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Experimental Spray Investigation of Biodiesel Fuels Derived from Corn Oil and Canola Oil

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Abstract: Spray characteristics of fuels are one of the most important factors for engine research owing to their relationship between performance output and emission level. The aim of this study was to investigate the spray behavior of biodiesel fuels derived from corn oil and canola oil, utilizing a piezo injector. Effects of ambient pressure and injection pressure on spray characteristics like spray penetration length and spray cone angle were investigated in a constant volume combustion chamber. Ambient and injection pressures were in range of 0-15 bar and 600-1000 bar, respectively. As a result of this study, sampled biodiesel fuels have longer penetration and smaller spray angles. This can be explained by having higher viscosities resulting in slower evaporation and atomization.

Keywords: Biodiesel, Constant volume combustion chamber, Spray investigation

Introduction

Diesel engines have been very important devices for power generation so far owing to their higher torque capability and energy density than their gasoline counterparts. Although their widespread usage, they are focus of criticism due to their pollutant emission levels and utilization of nonrenewable fossil fuels. Important organizations like European Union (EU) and Environmental Protection Agency (EPA) of United States of America brought strict regulations to pollutant levels from automobiles. These regulations have been obligating researchers to find ways of decreasing emissions since 1990s (Rodriguez, 2009). Therefore, investigation of pollutant emissions in every aspect has had an important place in engine research up to now.

One of the promising ways to overcome the problems of diesel engines is to develop renewable fuels from vegetable oils or animal fats, which are called as biodiesel fuels. Many studies have been performed to obtain a biodiesel from a source, such as pyrolysis, transesterification, gasification followed by Fischer-Tropsch synthesis (Oumer, Hasan, Baheta, Mamat, & Abdullah, 2018). Among these techniques, transesterification is the most common method owing to its simplicity and efficiency. Plenty of raw materials have been employed for biodiesel production, such as palm oil, jatropha, soybean oil, coconut oil, rapeseed, canola, sunflower, corn, and olive oils (Mirhashemi & Sadrnia, 2019). In Turkey, sunflower, olive, canola, and corn oils are the most widespread oils for biodiesel generation.

Biodiesel fuels have several advantages which are subject of current research in this field. Firstly, it is mechanically advantageous to use biodiesel fuels instead of diesel fuels in diesel engines (Mirhashemi & Sadrnia, 2019) because lubrication properties of biodiesel fuels are better than those of mineral diesel fuels and

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biodiesels have higher flash points. Furthermore, some biodiesels have higher cetane numbers than those of diesel fuels while some of them possess lower cetane numbers (How, Masjuki, Kalam, & Teoh, 2018). Biodiesels having higher cetane number can be comparable with conventional diesel fuels in terms of ignition properties. Hence, these advantages may lead to a replacement of diesel fuel with biodiesel fuel.

On the other hand, biodiesels own some disadvantages over mineral diesels. Firstly, biodiesel fuels possess higher viscosities than conventional diesels (Deng, Li, Hu, Wu, & Li, 2010). Thence, biodiesels perform slower atomizations which cause slower break-up. Secondly, biodiesels have higher densities which affect the spray pattern (Gupta & Agarwal, 2016). Thirdly, calorific values of biodiesels are lower than those of mineral diesels (Gharehghani, Mirsalim, & Hosseini, 2017). Besides, biodiesels are more expensive and less available than conventional diesel fuels. According to drawbacks of biodiesel fuels, it is undesirable to use pure biodiesel in compression ignition engines. Instead, the use of diesel-biodiesel blends is desirable to achieve good physicochemical properties. By this way, a fuel which can utilize both advantages of diesel and biodiesel may be presented.

Numerous studies are available in the literature about performance of diesel-biodiesel blends. An et al. (2012) researched the pure biodiesel performance in a diesel engine. They found that the power reduced on average by 12.2% from 1600 rpm to 3600 rpm. Moreover, Özkan et al. (2005) observed greater reductions in power for diesel-biodiesel blends. On the contrary, Al-Widyan et al. (2002) reported that diesel-biodiesel blends performed higher power output than conventional diesel fuel. Forson et al. (2004) also found greater power output and higher brake thermal efficiency for diesel-biodiesel blends.

Emissions from a diesel engine consists primarily of nitric oxides (NO_x), carbon monoxide (CO), hydrocarbons (HCs). Although emissions vary from engine to engine depending on the operating conditions, fuel properties and engine design, a general inference can be made (Oumer et al., 2018). HC and CO emission levels decrease with the use of diesel-biodiesel blends. However, significant decrease in NO_x level can not be observed. In many times, NO_x increases with the utilization of biodiesel in mineral diesel fuel.

Moreover, spray investigation is crucial for diesel engine research. Because, it directly affects the combustion behaviour thus the performance and emission levels. Hence, spray behaviour of biodiesel fuels has to be researched in order to understand the development pattern and to develop an idea on the combustion properties of fuels (Baumgarten, 2006). Some of the key parameters of interest are spray break-up length, spray penetration length, and spray cone angle for a spray analysis. These parameters can help researchers predict how fuel mixes with surrounding air. Moreover, a constant volume combustion chamber (CVCC) which is covered with transparent windows can be used to perform the spray tests where transparent windows allow the light to pass the chamber for spray visualization.

In literature, several studies can be found for spray investigation of biodiesel fuels. For example, Deng et al. (2010) observed that spray penetration lengths of biodiesel fuels are longer than conventional diesel fuel due to higher density and viscosity. They also reported that spray penetration length and spray cone angle get larger as the injection pressure increases for both diesel and biodiesel fuels. Also, Desantes et al. (2009) concluded that biodiesel shows longer spray penetration and smaller cone angle compared to conventional diesel due to the higher density and surface tension. On the other hand, Gupta et al. (2016) found that biodiesel spray pattern is not significantly different from the conventional diesel. They concluded that biodiesel and diesel fuels are comparable in terms of spray tip penetration and spray cone angle.

The aim of this study was to investigate the spray characteristics of biodiesel fuels in terms of spray penetration length and spray cone angle for biodiesel fuels derived from corn oil and canola oil. Biodiesels were selected due to their abundance in Turkey. Tests were performed in a constant volume combustion chamber with a common rail system. Then, desired spray parameters of biodiesel fuels are obtained and compared with those of diesel fuels.

Experimental System

Experimental Setup

A schematic sketch of the spray test rig which consists of three subsystems is shown in Figure 1. These three subsystems are gas filling system, fuel injection system and constant volume combustion chamber. A high-speed camera is utilized to record an injection event at 20,000 fps, shutter speed of 1/62,000 with a resolution of

512x512 pixels during the experiments. After the experiments, spray characteristics can be obtained from the videos which are recorded by the camera. These videos are then post processed to acquire the required parameters.

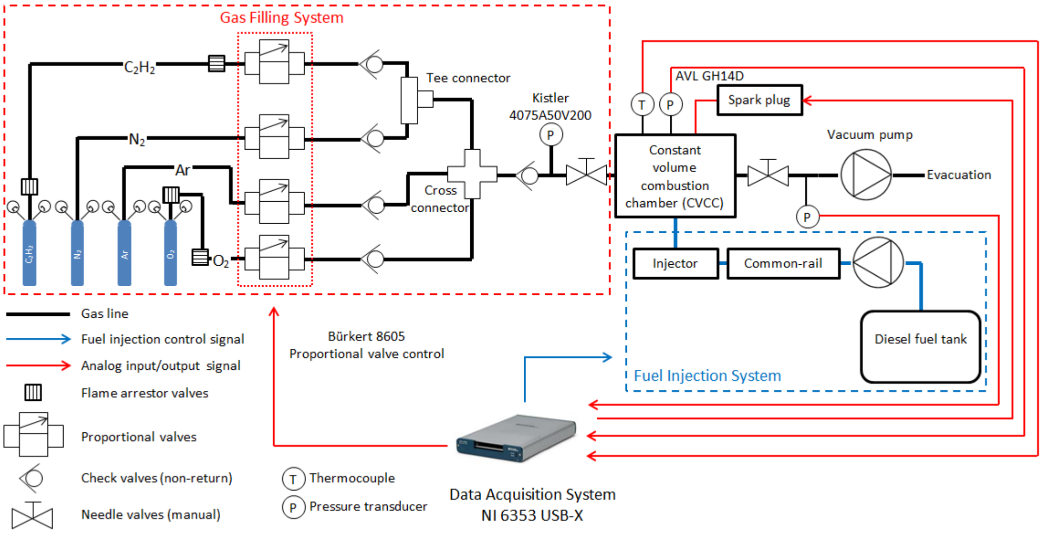


Figure 1. Schematic of experimental setup

Constant Volume Combustion Chamber (CVCC)

CVCC is a useful chamber to simulate an engine-like environment in order to obtain the spray characteristics of any fuel with any injector. Chamber is filled with nitrogen gas to control the ambient pressure which can be measured via data acquisition system with pressure sensors. Besides, CVCC has an optical window allowing the spray visualization via various optical techniques.

Gas Filling System

Gas filling system consists of 4 different gases which are nitrogen, oxygen, argon, and acetylene to simulate air and flammable gases. However, only nitrogen is used for spray investigation to prevent burning any portion of the fuel. Furthermore, proportional valves are used to fill the chamber from the gas tubes. PID control is available for more accurate filling.

Fuel Injection System

Fuel tank, fuel filter, high pressure pump, common rail, fuel lines, and the injector are the components of the fuel injection system. Injector is a piezo type injector.

Fuel Properties and Test Conditions

Three samples are prepared from corn oil, canola oil, and diesel fuel. Canola oil and corn oil are named as CAB100 and COB100, respectively. Table 1 shows the viscosity and density values of the tested fuels. Diesel fuel has the lowest viscosity and density values. Although both biodiesel fuels have similar density and viscosity values, biodiesel derived from corn oil has higher density and viscosity than the biodiesel derived from canola oil.

Table 1. Properties of tested fuels

Test Fuel	Viscosity @ 40°C (mPa.s)	Density @ 25°C (kg/m^3)
Diesel	3.071	829.546
CAB100	5.149	869.915
COB100	5.868	877.069

During the experiments, three different injection pressures were utilized, which are 600, 800, and 1000 bars. Ambient pressure was adjusted from 0 bar to 15 bar by increasing the pressure 5 bars. Operating conditions are presented in Table 2.

Table 2. Test conditions

Injector type	Piezo CRDI injector
Number of the nozzle holes	1
Injection angle	145^o
Injection duration (ms)	1
Injection pressure (bar)	600, 800, 1000
Ambient pressure (bar)	0, 5, 10, 15

Image Processing Algorithm

An example for an original and its post processed images is shown in Table 3. Then, spray penetration length and spray cone angle are obtained by a MATLAB based in house code and ImageJ. The logic behind the algorithm is that a threshold pixel intensity search given at the below charts, Figure 2 and Figure 3.

Spray penetration measurement from the video is obtained by taking four images of the respective sequence before fuel injection. These images are used for correction of the raw images taken from each complete injection. Background subtraction is applied. After that, a threshold value is calculated, and the last pixel of each image is defined, and spray penetration is calculated by using the formula for finding the distance between two points.

Spray angle measurement is obtained by an angle measurement tool created in house code. This tool creates 2 vectors according to the position of the injector tip as shown in Figure 3. After obtaining these vectors, end points of the vectors can be moved towards the desired point manually while keeping the vectors tangentially to the spray outline.

Figure 2. Schematic of spray penetration algorithm

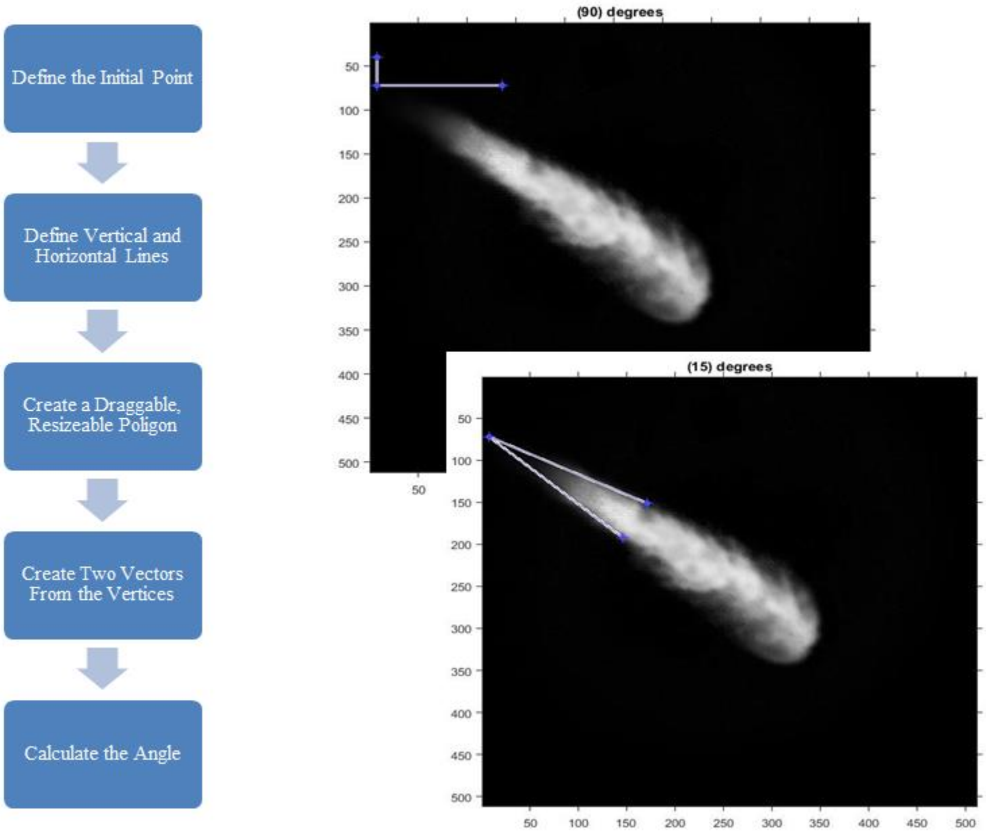
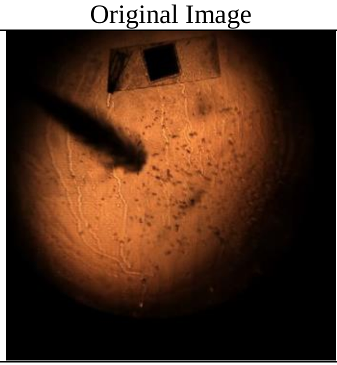
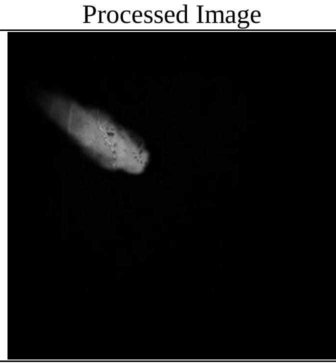


Figure 3. Schematic of spray angle algorithm.

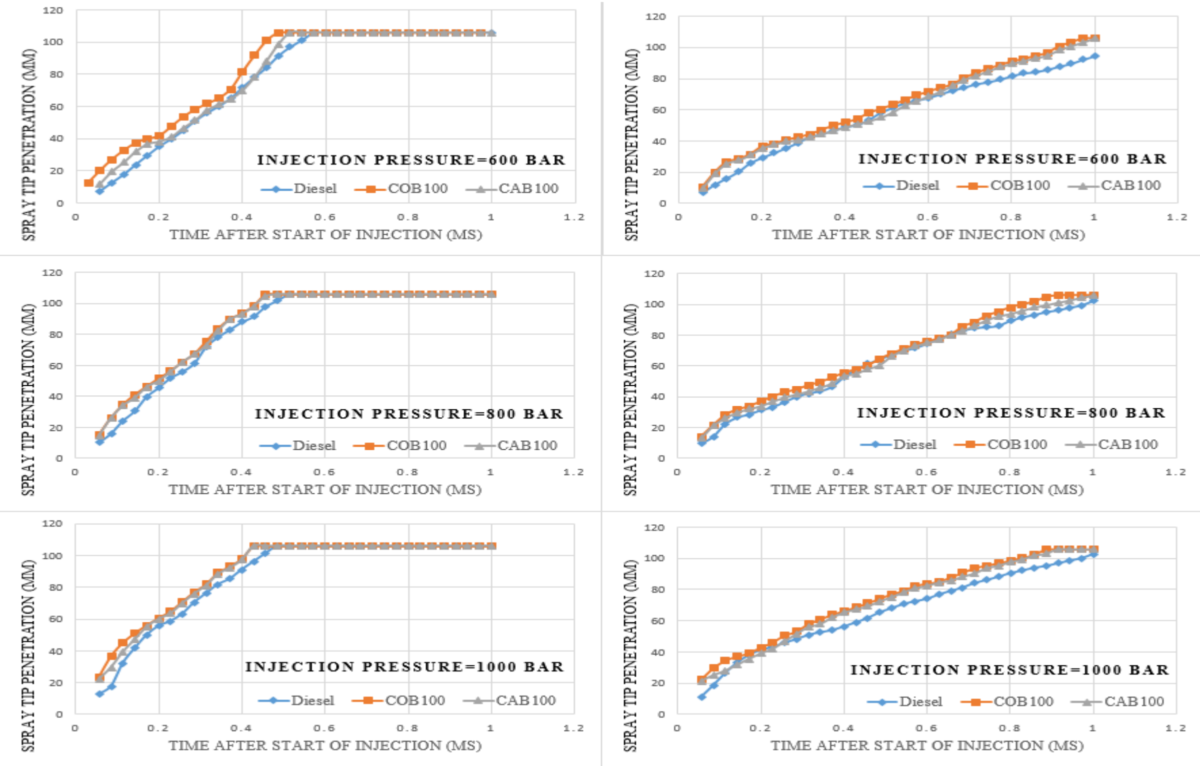
Table 3. Comparison of original image and processed image

Conditions	Original Image	Processed Image
Injection pressure: 800 bar Ambient pressure: 1 bar Time after start of injection: 0.7 ms Frames per second: 20,000 Fuel: Mineral diesel		

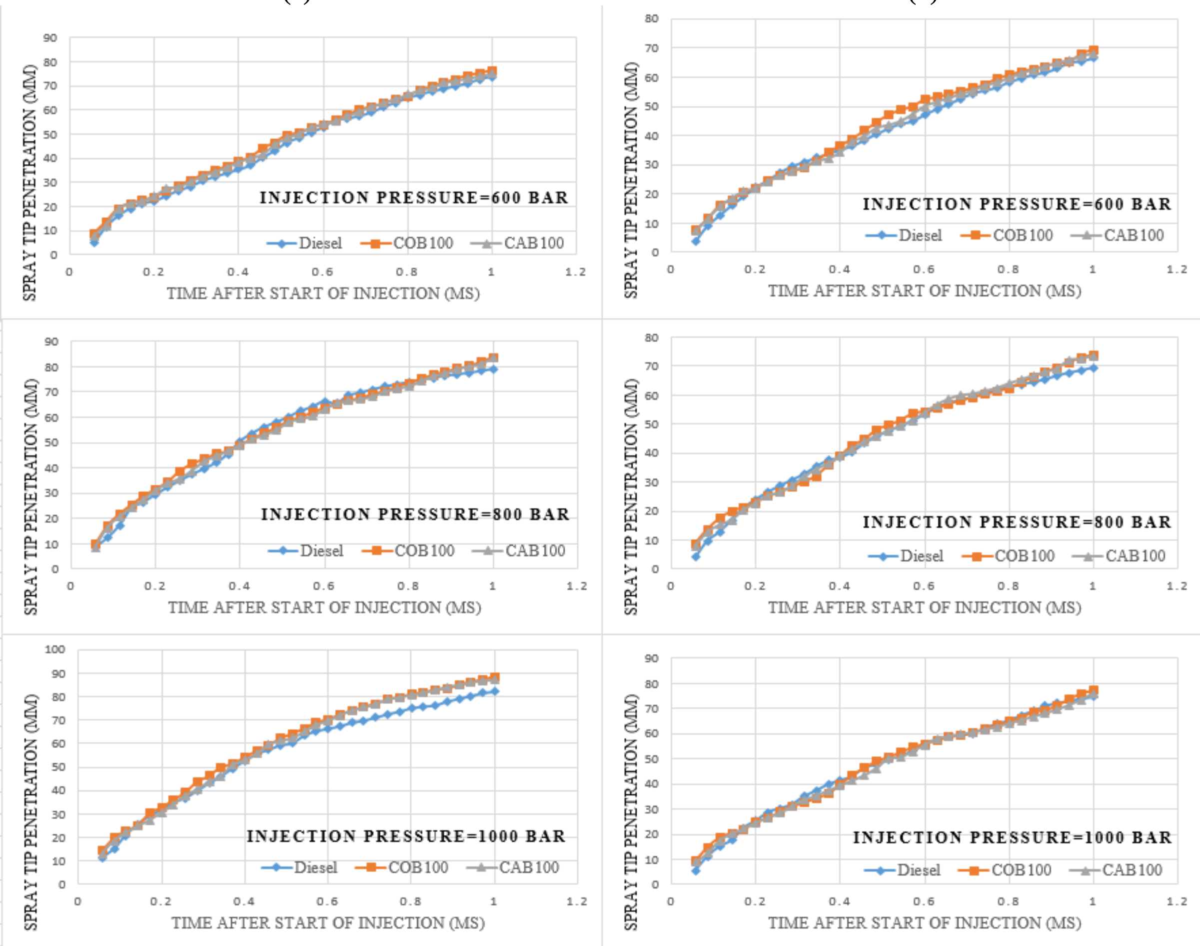
Results and Discussion

The definition of spray penetration is the maximum distance measured from the injector tip to the spray tip. The definition of spray angle is the angle between two lines being tangent to the spray outline. Both parameters are affected by injection pressure and ambient pressure. Figure 4 and Figure 5 represent the comparision of spray penetration under different conditions.

Figure 4a to 4d shows how spray penetration length develops in time at three different injection pressures (600, 800 and 1000 bars) and four ambient pressures (0, 5, 10 and 15 bars). These graphs show that the spray penetrates longer when COB100 is used as fuel. CAB100 fuel spray penetration length follows it and, the diesel’s spray penetration length is the least. Biodiesel fuels evaporates slower than diesel fuel due to their higher density and viscosity. Biodiesel fuels penetrate longer when compared to neat diesel fuel spray for all ambient pressures. As the injection pressure increases, spray penetration length increases for all fuel types (Figure 5). As expected, spray penetration length decreases as the ambient pressure increases due to higher drag forces.



(a) (b)



(c) (d)

Figure 4: Comparison of spray tip penetration for diesel, COB100 and CAB100 at (a) 0 bar, (b) 5 bar, (c) 10 bar and (d) 15 bar ambient pressure of spray chamber

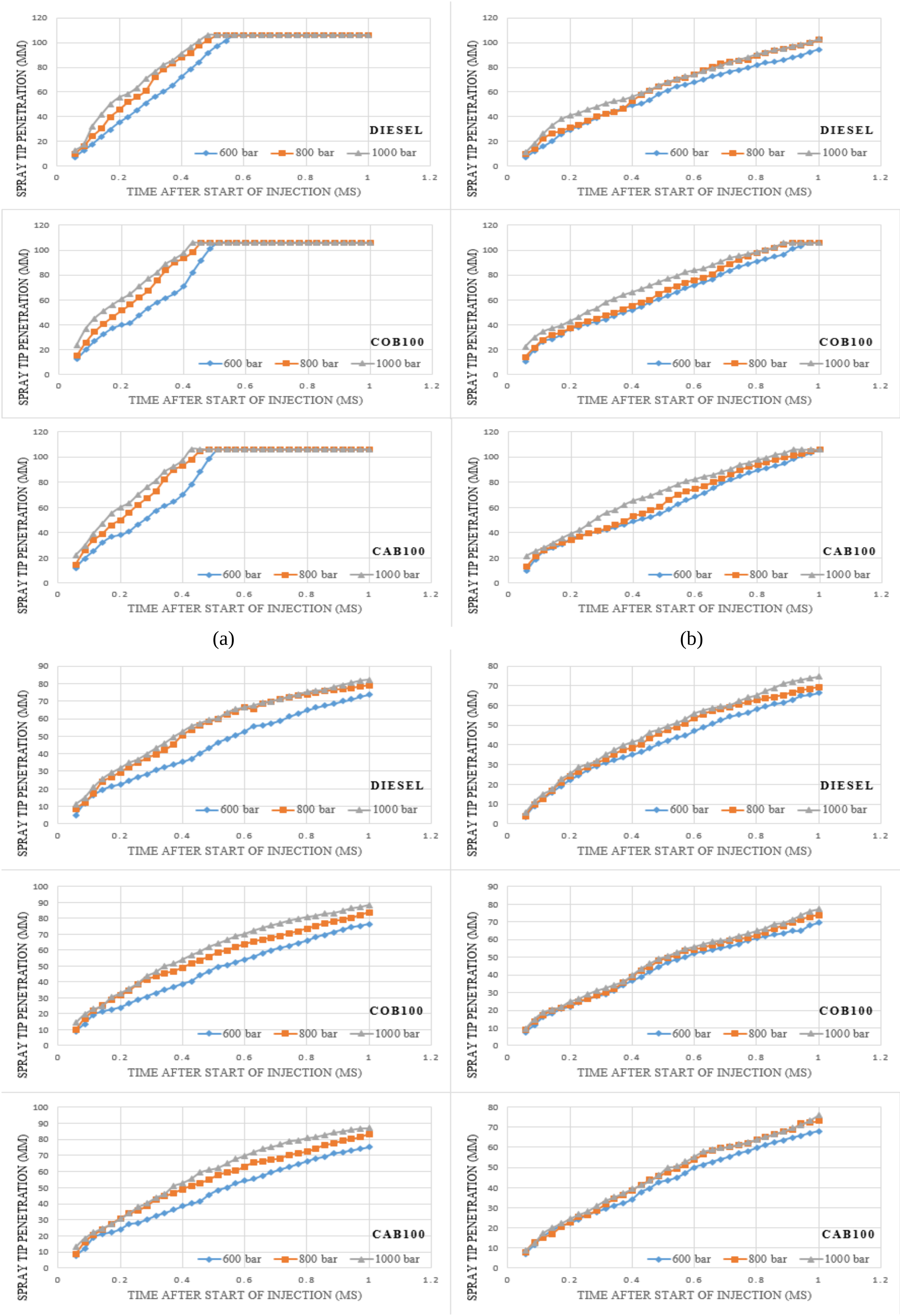
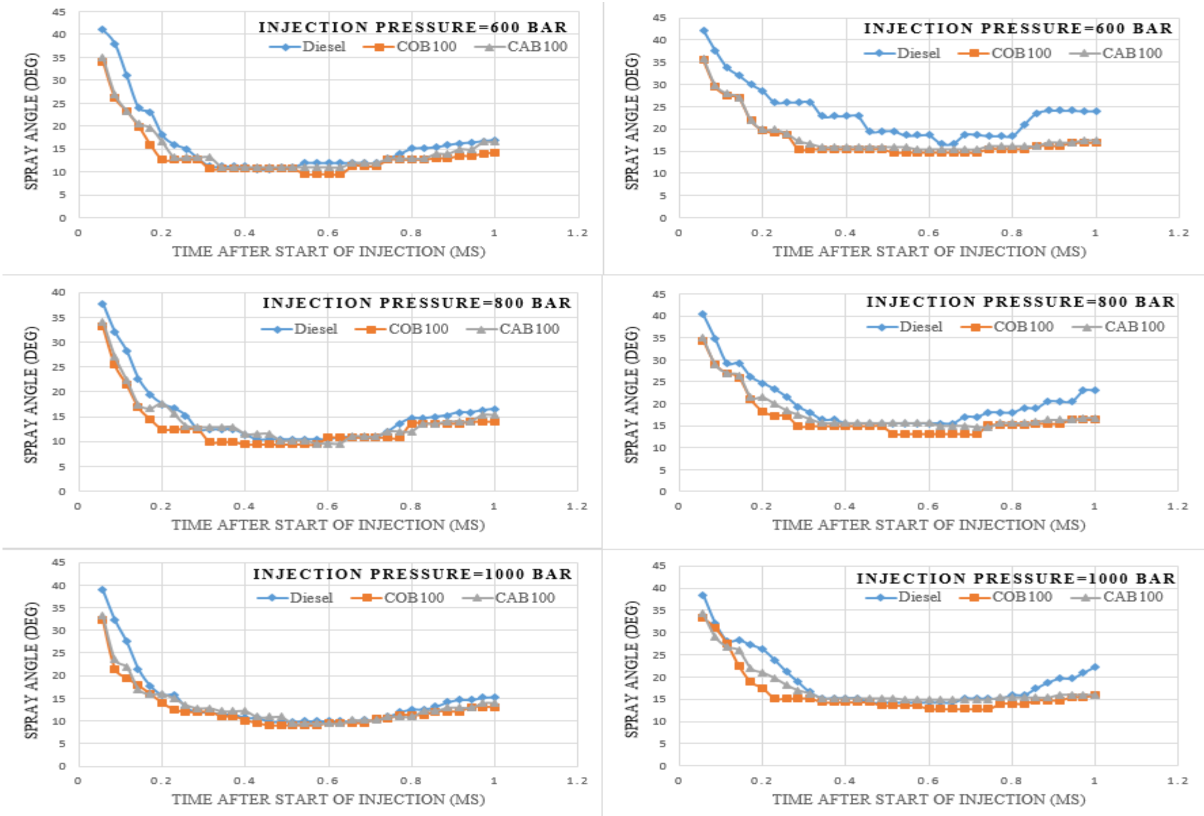
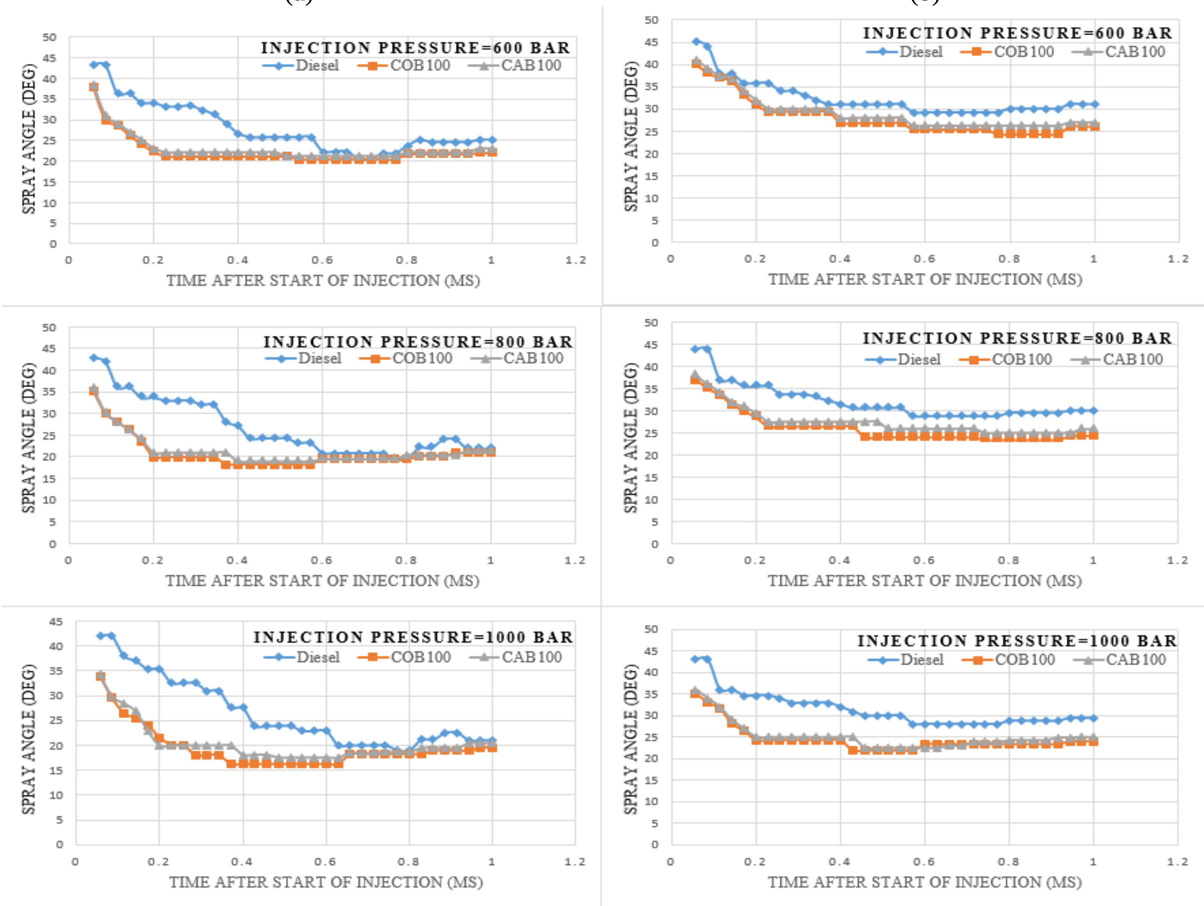


Figure 5. Effect of injection pressure on spray tip penetration for diesel, COB100 and CAB100 at (a) 0 bar, (b) 5 bar, (c) 10 bar and (d) 15 bar ambient pressure of spray chamber

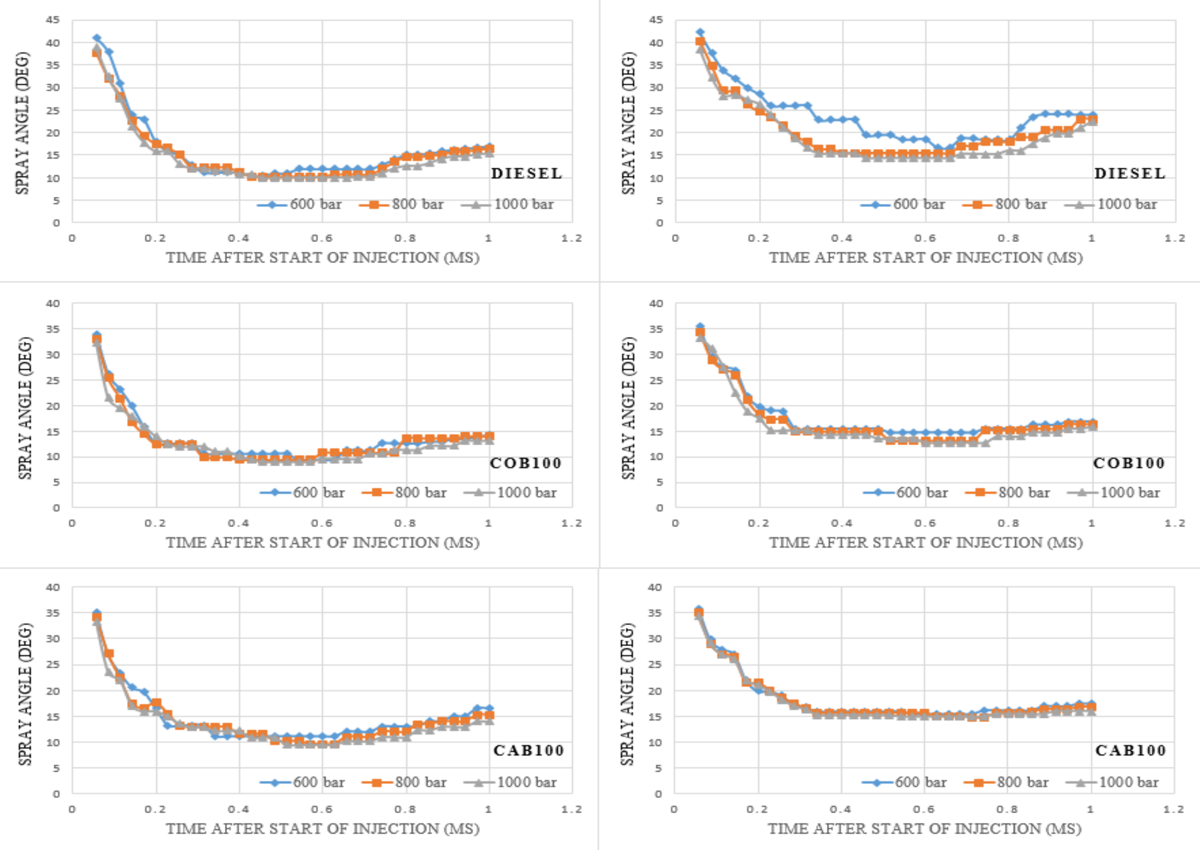


(a) (b)

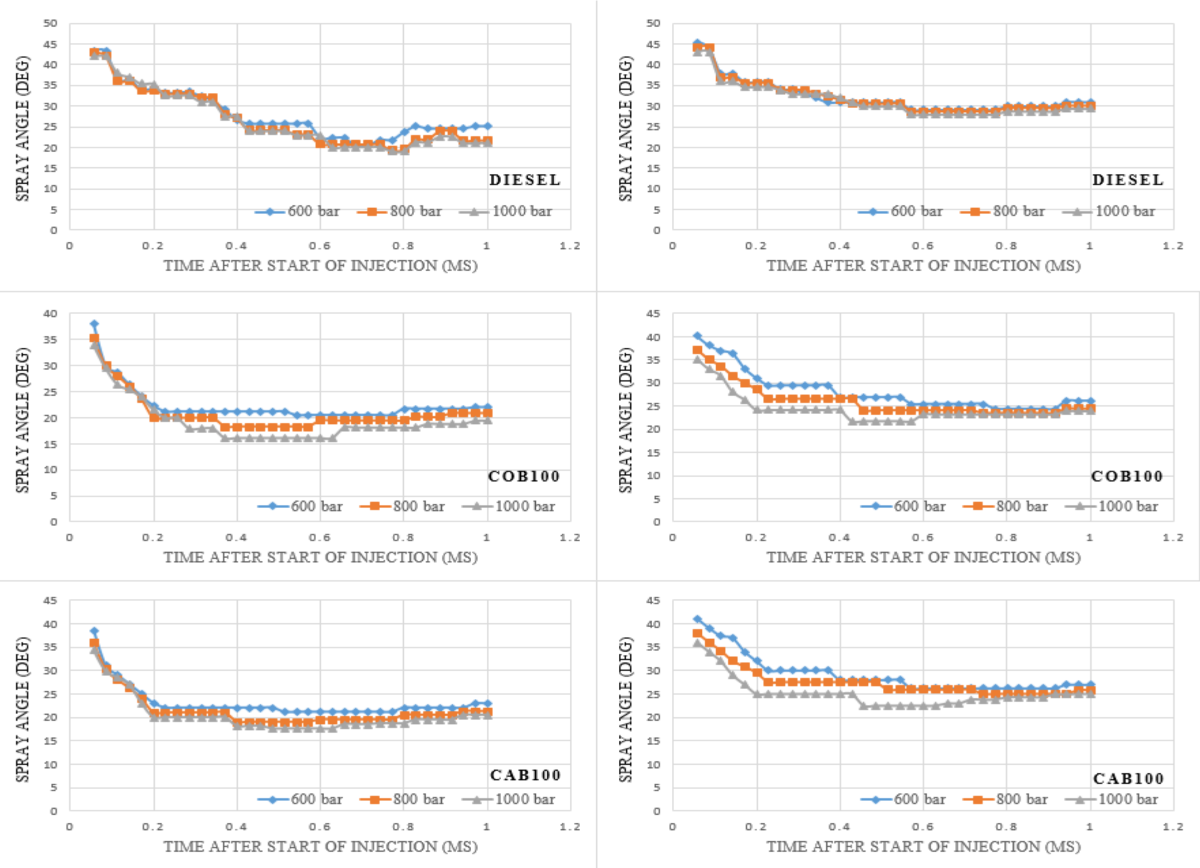


(c) (d)

Figure 6. Comparison of spray cone angle for diesel, COB100 and CAB100 at (a) 0 bar, (b) 5 bar, (c) 10 bar and (d) 15 bar ambient pressure of spray chamber.



(a) (b)



(c) (d)

Figure 7. Effect of injection pressure on spray cone angle for diesel, COB100 and CAB100 at (a) 0 bar, (b) 5 bar, (c) 10 bar and (d) 15 bar ambient pressure of spray chamber.

Figure 6 and Figure 7 represent the comparison of spray angle under conditions similar to Figure 4 and 5. Spray angle gets narrower when using biodiesels as fuel. It is because of the slowness of evaporation speed as a consequence of higher density and surface tension of biodiesel fuels. Furthermore, spray angle decreases as the injection pressure increases (Figure 7) due to its higher momentum.

Conclusion

The purpose of the study was investigation of spray characteristics – spray penetration and spray angle – of biodiesel fuels derived from canola oil and corn oil. In the direction of this purpose, a CVCC and high-speed optical system was utilized. The experiments were performed under different ambient and injection pressures. Ambient pressure varied from 0 bar to 15 bar with increment of 5 bar. Injection pressure varied from 60 Mpa to 100 Mpa with increment of 20 Mpa. The experiments were recorded by a high-speed camera and investigated by using a Spray Angle and Spray Penetration Calculation algorithm.

According to the results, biodiesel fuel had longer spray than diesel spray. Due to higher viscosity and density of biodiesel, spray was longer. The longest spray is obtained under 0 bar ambient pressure for biodiesel derived from corn oil. The penetration length decreased as the ambient pressure increased. It is caused by higher drag forces due to higher ambient pressures. Spray angle was narrower for biodiesel fuels due to viscosity and density difference between diesel and biodiesel.

Recommendations

Although spray penetration length and spray cone angle are important parameters, they are insufficient to explain how biodiesel fuels affect the engine performance and emission levels. Also, atomization behaviors of biodiesels are needed to be researched in order to better understand the effects of viscosity and density. Furthermore, combustion properties like flame lift-off length and flame angle should be analyzed to better explain the combustion behavior of biodiesel fuels.

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