MACROSCOPIC SPRAY CHARACTERISTICS OF DIESEL AND BIODIESEL-DIESEL BLEND: AN EXPERIMENTAL COMPARISON

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ABSTRACT

The qualitative aspects of the fuel spray particularly spray length and cone angle play a significant role not only in the temporal sequence of clean and efficient combustion, but also in the control of engine exhaust emissions and efficiency optimization. This paper investigates the effect of injection duration and ambient pressure on spray development, spray tip penetration (L) and cone angle (β) of biodiesel-diesel (20%/80%: v/v) blend (B20) and diesel, and hence compares the quality of the fuels. Both 'L' and 'β' play a key role in the fuel evaporation and mixing of fuel with air in the combustion chamber. It was found that the injection pressure, spray tip penetration and cone angle of the fuels increased with the increase in injection duration. Furthermore, the injection pressure of B20 was higher than that of diesel because of its higher incompressibility, which increased the droplet momentum and tip penetration. The ambient pressure displayed a stronger impact on 'L' and 'β' of the fuels, compared with injection duration. The 'L' was increased, while 'β' decreased with the decrease in P_{amb} due to the decrease in resistance to penetration velocity. The shapes of spray images of two fuels were almost similar. However, B20 exhibited larger 'L' and 'β' due to higher initial velocity and mass of droplet, compared with diesel. This indicates that relative to diesel fuel, B20 has a stronger impact on the spray performance, and thus improves both 'L' and 'β'. During the earlier phase of time after start of injection, the relative difference between two fuels in terms of their spray tip penetration was smaller. This difference augmented, and then became roughly stable. Before the commencement of a comparatively steady phase of time after the start of injection, the test fuels revealed an appreciable relative difference in terms of their 'β'.

Keywords: *alternative fuels, biodiesel, spray properties, cone angle, tip penetration*

INTRODUCTION

Biodiesel is receiving increasing attention as an alternative fuel during the past few years. It is renewable, biodegradable, readily available, environmentally more benign, and clean burning fuel. It is produced by the transestrerifcation process of the vegetable oils, waste cooking oils or animal fats with methanol or ethanol using acids or bases as catalysts[1]. It is an ultra low sulfur, non-toxic, and carbon neutral fuel having increased lubricity, lower volatility, higher cetane number, higher flash point and enriched oxygen[2-4].

It has been reported that biodiesel reduces the carbon monoxide, total hydrocarbon and particulate matter emissions due to its complete combustion[5-6]. However, discordant findings have been reported in the literature for the NO_x emissions. Some authors have claimed that NO_x emissions are increased with the use of biodiesel[7-8]. On the other hand, in the viewpoint of some authors biodiesel usage decreases the NO_x pollutants[6,9]. Many studies focused on unregulated emissions have revealed that biodiesel can reduce the polycyclic aromatic hydrocarbons[10], volatile organic compounds[11], and that it has less adverse effect on human health relative to petroleum diesel fuel[12].

Biodiesel is completely miscible with petroleum diesel in any proportions, as different blends, and may replace petroleum diesel with little or no modification of the diesel engine[6,13]. The engine performance remains almost unaffected when the biodiesel and diesel are compared on the basis of their relative equivalence ratio[14]. Lin et al.[10] performed experiments

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on a naturally aspirated 2.84 L engine fuelled on ultra low sulfur diesel, pure palm-oil based biodiesel and B20. At full load, the loss of power was only 3.5% with neat biodiesel and 1% with B20. Shah et al.[15] carried out experiments on a turbocharged, direct injection, heavy duty and inter-cooled diesel engine fuelled on commercial diesel, neat biodiesel from soybean oil and B20. According to the results, the loss of power at 50% load of maximum torque speed was only 1.5% with neat biodiesel and almost zero with B20.

The main thrust of the current work is to study the macroscopic spray characteristics of conventional diesel and B20, and hence take a closer look at their spray tip penetration and cone angle because these properties play a critical role in the injection, atomization, combustion, engine performance and exhaust emissions[16]. Moreover, the knowledge of spray shape evolution is very important for the optimum fuel distribution within the combustion chamber together with high air-fuel mixing rate[17]. Although some data is available in the literature on physical properties like injection characteristics, combustion parameters (such as start of injection, ignition delay, maximum combustion pressure, maximum rate of pressure rise, heat release rate, etc.) and atomization of biodiesel, spray characteristics of biodiesel and its blends still need to be addressed comprehensively. This study is believed to be informative and useful for comprehending the phenomenon of internal mixture formation and spray development with B20.

The reason for selecting B20 as a biodiesel-diesel blend in this study is that B20 has become the most popular biodiesel-diesel blend in different countries[18]. For example, in Taiwan, the B20 usage has been incorporated in energy policies, and thus its use has been encouraged in public sector vehicles[19]. Moreover, the current study is an extension of previous work in which authors have already shown that B20 has the potential to reduce the carbon monoxide, hydrocarbon and particulate matter emissions with a little or no increase in the NO_x emissions[15]. Relative to commercial diesel, B20 can decrease the polycyclic aromatic hydrocarbons and their toxic equivalent[20], volatile organic compounds[21], and ozone forming potential of carbonyls in terms of specific reactivity[22].

MATERIALS AND METHODS

Test Fuels and Experimental Conditions

Two test fuels namely diesel and B20 were used in this study. Diesel was purchased from a commercial fuel station, and is the representative of fuel being sold in Beijing China, while biodiesel was produced from the waste cooking oil by the process of transesterification. The main properties of the test fuels are listed in Table 1.

Table 1: Properties of fuels

Properties	**D**	**B20**	**Test Method***
Bulk modulus (40°C)	1350	1380	–
Density (kg/m^3)	834.8	845.1	SH/T 0604
Viscosity (mm^2/s) at 20 ºC	3.393	3.807	GB/T 265
Lower heating value (MJ/kg)	42.8	41.57	GB/T 384
Sulfur content (ppmw)	22	20.63	SH/T 0253-92
Cetane index	52.7	54.9	GB/T 386-91
Carbon content (%)	87	84.1	SH/T 0656-98
Hydrogen content (%)	13	13.2	SH/T 0656-98
Oxygen content (%)	0	2.27	Element analysis

*Chinese standard[23]

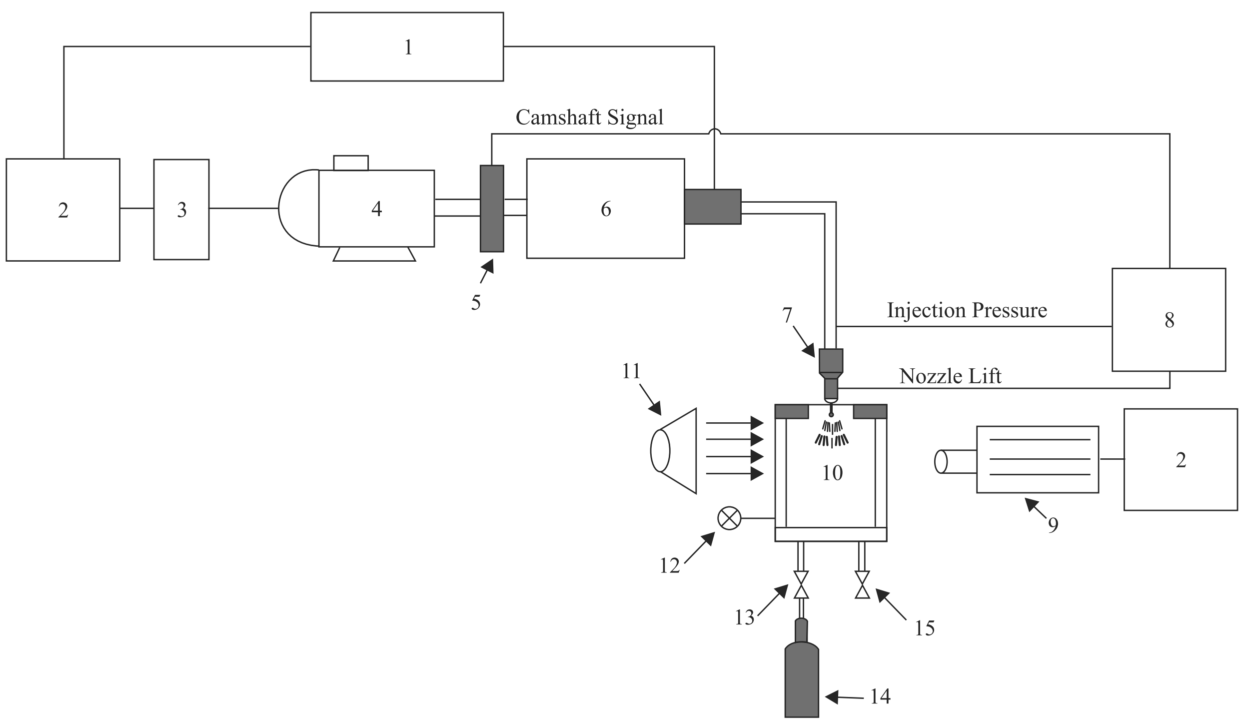
In order to pressurize the constant volume chamber (CVC) and simulate the cylinder inside environment, the CVC was charged by a high pressure vessel filled with sulfur hexafluoride (SF_6). The SF_6 was preferably used as an ambient gas in this study because of its high molecular weight, viscosity and optical properties, very similar to those of air. Furthermore, it is an inert, good insulator, non-toxic and inexpensive gas with no corrosive effects on the test bench[24]. The ambient pressure (surrounding pressure of SF_6 with which fuel droplet comes in contact) was varied from 1.6 to 0.4 MPa with the help of a leakage valve. The rotational speed of the shaft was fixed at 1800 rpm, but the injection duration was varied from 21 to 33 degree crank angle with a difference of 4 CAD. The spray images recording speed was 6000 frames per second (fps), and images were recorded at 250*496 pixels.

Table 2: Experimental conditions

Parameter	**Value/Characteristic**
Nozzle diameter (mm)	0.28
Ambient gas	SF_6
Ambient Temperature (K)	300
Ambient Pressure (MPa)	0.4, 0.8, 1.2, 1.6
Ambient gas density (kg/m^3)	6.09
Speed (rpm)	1800
Injection duration (CAD)	21, 25, 29, 33
Spray image (fps, pixel)	6000, 250*496

Equipments and Procedure

The spray measuring system consists mainly of an electronic unit pump bench, a constant volume chamber and a spray visualization system, as shown in schematic diagram Figure 1. The electronic unit pump further consists of an injector having five holes, an electronic control unit, a unit pump, an electromotor, a frequency converter and a combustion analyzer – Dewetron (CA-5000). The combustion analyzer receives the signals of nozzle valve lift, driving shaft angle and injection pressure. The injection duration angle was changed by changing the driving



1-ECU, 2-Computer, 3-Frequency converter, 4-Electromotor, 5-Connector, 6-Unit-pump, 7-Fuel injector, 8-Combustion analyzer, 9-Camera, 10-CVC, 11-Dyprosium light, 12-Pressure gauge, 13-Inlet valve, 14-SF_6, 15-Leakage- valve

Figure 1: Scheme of the experimental setup.

shaft angle with the variation of pulse width of the controlling signal from the unit pump. Further, the speed of electronic unit pump was controlled through signals using electronic control unit. In order to get different ambient pressures, a constant volume chamber was used. It is transparent from both sides making the inside visible for the observers. Since, the basic technique used in this study was the photography of the spray development with a fast video camera under direct lighting. Therefore, a spray visualization system was used for the acquisition of spray images. The SVS consists of a high speed digital camera (Redlake Corp., HG-LE) and two 1000 W dysprosium lights. Among the five holes of the injector or nozzle, only one was used in this study. The diameter of each nozzle hole is 0.28 mm as given in Table 2. The ambient gas temperature, speed of shaft, and other experimental conditions are also listed in Table 2. Since, the fuel temperature is an important parameter, which can affect the fuel properties, injection and spray characteristics. Therefore, the injected fuel was not allowed to return to the fuel tank. In this way, the fuel temperature was kept constant at almost 300 K. Three measurements were taken at every mode of the experiments, and their mean was taken to present the result. The accuracy of the measurements of 'L' and 'β' were ±0.5 mm and ±0.5°, respectively.

The photographs taken during the experiments were stored in the files by the video acquisition station, and every stored image was off-line digitally elaborated/analyzed to investigate the geometric characteristics of the fuels spray and their evolution. In order to recover the images, and hence know the behavior of the injected fuel, an automatic procedure based on VC + + and MATLAB version 7.4 (R 2007 a) was developed. The developed software is capable of processing, and thus analyzing the large number of pictures.

In the processing technique, the first step is the binarization of the acquired images. Binarization is an operation which decreases the image dynamic (range of scenes being captured or photographed in motion) from 8 to 1 bit[25]. The threshold was set either to 1 or 0 depending on the light level. When the light level was above the threshold, its value was set to 1 and the pixel was recognized as a liquid particle, otherwise the threshold was set to 0. Pixels are recognized as liquid particles when their light level is above a threshold[25]. After the binarization process, the tip penetration of the binarized image was found by scanning it, and thus determining its top and bottom ends where the pixel value was changed from 0 to 1 or 1 to 0. The spray tip penetration which is defined as maximum distance that spray can cover from nozzle tip[26] can also be used to determine the spray cone angle. The spray cone angle is defined as the angle subtended between two lines from nozzle tip passing through the edges of the spray on the horizontal line at 1/3 L downstream of the nozzle tip as shown in Figure 2.

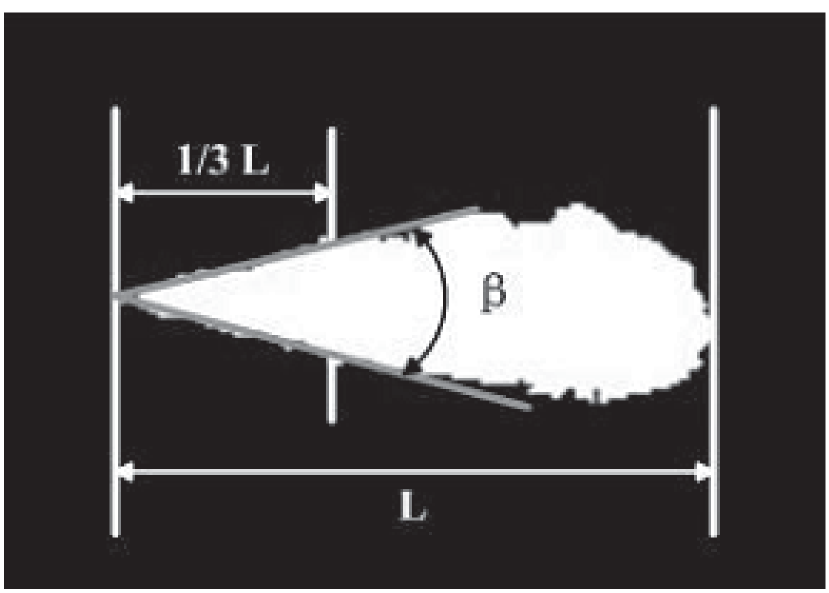


Figure 2: A spray model to define the tip penetration and cone angle.

RESULTS AND DISCUSSION

In diesel engines both qualitative and quantitative aspects of injected fuel play a key role in engine performance, combustion and emission characteristics. The quantitative aspect deals with the amount or quantity of fuel required to develop a fuel-air mixture able to produce clean and complete combustion. A slight increase or decrease in this optimized quantity may result in incomplete combustion, and hence increased emissions. However, the discussion of this aspect of injected fuel is beyond the scope of this study, since the current study is focused on two important qualitative parameters, namely spray tip penetration and cone angle of the test fuels. Both these geometrical or macroscopic characteristics play a dominant role in the fuel evaporation, atomization, primary and secondary break-up, fuel-air mixing, and thus in combustion and exhaust emissions.

Spray tip penetration is of great importance in a diesel engine. According to Lefebvre[27], over-penetration of spray causes the fuel to impinge on the walls of combustion chamber. This causes no harm if a great air swirl is present and the combustion chamber walls are hot. However, if air swirl is not enough as it does in case of large engine with quiescent type combustion chambers, the over-penetration leads to fuel impingement on cold walls with a result of fuel wastage and, thus poor performance. Inadequate spray tip penetration, on the other hand, results in unsatisfactory fuel-air mixing, and hence incomplete combustion. So, it is imperative for a diesel engine to have spray tip penetration well matched with the size and geometry of the combustion chamber so that the optimum engine performance can be obtained. Spray cone angle is also of prime importance because an increase in cone angle increases the spray exposure to the influence of surrounding air to a great extent. Generally, an increase in cone angle tends to increase the spray dispersion, which is defined as the 'ratio of the volume of the spray to the volume of the liquid contained within it[27]. Good spray dispersion leads to better mixing of fuel with surrounding gas, and hence higher evaporation rates. Further, the study of effect of injection duration and ambient pressure on macroscopic characteristics would also be helpful in deciding the injection pressure of the injector. Similarly, the ambient conditions in the combustion chamber are also of great concern because they decide how dense the medium is for proper mixing of fuel with air. In the light of above discussion, it would be easy for readers to understand the effect of the macroscopic spray characteristics on the engine performance and combustion.

Effect of injection duration on injection pressure

Figure 3 presents the variation in P_{inj} of the test fuels for different D_{inj}. It is evident that P_{inj} increases with the increase in D_{inj} for both the fuels. The P_{inj} of B20 is 4.7 – 10.8% higher than that of commercial diesel for the various D_{inj}. This finding is in good agreement with that of Kegl and Hribernik[28] i.e. the injection pressure with biodiesel is higher, compared with diesel fuel. This higher injection pressure with B20 may be attributed to the higher density and bulk modulus or incompressibility (property measuring the resistance of fuel to uniform compression or an increase in pressure required to produce relative de-

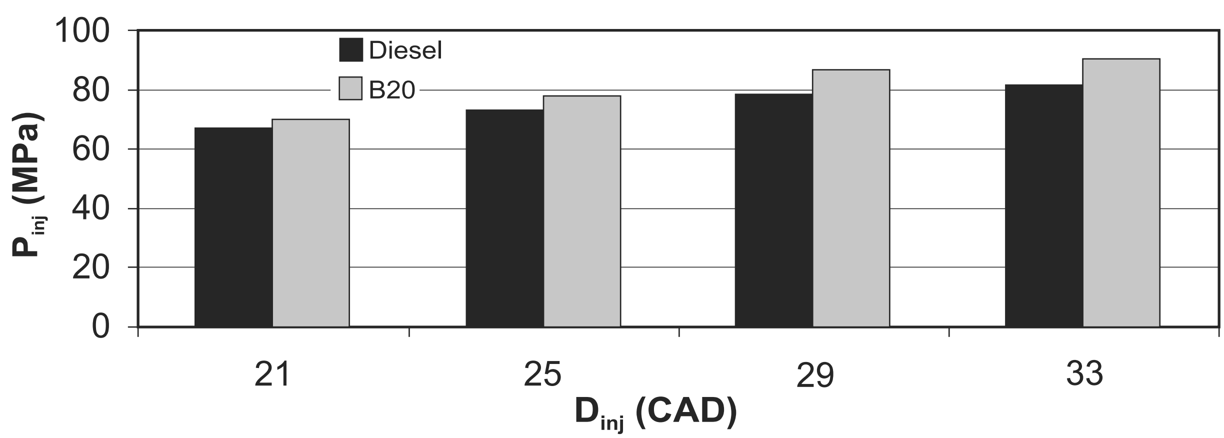


Figure 3: Effect of injection duration on the injection pressure of diesel and B20.

crease in volume[29]) of B20 relative to conventional diesel fuel, because higher bulk modulus of biodiesel causes the pressure to be developed faster in the fuel injection system relative to the lower bulk modulus of commercial diesel fuel[30]. Hence, the faster developed fuel pressure increases the injection pressure. Above finding that injection pressure is increased with the increase in injection duration would be helpful to understand the effect of injection duration on spray tip penetration and con angle to be discussed in next section 3.2.

Effect of injection duration on spray tip penetration and cone angle

The effect of injection duration on 'L' and 'β' of both fuels at the same P_{amb} of 1.5 MPa is shown in Figure 4. It is clearly displayed that 'L' of the fuels increases as a function of time after the start of injection. It is also shown that 'L' increases with the increase in D_{inj}. The trends of variation in 'L' are almost same for both the fuels, showing a maximum increase of 22.5% and 24.3% in 'L' at 33 CAD relative to 21 CAD for diesel and B20, respectively. This increase in 'L' at 33 CAD relative to 21 CAD may be due to the increase in injection pressure because pressure difference at the nozzle hole increases with the longer injection duration as shown in Figure 3. The higher injection pressure causes the faster propagation of pressure wave and increases the fuel injection rate and mass[30], and hence results in the increase in droplet momentum. It is well known that linear momentum depends also on mass of the droplet. Thus higher momentum caused by the increased droplet mass may result in longer tip penetration.

As far as the spray cone angles of the fuels are concerned, it is evident that they decrease sharply at the commencement of injection, then fluctuate and become almost stable after 1.0 ms time after start of injection. It means after a certain interval of t_{asoi}, the length of the spray jet grows without any significant change in the width of the spray plume. This may be attributed to the balancing of liquid droplet momentum of fuels with the ambient pressure (i.e. two opposite forces produced by rate of change of momentum and due to ambient pressure respectively, become equal in magnitude after certain interval of time), causing the cone angles to maintain almost constant values. The trends of 'β' for both fuels are almost similar and increase with the increase in D_{inj}, since increase in injection duration leads to increase in injection pressure, and ultimately increase in droplet mass as discussed earlier. Further, increase in droplet mass leads to increase in droplet size or volume considering the density of fuel as constant, which may finally result in increase in cone angle. The trends of 'β' exhibit a maximum increase of 17.4% and 21.8% at 33 CAD relative to 21 CAD for diesel and B20, respectively.

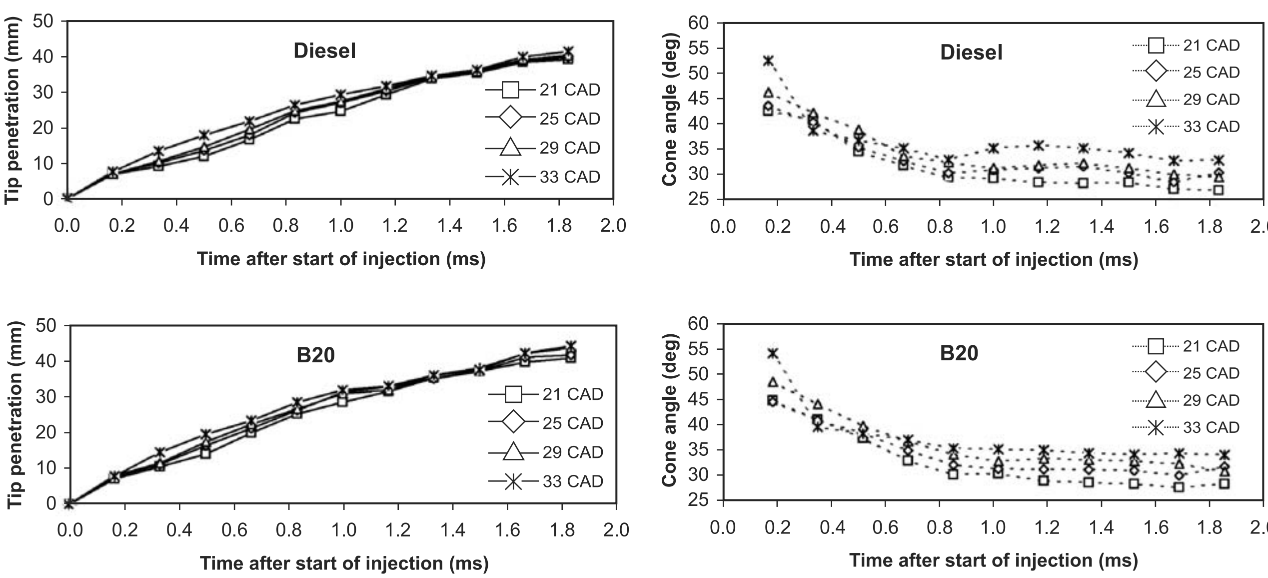


Figure 4: Effect of injection duration on spray tip penetration and cone angle with diesel and B20.

Effect of ambient pressure on the tip penetration and cone angle

The influence of P_{amb} on 'L' and 'β' of the fuels under the same D_{inj} of 30 CAD is illustrated in Figure 5. It is clear that 'L' of both fuels increases as the time is elapsed for all the ambient pressures. Moreover, the 'L' increases with the decrease in P_{amb} from 1.6 to 0.4 MPa. The maximum relative increase in 'L' is 34.3% and 37.5% with diesel and B20, respectively. This increase in 'L' with decrease in P_{amb} is ascribed to increase in spray development of both the fuels, since lower drag force caused by the decreased ambient gas density helps the spray to be developed quickly with higher penetration velocity owing to increase in evaporation rate of the fuel droplet. It is worthwhile to observe that the change in P_{amb} displays the stronger impact on 'L' as compared to the change in Dinj causing the change in P_{inj} as discussed earlier in section 3.2. This stronger impact of the change in P_{amb} relative to the change in P_{inj} is attributed to the higher density of the ambient gas used in this study.

Moreover, the spray cone angles of the fuels present decreasing trends with tasoi and behave haphazardly after 1 ms t_{asoi}. Furthermore, the cone angles decrease with the decrease in P_{amb} from 1.6 to 0.4 MPa. The maximum relative decrease in 'β' is 28.3% and 33% with diesel and B20, respectively. This decrease in 'β' with the decrease in P_{amb} may again be attributed to the reduction in resistance to the fuel spray and increase in penetration velocity, both of which are conducive for the axial penetration of the droplet. On the other hand, higher P_{amb} offers more resistance to the fuel spray and exerts upward pushing force, which causes the droplet to develop transversely, and hence may result in larger cone angle. From the above discussion, it can be inferred that the effect of lower P_{amb} on macroscopic characteristic is two-fold: on one side, to increase the 'L', but on other side, to decrease the 'β'.

Effect of biodiesel on the spray development, tip penetration and cone angle

The spray image is one of the important macroscopic characteristics of a fuel, since it facilitates to measure the spray tip penetration and cone angle of a fuel. In addition, it provides a picture to observe the axial penetration distance of the fuel droplet. A comparison of spray development images of B20 and diesel fuels at D_{inj} of 33 CAD and P_{inj} of 1.6 MPa is depicted in Figure 6. It is clearly displayed that the spray development improves with the passage of time after the start of injection of the fuels. The shapes of spray images of two fuels are almost similar. However, B20 exhibits a longer penetration distance as compared to diesel. The B20 fuel having higher P_{inj} may cause a rapid increase of injection flow rate with higher injection velocity, momentum and kinetic energy of droplet, and thus exhibits larger penetration distance, compared with diesel.

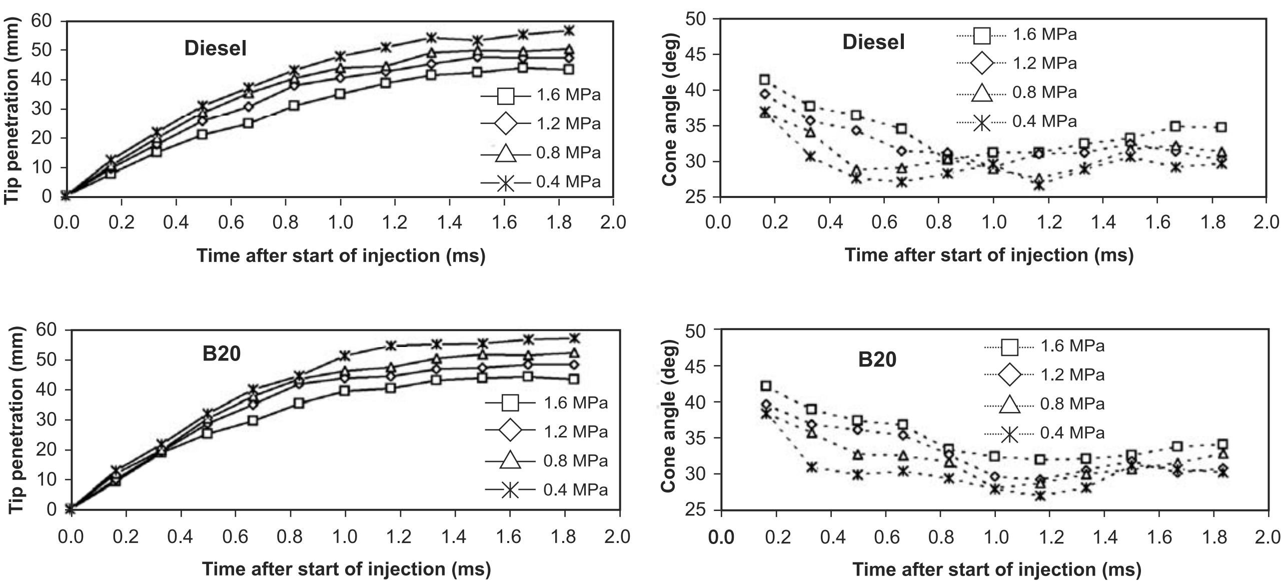


Figure 5: Effect of ambient pressure on spray tip penetration and cone angle with diesel and B20.

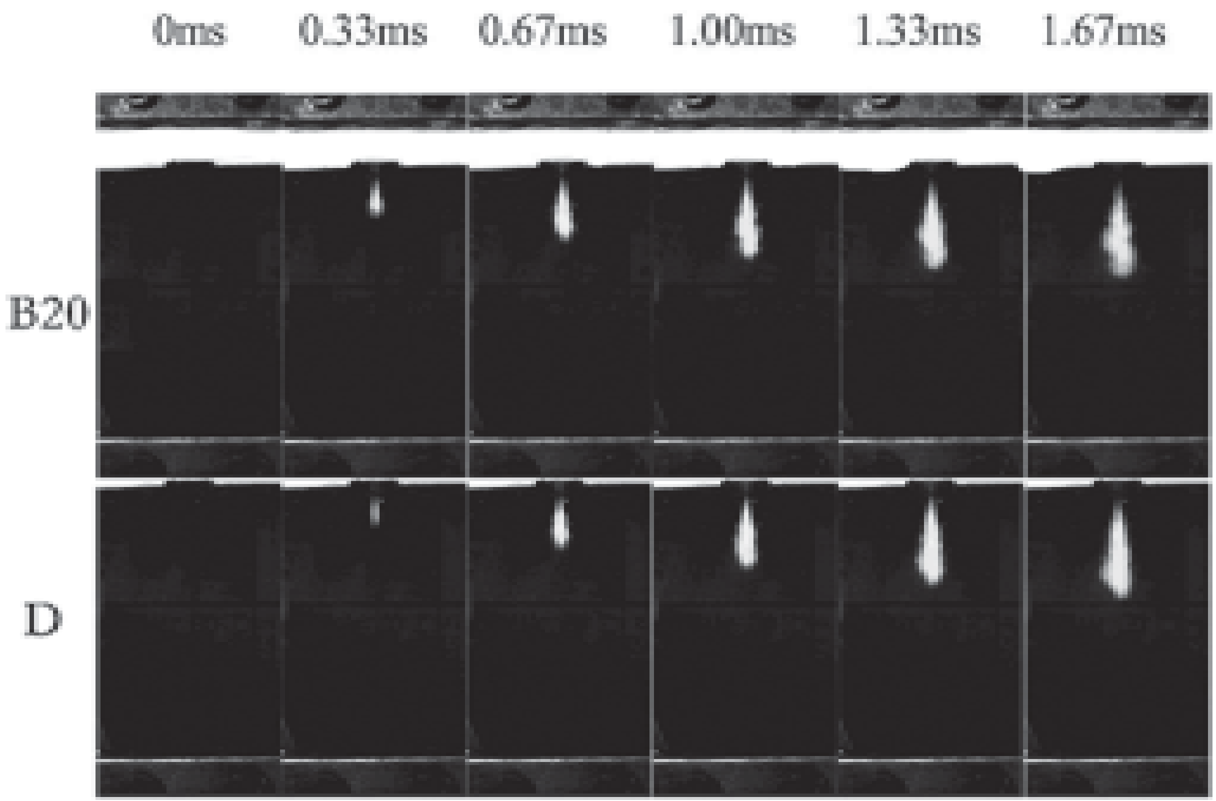


Figure 6: Comparison of spray development between B20 and diesel at an injection duration of 33 CAD and an ambient pressure of 1.6 MPa.

Figure 7 presents the tip penetrations of two fuels for varying D_{inj} (at 1.6 MPa P_{amb}) and for varying P_{amb} (at constant D_{inj} of 33 CAD). From these various conditions, it is clear that trends of 'L' with B20 and diesel are similar. However, B20 reflects larger 'L' compared with diesel under the same conditions. The maximum relative increase in 'L' of two fuels is 12.8% with a mean relative increase of 6.2% for varying D_{inj}, while it is 16.5% with a mean relative increase of about 7% for varying P_{amb}. Above finding is in line with the results of previous study that biodiesel and its blend with commercial diesel generate larger tip penetrations relative to petroleum diesel[25]. During the earlier phase of time after start of injection, the difference in tip penetrations of two fuels is smaller. However, this difference increases rapidly as the time progresses. Finally, it becomes approximately stable after 1.6 ms t_{asoi} and 1.4 ms t_{asoi} for varying D_{inj} and P_{amb}, respectively.

It can be seen from Figure 8 that the curves of B20 and diesel exhibit almost similar trends. However, it is evident from these trends that 'β' with B20 is larger than that of diesel under the same conditions. The maximum relative difference of 'β' between two fuels is 14.3% with a mean relative difference of 5.4% for varying D_{inj}, while it is 19.8% with a mean relative difference of about 7.8% for varying P_{amb}. It is worthwhile to note the peculiar trends of both B20 and diesel for varying P_{amb}, compared with varying D_{inj}. In addition, at constant D_{inj} but varying P_{amb}, the discrepancy of 'β' between two fuels is more profound as shown in Figure 8. Above mentioned peculiar trends with both fuels are again indicative of how strongly the fuel spray is affected by P_{amb}, compared with D_{inj}. From these discussions, it can be deduced that ambient conditions inside the combustion chamber are more responsible for the better performance of the engine as compared to injection conditions.

Lee et al.[31] have reported that axial mean velocity (velocity with which a fuel droplet falls axially downwards in the combustion chamber) of biodiesel-blended fuel is lower than that of diesel fuel during the earlier period after the start of injection and then becomes higher after 1 ms t_{asoi}. Meanwhile, Saucer Mean Diameter (commonly known as SMD) of biodiesel spray is bigger than that of diesel because

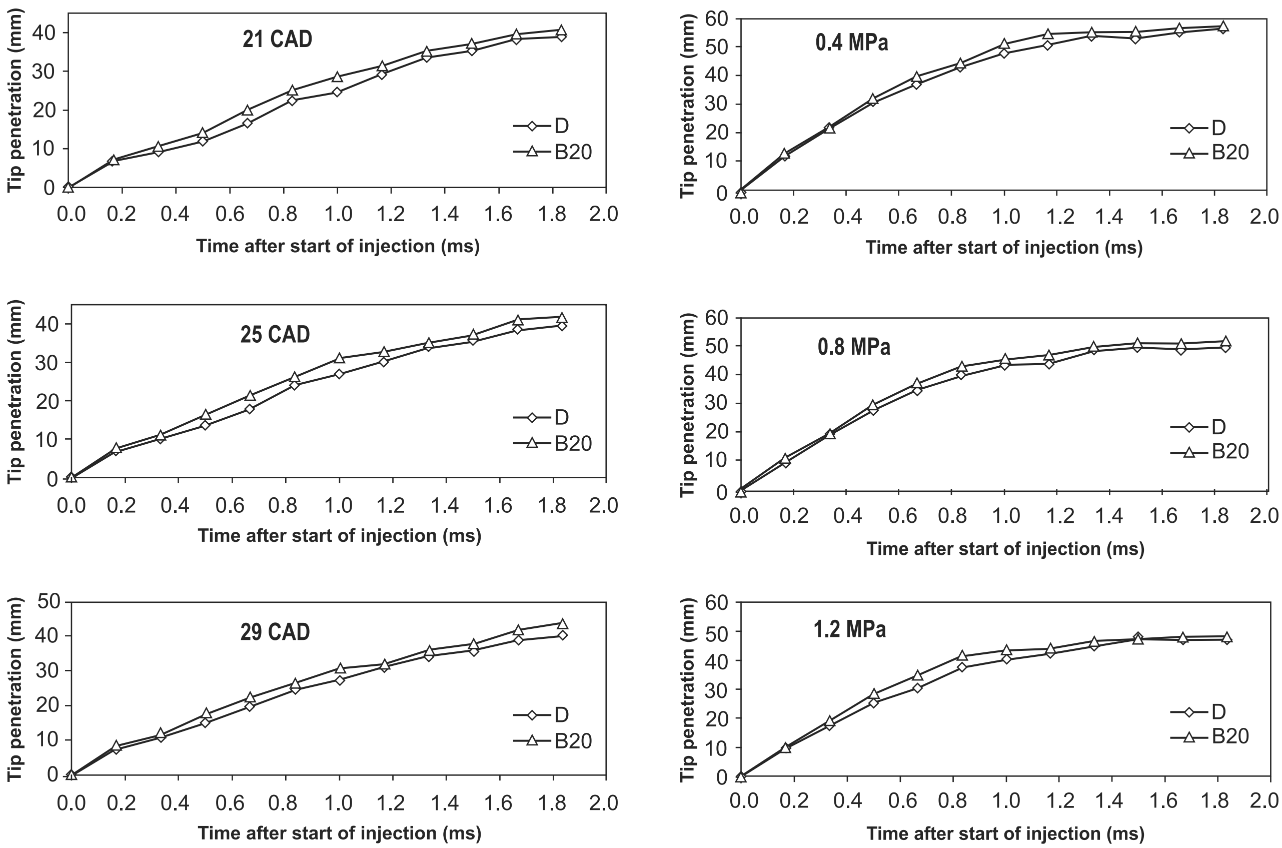


Figure 7: Comparison of tip penetration between diesel and B20 at constant ambient pressure (1.6 MPa) but varying injection duration and at constant injection duration (33 CAD) but varying ambient pressure.

higher viscosity and surface tension of biodiesel affect the spray atomization[32]. On the other hand, Desantes et al.[24] examined the impact of both density and viscosity on the injection process and reported that viscosity has no noticeable influence on the injection rate, injection duration and injected mass, but all these parameters increased with fuel density. From above discussed studies[24,31-32], it can easily be inferred that in the spray development process, viscosity may decrease the axial mean velocity and cone angle, while density may increase the spray tip penetration.

Unlike the observation of Lee at al.[31], our results reveal that there might be higher axial mean velocity with B20 right from the beginning during the earlier phase after the start of injection. This may be due to the different source and origin, and hence due to the different physical properties of biodiesel used in this study. This higher axial mean velocity leads to the development of higher linear momentum (because momentum is the product of mass and velocity) right from the beginning. Although during the earlier phase after the start of injection, viscosity of B20 offers some resistance to fuel droplet and reduces the effects of its higher density and injection pressure. However, it can not dominate the influence of initial higher momentum. This is why both 'L' and 'β' are larger with B20 compared with diesel, even during the earlier stage of t_{asoi}. Furthermore, the momentum of B20 droplet continues to be increased with the passage of time and becomes appreciable to completely overcome the effect of viscosity. This is the reason for longer 'L' with B20 relative to diesel in the middle and somewhat later stages of t_{asoi}.

In the end it can be summarized that relative to petroleum diesel, B20 with increased density and injection pressure may have higher injection velocity, injected mass, kinetic energy and momentum and, thus produces longer tip penetration. At the same time, higher viscosity of B20 responsible for larger SMD

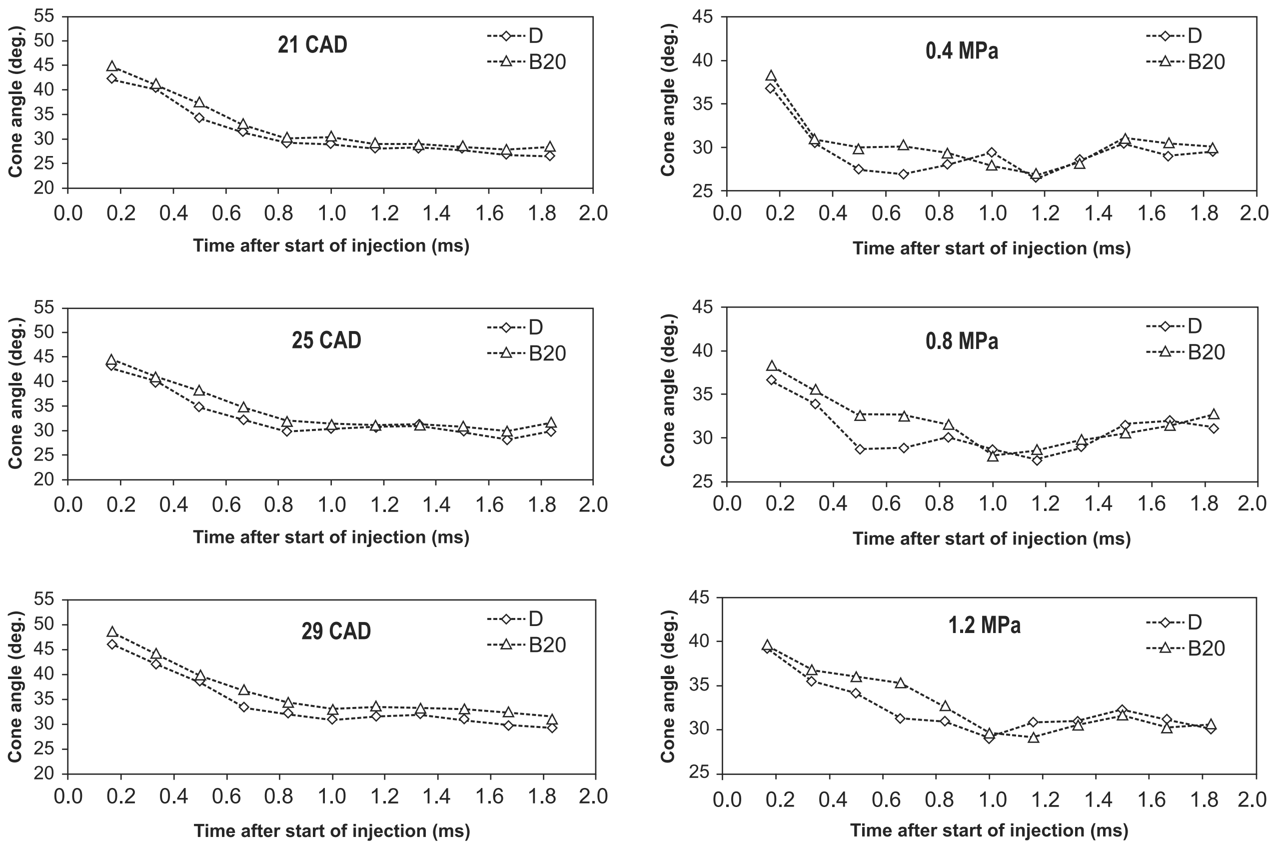


Figure 8: Comparison of cone angle between diesel and B20 at constant ambient pressure (1.6 MPa) but varying injection duration and at constant injection duration (33 CAD) but varying ambient pressure.

may be conducive for the increase in spray cone angle. The authors conjecture that higher viscosity with B20 plays a supporting role for the development of a relatively massive droplet with increased momentum and kinetic energy, which contributes to density in the increase of both 'L' and 'β' simultaneously. This argument is further strengthened by the finding of Choi et al.[33] that higher viscosity of biodiesel plays a positive role in reducing the fuel losses during the injection process, and in the faster developing of pressure. Therefore, it is presumed that in case of B20 fuel losses are less and, thus pressure rise is faster with higher mass, compared with petroleum diesel. Consequently, both spray tip penetration and cone angle are larger with B20, relative to diesel.

In the experimental setup, the authors have used a CVC to simulate the cylinder environment. However, the spray development phenomenon including spray tip penetration and cone angle in the engine cylinder is more complicated than that in the CVC. The temperature, pressure and background gas are expected to be different in the actual conditions in engine cylinder than those in the CVC. The temperature of the fuel varies in accordance with the actual engine conditions, and thus can affect the fuel spray. However, in this study the fuel temperature has been kept constant. In addition, the fuel spray may touch the top of the piston in the cylinder, and may affect the 'L' and 'β' of the fuel. Unfortunately, this factor has not been considered in this study due to the limitations of the experimental setup.

CONCLUSIONS

The current work is aimed at the experimental comparison of spray development, tip penetration and cone angle of diesel and B20. According to the results, the P_{inj} of B20 was higher than that of diesel due to its higher density and incompressibility. Spray tip penetration and cone angle were increased with the increase in D_{inj} with both the fuels, since higher injection duration caused the increase in injection pressure. The higher injection pressure was then responsible to increase the droplet momentum and tip penetration. The spray tip penetration was also increased with the decrease in ambient pressure with both the fuels due to the decrease in resistance to penetration velocity caused by the decreased in ambient density (or by less dense medium). On the other hand, the spray cone angles of the fuels were decreased with the decrease in P_{amb} again due to less resistance to flow. Although the shapes of spray images of two fuels were almost similar, both the spray tip penetration and cone angle were higher with B20, compared with diesel. The spray performance of both fuels was highly affected by the ambient conditions as compared to injection conditions. The B20 fuel exhibited a stronger impact on the spray performance, compared with diesel. It increased not only the spray tip penetration, but also the spray cone angle of the fuel. However, it is premature to decide whether the overall impact of B20 on the spray and engine performance is favorable or adverse, since the matching of spray tip penetration with the size and geometry of combustion chamber dictates the performance of an engine.

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ACRONYMS

injection duration	D_{inj}	injection pressure	P_{inj}
ambient pressure	P_{amb}	time after start of injection	t_{asoi}
spray tip penetration	L	sulfur hexafluoride	SF_6
spray cone angle	β	crank angle in degree	CAD
20% biodiesel-80% diesel (v/v)	B20	saucer mean diameter	SMD
diesel	D	constant volume chamber	CVC
electronic unit pump	EUP	spray visualization system	SVS
oxides of nitrogen	NO_x	electronic control unit	ECU

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