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Analysis of Injection Pressure and High Ambient Density of Biodiesel Spray using Computational Fluid Dynamics

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ABSTRACT

Blended fuels have great potential for substitution with petroleum fuel for the purpose of emission control and fuel efficiency improvement. This research is to investigate the effect of high injection pressure and high ambient condition of biodiesel blends on spray characteristics using Computational Fluid Dynamics (CFD). The variables in this study are the various injection pressure (220, 250 and 280 MPa) and ambient temperatures (850, 950, and 1050 K), while the ambient pressure is kept constant at 8 MPa. The simulation in ANSYS FLUENT was used to observe the spray characteristics of biodiesel blends at various conditions. Simulation results show that longer spray penetration length with smaller spray significantly affects the mixture formation biodiesel blends compared to pure diesel at high injection pressure and ambient temperature.

1. Introduction

Internal combustion (IC) engines are widely used to produce mechanical power in many engineering applications, e.g. road and off-road vehicles, locomotives, marine vehicles, airplanes, and in stationary applications such as electric power generation and gas pipelines [1–6]. Biodiesel is renewable, non-toxic, less sculpture and aromatic contents. It can reduce the HC, CO, and PM which directly causes less greenhouse gas emissions [7-9]. However, since biodiesel has a higher flashpoint than diesel [1], the emission of NOx increases causing it to be one of the weaknesses of using biodiesel fuel [10-12]. Injection pressure and ambient temperature play a very important role in mixture formation and reducing the emission of NOx. The visualization of formation of biodiesel spray is important to understand the in-cylinder injection performance, spray characteristics and

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combustion to control the emission [1]. Abdul *et al*., [2] carried out the numerical simulation in various swirl air motion in small diesel engines and reported that; along with air motion, spray characteristics such as injection pressure, spray angle, injector-hole diameter and injection timing also have a significant effect on diesel combustion.

Biodiesel is a processed fuel that can be readily used in diesel-engine vehicles, which distinguishes biodiesel from the straight vegetable oils or waste vegetable oils used as fuels in some modified diesel vehicles [13-15]. ASTM International (originally known as the American Society for Testing and Materials) defines biodiesel as a mixture of long-chain monoalkylic esters from fatty acids obtained from renewable resources, to be used in diesel engines. Blends with diesel fuel are indicated as ‘‘Bx’’, where ‘‘x’’ is the percentage of biodiesel in the blend. For instance, ‘‘B5’’ indicates a blend with 5% biodiesel and 95% diesel fuel; in consequence, B100 indicates pure biodiesel [16-17]. Most of biodiesel fuel are mixed between diesel and vegetable oils such as almond, andiroba (Carapa guianensis), babassu (Orbignia sp.), barley, camelina (Camelina sativa), coconut, copra, cumaru (Dipteryx odorata), Cynara cardunculus, fish oil, groundnut, Jatropha curcas, karanja (Pongamia glabra), laurel, Lesquerella fendleri, Madhuca indica, microalgae (Chlorella vulgaris), oat, piqui (Caryocar sp.), poppy seed, rice, rubber seed, sesame, sorghum, tobacco seed, and wheat [17-19]

Biodiesel fuels have a higher penetration length than diesel fuel as the viscosity of biodiesel is higher than diesel [18]. Agarwal *et al*., [18] indicated in a study on in-nozzle-flow and spray characteristics for mineral diesel, Karanja and Jatropha biodiesels that the spray penetration increases as the blend percentage of Karanja oil increases. Meanwhile, diesel has the lowest spray penetration amongst all other blends. This is due to relatively higher degree of cavitation for diesel, along with cavitation patterns reaching the nozzle exit, a higher degree of atomization was expected in the zone near the nozzle exit [16-19]. Computational Fluid Dynamics (CFD) is a type of fluid mechanics that used numerical methods and algorithms to analyze problems which involves fluid flows. Computers are required to perform the calculations for simulation between the interaction of liquids and gases with surfaces defined by boundary conditions. Furthermore, better solutions can be achieved with high-speed supercomputers. Research could be done by this software which can improve the accuracy and speed of complex simulation scenarios like transonic or turbulent flows.

The above literatures show that studies have been carried out on the effects of fuel along with mixture formation on the combustion process and emission formation of a diesel engine. Therefore, to have better understanding the research gap, it is very important to analysis the fuel air mixing and sprays characteristics using Computational Fluid Dynamics (CFD). This research is to investigate the effect of high injection pressure and high ambient condition of biodiesel blends on spray characteristics using Computational Fluid Dynamics (CFD). Hence, the objective of this study is to analyze the effects of injection pressure and ambient density to the formation of fuel spray with constant orifice diameter in the constant volume chamber by using CFD. The variables in research are the various injection pressure (220, 250 and 280 MPa) and ambient temperatures (850, 950, and 1050 K), while the ambient pressure is kept constant at 8 MPa. The simulation in ANSYS FLUENT was used to observe the spray characteristics and mixture formation of biodiesel blends at various operating conditions. In this simulation, the parameter of fuel injector was held fixed is with orifice diameter of 0.12 mm and angle of 60^0.

2. Simulation Setup

Generally, the simulation in ANSYS FLUENT involves three main stages which are pre-processing, solver, and post processing. The design of injector used in this study is only focused on the injector head and combustion chamber. Figure 1 shows the overall the simulation and analysis flow chart. Figure 2 shows the schematics of 3D model of cross section of combustion chamber of rapid compression machine (RCM), while Figure 3 shows the geometry of fuel injector has six orifice holes, diameter 0.12 mm with an angle of 60^0 between each other. Figure 4 shows the section geometry of the combustion chamber used for geometry modeling. It is shows the 1/6 section from the overall combustion geometry in order to reduce the simulation time processing and sufficient analysis.

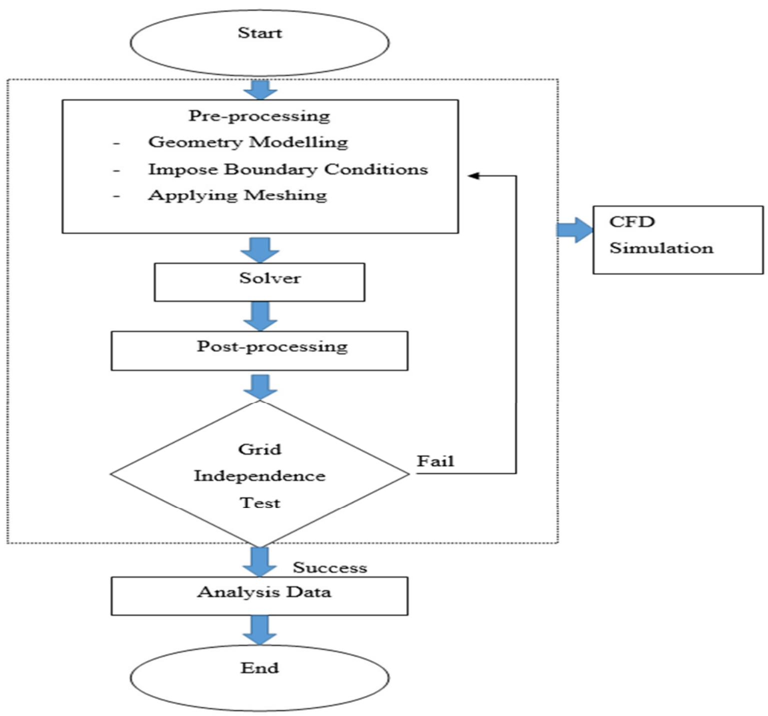

Fig. 1. Modelling flowchart in ANSYS Fluent

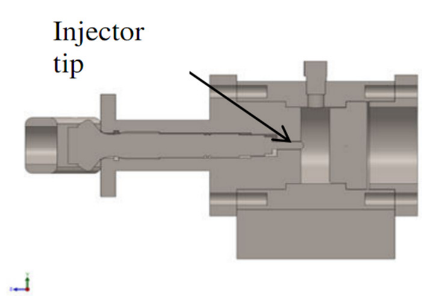

Fig. 2. 3D model of cross section in internal combustion chamber of rapid compression machine

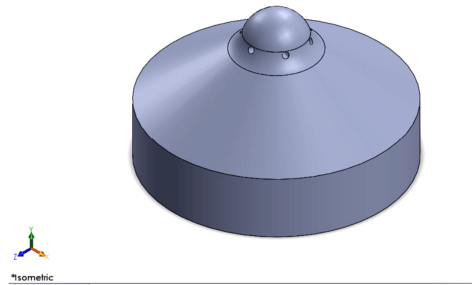

Fig. 3. The geometry of injector with six orifice holes

Fig. 4. Geometry of 1/6 part of injector and its combustion chamber

Mesh independence study has been conducted for the operating parameter with Hemispherical Combustion Chamber to study the effect of mesh density on the predicted results such as spray characteristics. In simulation and modeling aspects, the meshing used on the injector as shown in Figure 5. To show the mesh independence and boundary conditions simulations including the inlet, outlet and the wall were conducted at operating condition for all meshes and the predicted sprays behavior histories were shown in Figure 6, Figure 7 and Figure 8. Meanwhile, Table 1 shows the boundary conditions used in ANSYS Fluent to conduct the simulations.

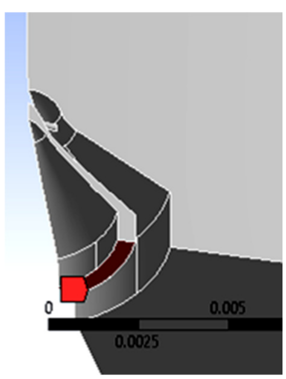

Fig. 5. Meshing used on the injector

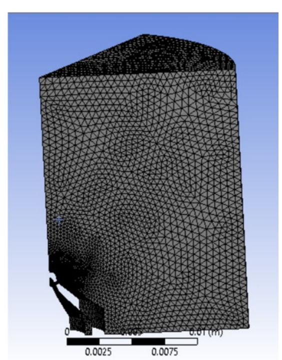

Fig. 6. Inlet position at spray injector

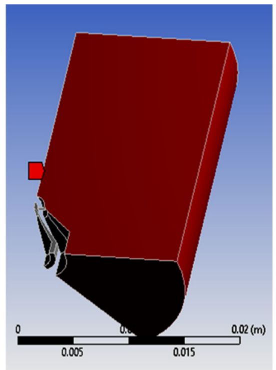

Fig. 7. Outlet position at the spray chamber

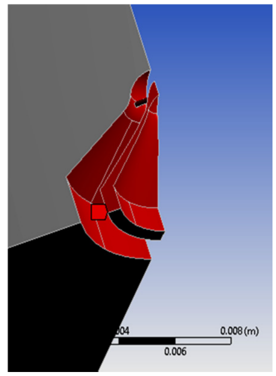

Fig. 8. Wall position at injector and spray chamber

Table 1
Boundary conditions used in ANSYS Fluent

General	Pressure based absolute velocity formulation	Transient time
Model	Species transport	Biodiesel
Viscous	k-epsilon (2 equations)	Realizable
Material	Air	Diesel-vapor
Boundary Condition	Inlet	Outlet Wall
Parameters	Injection pressure	220 MPa 250 MPa 280 MPa
	Ambient pressure	8 MPa
	Ambient temperature	1050 K

In this study, the computational fluid dynamics problem which include the Continuity equation is considered for simulating flow inside the combustion chamber. Equations were solved in the computational fluid dynamics problem which include the Continuity equation, Momentum equation (Navier Stokes equation), and Energy equation for computations involving meshes with moving boundaries and compressed flows as it is the case in IC-engines. Thus, the application of the mass, momentum and energy conservation, the three stated equations can be derived as follows.

a) Continuity equation

$$\frac{D\rho}{Dt} + \rho \frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

b) Momentum equation

$$\underbrace{\rho\frac{\partial U_j}{\partial t}}_{I}+\underbrace{\rho U_i\frac{\partial U_j}{\partial x_i}}_{II}=-\underbrace{\frac{\partial P}{\partial x_j}}_{III}-\underbrace{\frac{\partial \tau_{ij}}{\partial x_i}}_{IV}+\underbrace{\rho g_j}_{V} \quad (2)$$

Where,

$$\tau_{ij}=-\mu\left(\frac{\partial U_j}{\partial x_i}+\frac{\partial U_i}{\partial x_j}\right)+\frac{2}{3}\delta_{ij}\mu\frac{\partial U_k}{\partial x_k} \quad (3)$$

c) Energy equation

$$\underbrace{\rho c_\mu\frac{\partial T}{\partial t}}_{I}+\underbrace{\rho c_\mu U_i\frac{\partial T}{\partial x_i}}_{II}=\underbrace{-P\frac{\partial U_i}{\partial x_i}}_{III}+\underbrace{\lambda\frac{\partial^2 T}{\partial x_i^2}}_{IV}\underbrace{-\tau_{ij}\frac{\partial U_j}{\partial x_i}}_{V} \quad (4)$$

I: Local change with time, II: Momentum convection, III: Surface force, IV: Molecular-dependent momentum exchange (diffusion), V: Mass force

3. Results and Discussion

This section investigates the simulation at variant of fuel and different injection pressure and ambient temperature. In this study the based condition is temperature 850 K. The simulation was performed at different injection pressures which are 220 MPa, 250 MPa and 280 MPa, while the different ambient temperature was held fixed at 850 K. The other operating parameters were kept constant at high ambient pressure at 8 MPa. The fuel was injected by six-hole injector with a diameter of 0.12 mm. The changes of spray simulation at different fuel injection pressure and fuel blending ratio under based condition of 850 K are shown in Figure 9.

However, Figure 10 and Figure 11 show the effects spray penetration and spray behaviour under ambient temperature of 950 K and high ambient temperature 1050 K, respectively. It seems that, the higher blending ratio and higher ambient temperature have great influences on the changes spray behaviour. It is shown that the injection pressure plays and different of fuel blending ratio a significant role on the changes of the spray angle that significantly influences on mixture formation. This is a result of fuel particles break into smaller particles as the difference of injection injector and combustion chamber is fairly large.

3.1 Effect of High Biodiesel Blending Ratio and Injection Pressure on Spray Characteristics

The effect of high biodiesel blending ratio and injection pressure on spray characteristics was firstly investigated. The biodiesel blending ratios are B10 and B20 and they were compared with a pure diesel at different injection pressures which are 220 MPa, 250 MPa and 280 MPa. The ambient pressure, 8 MPa was kept constant.

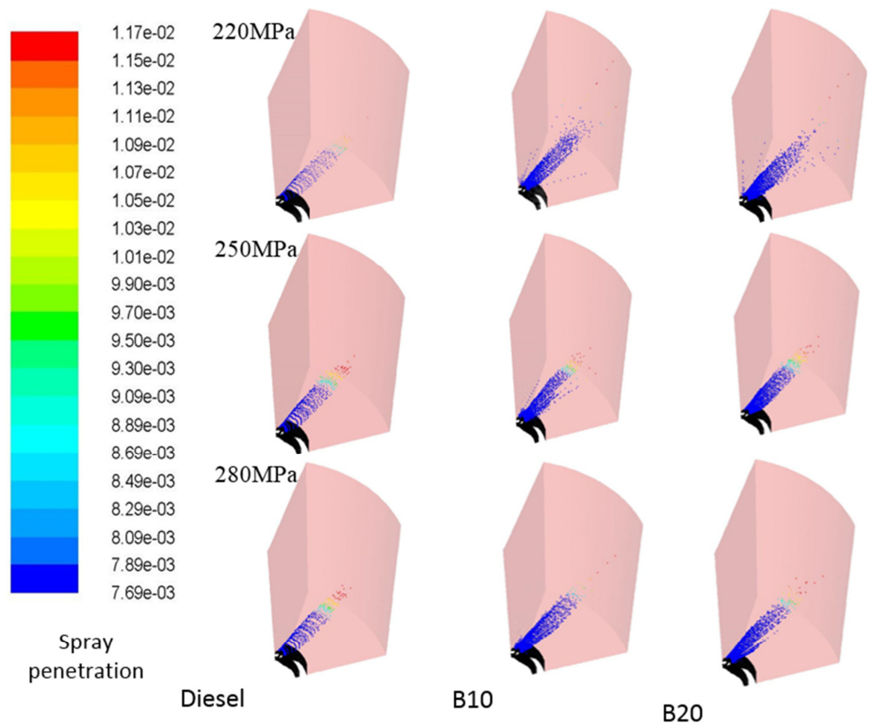

Fig. 9. Effects of variant blending fuel and injection pressure under based condition temperature of 850 K

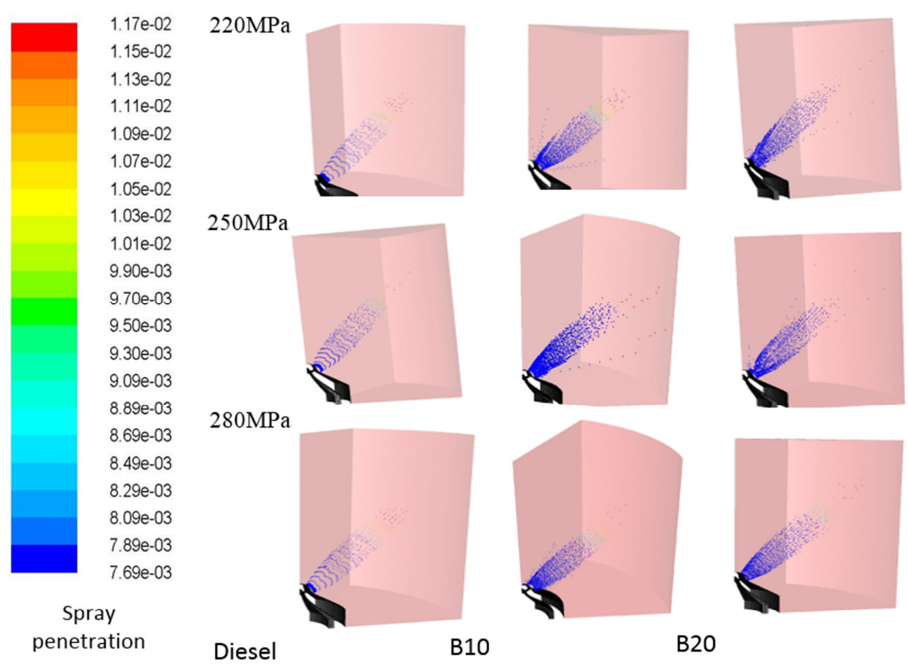

Fig. 10. Effects of blending fuel and injection pressure under ambient temperature of 950 K

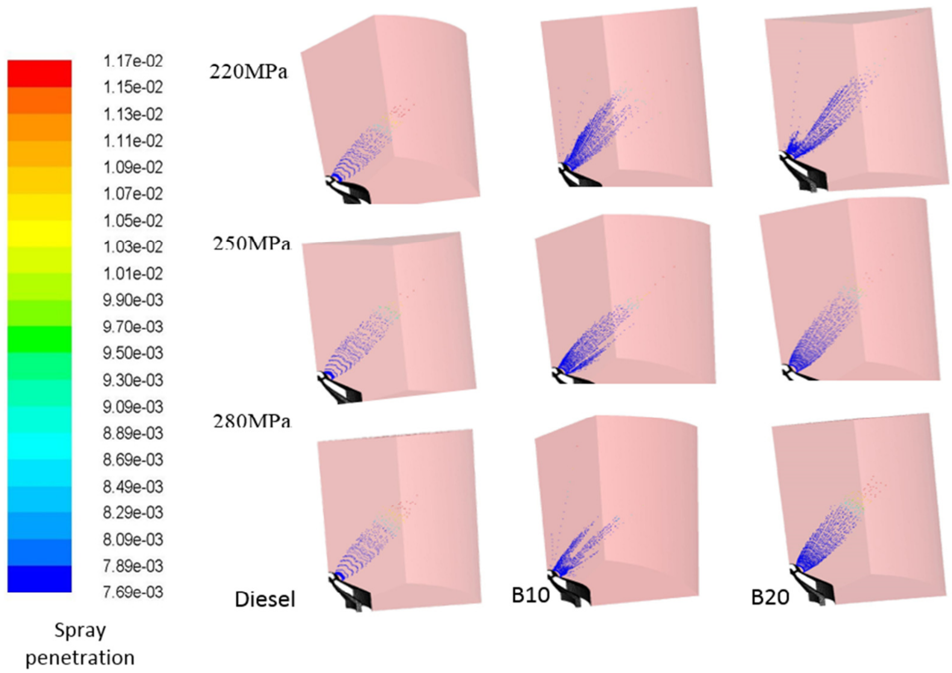

Fig. 11. Effects of variant blending fuel and injection pressure under high ambient temperature of 1050 K

Liquid phase spray penetration lengths of different CPO biodiesel blends at injection pressures are presented in Figure 12. From the data, it can be seen that both B10 and B20 blends have longer penetration length than that of pure diesel in all three ambient temperatures. Furthermore, as a blended fuel, B10 gives a remarkably longer spray penetration length than that of pure diesel. This finding is obtained when the difference of spray penetration length between B10 and B20 is small. Therefore, B10 and B20 give almost similar quantity of spray penetration length. In contrast, pure diesel, although gives shorter penetration length than B10 and B20, also increases with regard to the increase of injection pressure. Figure 13 illustrates the spray angle results under different injection pressure with temperature. Based on the data, it shows that the spray angle increases with respect to the increasing pressure and temperature. Injection pressure has a great influence on the spray behaviour and play an important role affecting the spray angle. Spray angle increases noticeably due to the effect of ambient temperature on fuel atomization. According to the graph, the spray angle of pure diesel is higher than both B10 and B20. This is mainly due to the high viscosity of B10 and B20, which is higher than pure diesel. Thus the spray particles of biodiesel blends do not disperse easily due to the opposing ambient pressure of combustion chamber. Meanwhile, the opposite occurs with diesel where diesel particles easily disperse as it is injected into the chamber causing in high spray angle.

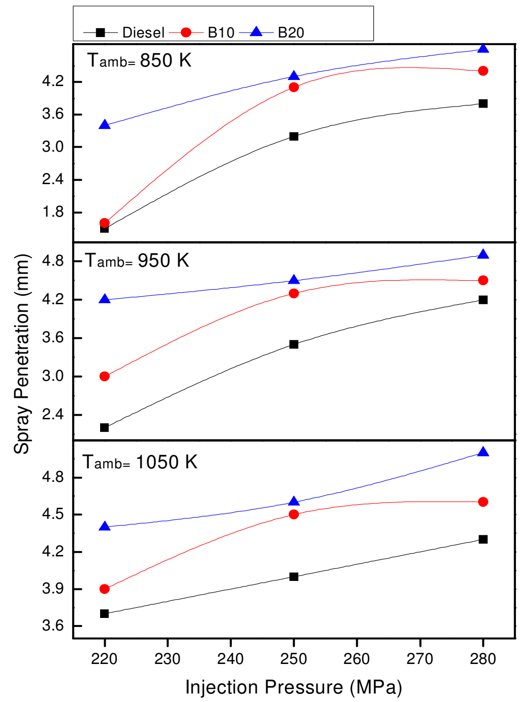

Fig. 12. Effect of Injection Pressure on Spray Penetration Length

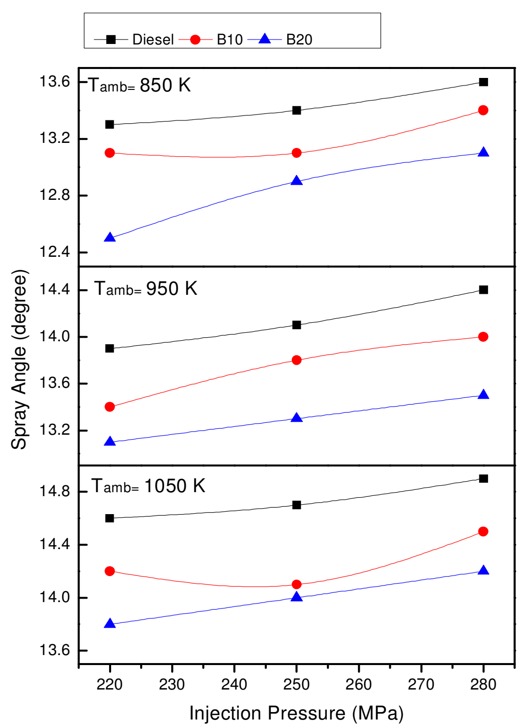

Fig. 13. Effect of Injection Pressure on Spray Angle

3.2 Effects of High Biodiesel Blending Ratio and Ambient Temperature on Spray Characteristics

This section attempts to illustrate the spray characteristics under the condition of high ambient temperature. Basically, the spray characteristics such as spray penetration length and spray angle were investigated under different ambient temperatures starting from 850 K to 1050 K with 100 K interval. The injection pressures, on the other hand were also increased as a variable from 220 MPa to 280 MPa with an interval of 30 MPa.

Figure 14 illustrates the spray penetration lengths of biodiesel blends comparing with pure diesel at ambient temperatures of 850 K, 950 K and 1050 K. Figure shows that the penetration length of both biodiesel blends and diesel as the ambient temperature increases. This is mainly caused by the high injection pressure used. The differences between ambient pressure and injection pressure forces the injected particles to travel further into combustion chamber before evaporating. In comparison to B20, the penetration length of pure diesel is rather short as it is easily evaporating. Meanwhile, the penetration length of B10 is longer than pure diesel but shorter than B20 due to the difference in blending.

Furthermore, data from the spray angle of biodiesel blends and pure diesel with respect to ambient temperature is illustrated in Figure 15. It can be seen that spray angle of all three fuels increases as the ambient temperature risen. Spray angle of pure diesel is the highest compared to B10 and B20. Meanwhile, lower spray angle can be detected in B20 as its high viscosity causing it harder to evaporate as soon as it is injected. However, increment in spray angle of both biodiesel blends can be seen as the injection pressure increases.

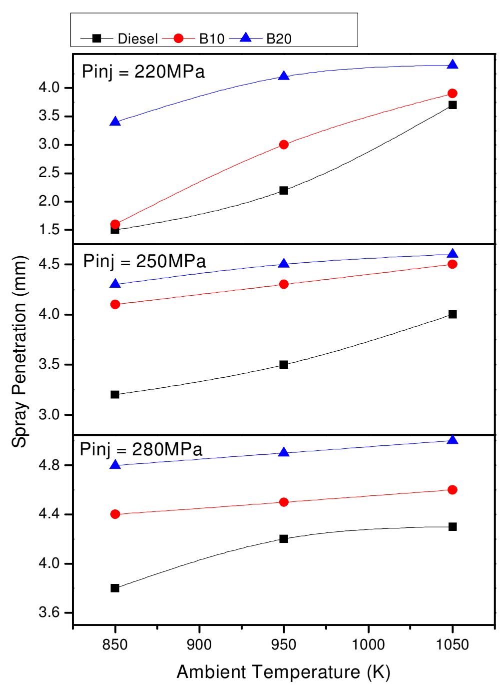

Fig. 14. Effect of Ambient Temperature on Spray Penetration Length

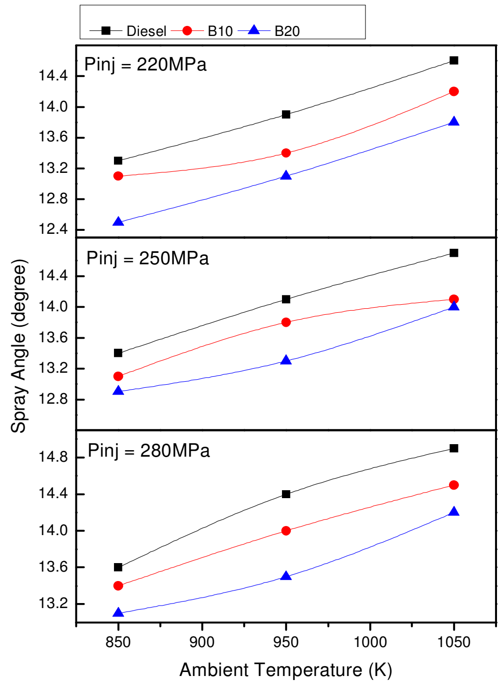

Fig. 15. Effect of Ambient Temperature on Spray Angle

3.3 Effect of High Injection Pressure and Ambient Temperature on Spray Characteristics

Figure 16 shows the relationship of both ambient temperature and injection pressure and spray penetration length. Steady increase in spray penetration length as the injection pressure and ambient temperature risen. The longest penetration is achieved by B20 at injection pressure 280 MPa and ambient temperature 1050 K. On the other hand, shortest penetration length can be seen in pure diesel at injection pressure 220 MPa and ambient temperature 850 K.

As for spray angle, the changes in spray characteristics can be seen in Figure 17. Unlike spray penetration, pure diesel has the highest spray angle compared to both B10 and B20 at injection pressure 280 MPa and ambient temperature 1050 K. Meanwhile, the lowest spray angle can be seen in B20 at injection pressure 220 MPa and ambient temperature 850 K. As the temperature and pressure increased, a great variation in the spray structure is observed. It promotes mixture formation and distributes larger amount of fuel between sprays thus creates good spray atomization and exhibits a greater amount of fuel-air premixing prepared for combustion. Furthermore, the increment of the ambient temperature promotes the evaporation process, or in other words, evaporation process is elevated by higher ambient temperature. Therefore, the increment of the ambient temperature causes the rate of fuel evaporation increased. Thus fuel droplets with small diameter tend to evaporate easily while those with greater diameter take a much longer time to evaporate.

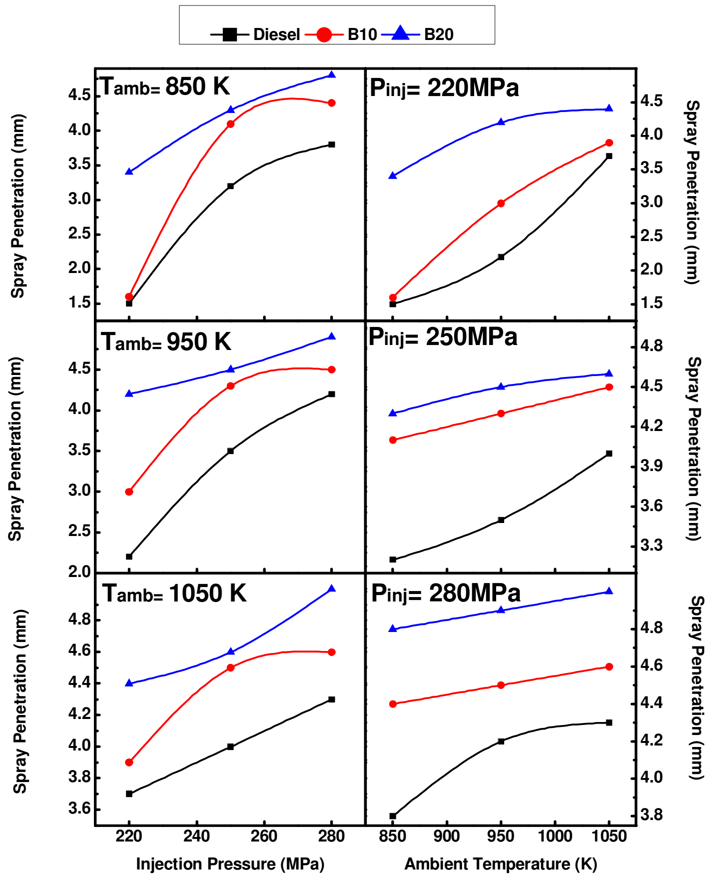

Fig. 16. Effect of Ambient Temperature and Injection Pressure on Spray Penetration

4. Conclusion

The results of the influence of injection pressure and ambient density on the spray characteristics of biodiesel spray are summarized as follows. This study has shown a simulation flow of the fuel flowing in the nozzle spray before the combustion process. This simulation was performed on single nozzle orifice diameter which is 0.12 mm. The ambient temperatures inside the chamber are 850, 950, 1050 K, while the injection pressures are 220 MPa, 250 MPa, 280 MPa, and with the constant ambient pressure at 8 MPa. Different temperature influences the droplet diameter of fuel. As the ambient temperature increases, the spray tends to easily evaporate and disperse. This results in wider spray angle of the fuel. Thus the increase in ambient temperature increases the spray angle of the fuel used. In this study, it was found that pure diesel has a higher spray angle as the ambient temperature increases compared to B10 and B20 blends. This is due to high viscosity of B10 and B20 which causes the droplet hard to break into smaller size and disperse. Different injection pressure influences the spray penetration length of the fuel; the higher the injection pressure, the longer the spray penetration length of fuel. This is the deduction made from this study. In all conditions, the penetration length of pure diesel, B10 and B20 blends increase as the injection pressure increases. The longest penetration length is achieved by B20 as it has the highest viscosity compared to B10 blend and pure diesel.

In conclusion, ambient temperature mostly influences the spray angle while injection pressure affects the spray penetration length. The summarized results from this study are as follows:

a) Increase in injection pressure causes the spray penetration length of biodiesel and pure diesel. The spray penetration of biodiesel is higher than that of pure diesel.
b) The increasing biodiesel's spray penetration length can be seen well as the blending ratio of biodiesel increases. It is clearly seen that B20 has a longer penetration length than that of B10.
c) Increase in ambient temperature increases the spray angle of both pure diesel and biodiesel. In addition, biodiesel has smaller spray angle compared to pure diesel.

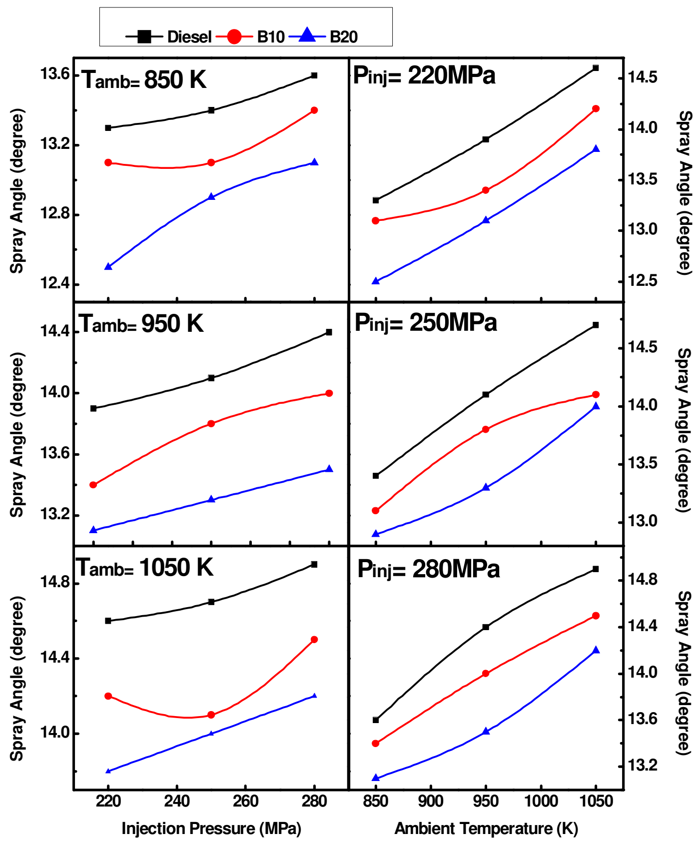

Fig. 17. Effect of Ambient Temperature and Injection Pressure on Spray Angle

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