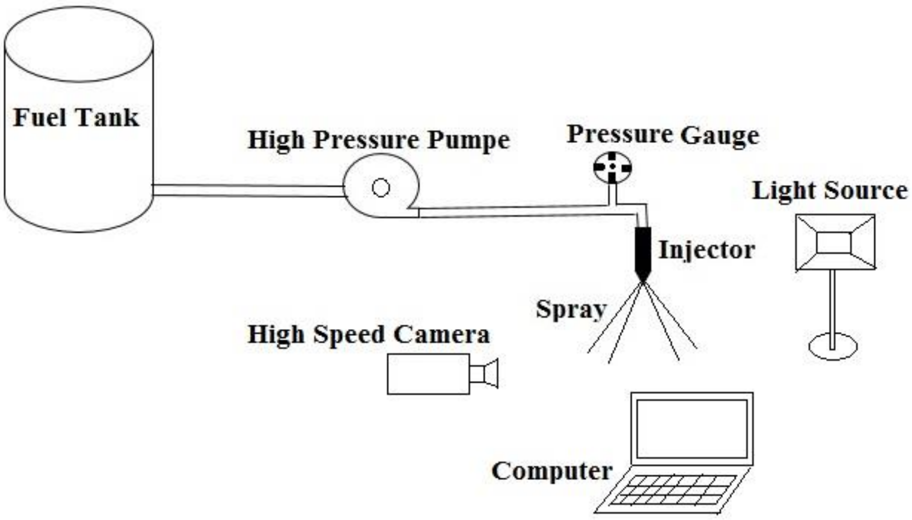

Figure 1. Fuel injection system

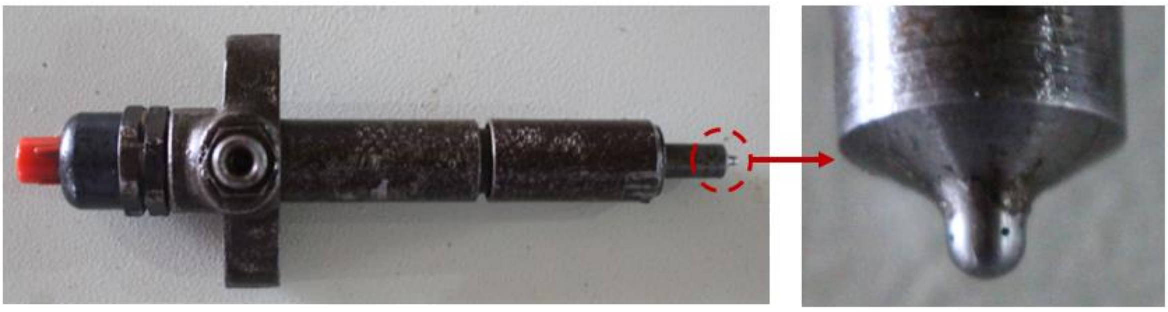

Figure 2. The shape of injector

The chemical properties of fuels are reported at Table 1. Also, the fuels used in this study are shown in Figure 3.

Table 1. Chemical properties of fuels

Fuel	Abbreviation	Density (g/ml)	Kinematic viscosity (mm2/s)	Surface tension (m N/m)
Diesel	D	0.83	2.65	30.3
Biodiesel	B100	0.87	4.60	34.7

Figure 3. Diesel (left) and Biodiesel (right)

The captured images were further processed using ImageJ software, which includes graphical tools to analyze the captured images. Spray tip penetration (spray length) was defined as the distance between the injector tip and the longest spot in the spray image and could be obtained using the graphical tool of ImageJ software. The spray cone angle was defined as the angle formed by two straight lines drawn from the tip of the injector to the outer periphery of the spray at a distance of one third of the spray length(s) downstream of the injector tip and could be obtained by drawing appropriate lines in the captured images using the graphical tool (see Figure 4).

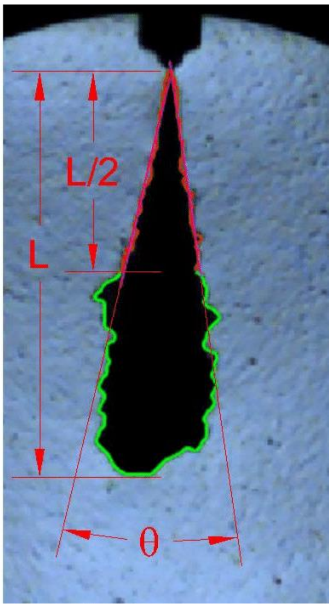

Figure 4. Spray tip penetration (L) and spray cone angle (θ)

The spray characteristics of the tested fuels for each injection pressure were measured by applying an image processing technique through frame-by-frame analysis of randomly selected pictures. To ensure the repeatability of the experimental results, each spray test was repeated four times; the values presented in this study are the average of six measurements. The spray images of diesel and biodiesel are shown in Figure 5.

Diesel **Biodiesel**

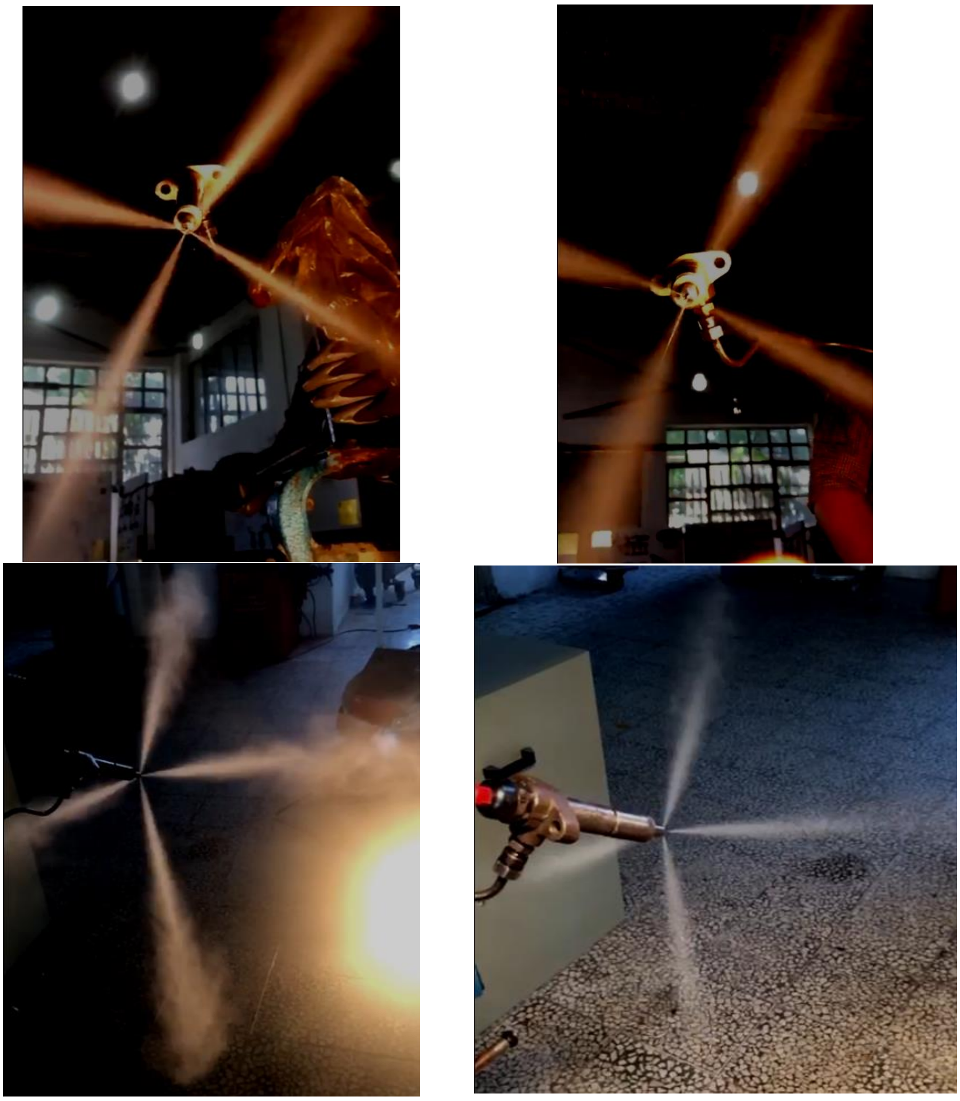

Figure 5. Spray images

3. Results and Discussion

The present study aims to investigate the spray characteristics and fuel droplet atomization behavior of the test fuels (Diesel and Biodiesel) by varying the injection pressures. Table 1 shows that mineral diesel presents a lower density and kinematic viscosity than biodiesel. Fuels with higher density exhibit inferior spray and atomization characteristics. When fuel injection is initiated, droplets move quickly and tend to break into smaller droplets. Atomization takes place quickly when the test fuels have lower density; in the case of higher density fuels, atomization requires a considerable amount of time because of van der Waals forces. This atomization phenomenon occurs within milliseconds after the start of injection. Fuels with higher density lead to higher spray penetration and poor atomization because of their higher inter-molecular forces, consequently leading to formation of larger-fuel droplets with relatively higher inertia, and thus travel longer distances in the spray chamber. Higher spray tip penetration and poor atomization behavior of the fuels may cause inefficient fuel-air mixing and consequently lead to extensive formation of soot in the engine.

3.1. Spray tip penetration

Spray tip penetrations of the fuels at different injection pressures are shown in Figure 6. Tip penetrations of the fuels increase with time after being injected from the injector and a higher injection pressure promotes this increase. This trend can be easily observed by looking at diesel and biodiesel penetration. Increases in injection pressure cause increases in initial spray momentum. The viscosity and surface tension of biodiesel are higher than diesel fuel; thus, biodiesel fuel shows longer spray tip penetrations. This result may be due to the fact that the relatively high density and viscosity of biodiesel delay the breakup of fuel particles, thereby increasing the spray length.

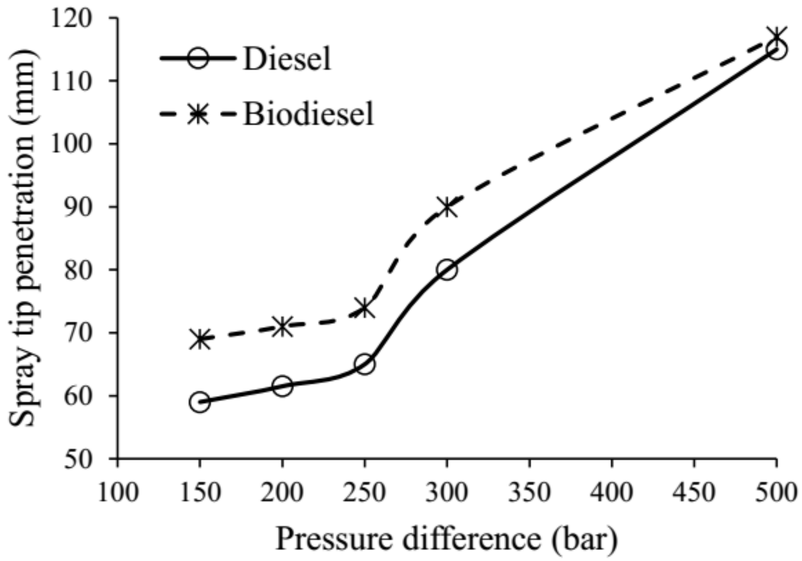

Figure 6. Spray tip penetrations in terms of injection pressures

3.2. Spray cone angle

Figure 7 illustrate the spray cone angle results under different injection pressures with time after the start of injection. As the spray penetrates, the droplets on the boundaries become smaller and diffuse easily, generating a decreasing trend of spray cone angle. Increasing the injection pressure raises the turbulence level into the orifice and the dispersion of the spray at the exit of the injector. As seen from Figure 7, the spray cone angles of the fuels converge to a constant value (steady state of the spray) and steady state is achieved sooner after injection as the injection pressure increases. These results show that the distinctions between the different fuels after achieving steady state decrease with increasing injection pressure. More obvious distinctions between the different fuels can be seen before their convergence. The spray of biodiesel starts with the smallest cone angle, resulting from its highest viscosity.

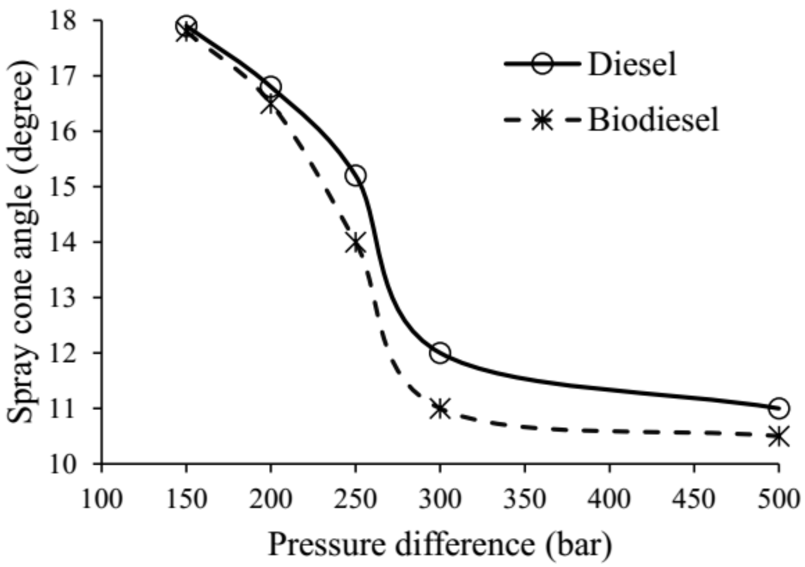

Figure 7. Spray cone angles in terms of injection pressures

3.3. Spray area

The spray area is the area covered by the fuel spray in the chamber at the given injection pressure conditions. The spray areas of all of the tested fuels at various injection pressure conditions are shown in Figure 8. The spray area increases with increasing injection pressure for all tested fuels, as shown Figure 8. The spray area of biodiesel has the highest for all injection pressures. When the injection pressure increases from 150 bar to 500 bar, fuel droplets begin to concentrate near the center of the spray because of increases in the density of the chamber air, which offers stiffer resistance to the fuel droplets and forces them to spread in radial direction, thereby increasing the spray area.

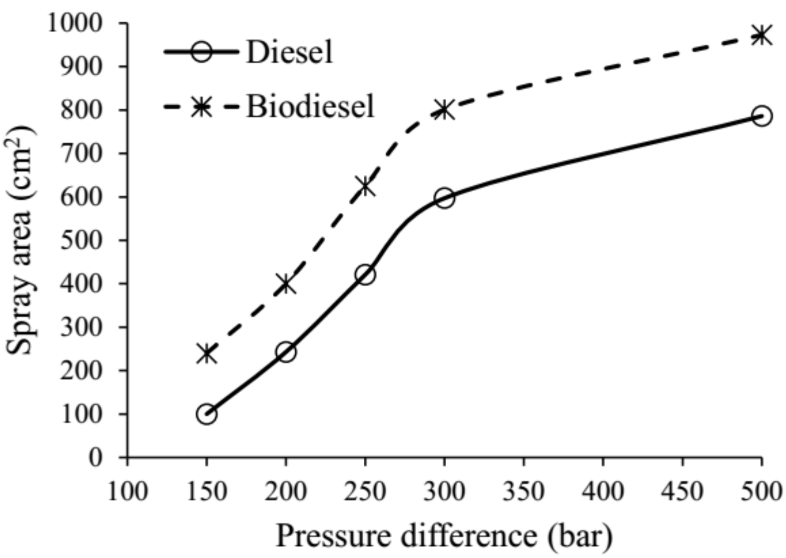

Figure 8. Spray areas in terms of injection pressures

3.4. Sauter mean diameter (SMD)

Figure 9 depict the SMD results for different conditions. Figure 9 shows the SMDs of the different fuels under 150, 200, 250, 300 and 500 bar injection pressures. It is clear from Figure 9 that SMDs decrease with an increase in the injection pressure for all the fuels. The SMD difference among the fuels is mainly due to the differences in their viscosity and surface tension (Table 1). A higher viscosity leads to a lower fuel jet velocity, leading to larger droplet size. A lower surface tension makes the spray easier to break up into small droplets. According to Figure 9, biodiesel has much bigger droplets than diesel due to its highest viscosity and surface tension. The effect of viscosity is more significant on the SMD than that of surface tension due to the fact that viscosity variations among fuels are higher than that of surface tension.

The atomization quality of a liquid spray can be estimated by the SMD. A determined SMD represents the equivalent diameter that characterizes the entire group of droplets of the spray. The SMD is one in which the characteristics of a population of various numbers of drops are present in a sample. Elkotb [12] suggested a Sauter mean diameter (SMD) correlation involving variations in viscosity, density, and surface tension. Ejim et al. [13] suggested that the SMD correlation given by Elkotb [12] is also applicable to biodiesel fuels. In the current study, the SMD correlation suggested by Elkotb [12] is used to investigate the atomization tendencies of diesel and biodiesel, which is given in Equation (1).

$$SMD = 615\nu^{0.385}\sigma^{0.737}{\rho_f}^{0.737}{\rho_g}^{0.06}\Delta p^{-0.54} \quad (1)$$

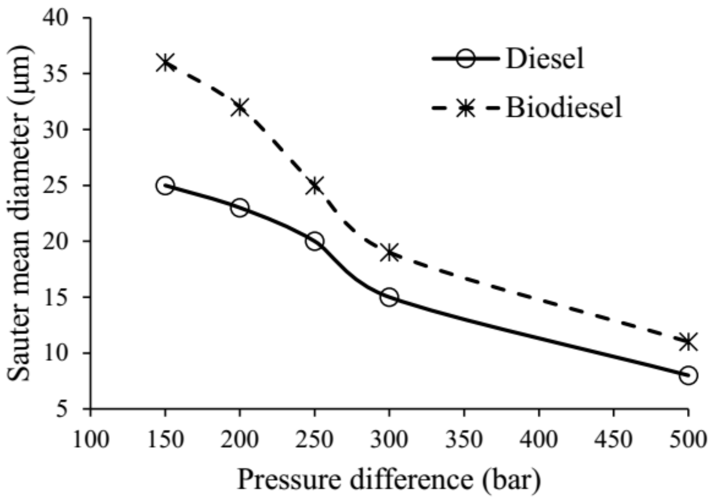

Figure 9. Sauter mean diameters (SMD) in terms of injection pressures

3.5. Spray volume

Figure 10 shows the calculated spray volumes of different fuels used in this study. Larger spray volumes can be found at higher injection pressure. Spray volume is mainly determined by the spray penetration length, since the variation of spray cone angles among different fuels is not significant. The spray volume can also be used to understand the fuel air mixing process in the combustion chamber. Fuel spray is assumed to consist of a cone and half a sphere; thus, spray volume is described by the correlation suggested by Delacourt et al. [4], which is given by Equation (2).

$$V(t) = \frac{1}{3}\pi S^3(\tan\frac{\theta}{2})^2\frac{1 + 2\tan\frac{\theta}{2}}{\left[1 + tan\frac{\theta}{2}\right]^3} \quad (2)$$

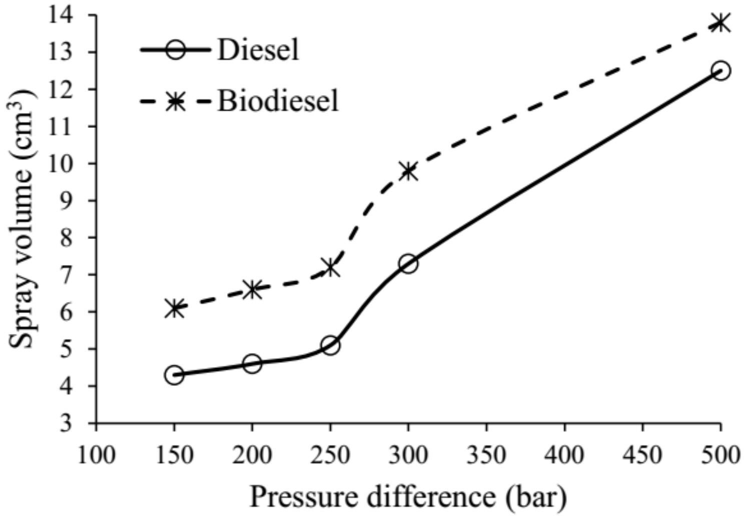

Figure 10. Spray volumes in terms of injection pressures

4. Conclusions

In this work, the spray and atomization characteristics were investigated for diesel fuel and biodiesel fuel. The SMD and spray volume were estimated using correlations determined for the tested fuels. Spray penetration length increased with increasing injection pressure. Higher values of density and viscosity of the biodiesel led to longer spray penetration in the combustion chamber. Spray volumes showed a trend similar to that of spray tip penetration, thereby providing comprehensive information of the range of the spray tip. Increasing the injection pressure raises the turbulence into the orifice and dispersion of the spray at the exit of the injector, leading to a decrease in spray cone angle. The spray area increases with increasing injection pressure. Fuels with higher viscosity and surface tension, such as biodiesel, does not easily break into small droplets compared with diesel. The smaller size of the droplets can improve spray atomization and air/fuel mixing efficiency in the combustion environment. The high injection pressure strategy is a common method used to reduce the droplet size of fuel particles.

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