IJST, Transactions of Mechanical Engineering, Vol. 39, No. M2, pp 389-398
Printed in The Islamic Republic of Iran, 2015

STUDY OF SPRAY CHARACTERISTICS OF BIODIESEL USING DIMENSIONLESS ANALYSIS UNDER NON EVAPORATING CONDITIONS*

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Abstract– The spray characteristics of the fuel greatly influence emissions from diesel engines. Spray development plays a vital role in improving the combustion and emission characteristics of fuel because it directly affects the air- fuel mixture formation. The spray characteristics of fuel mainly depend on fuel injection process, fuel density, fuel viscosity, ambient pressure and temperature. Among these, the effect of fuel injection pressure is a very important parameter directly affecting spray structure. This study investigates the effects of fuel injection pressure on the spray characteristics such as spray angle and spray tip penetration in a constant volume chamber under non evaporating conditions by image processing techniques. The macroscopic spray characteristics were quantified using dimensionless analysis by examining the role of the dominating forces associated with liquid jet breakup. The Weber number, Reynolds number and air- to- fluid density ratio were used to capture the primary forces including the inertia, surface tension and aerodynamics drag forces. The Weber number has a more profound effect on the spray penetration and spray cone angle compared to the Reynolds number contribution. This analysis yielded dimensionless correlations for spray cone angle and spray tip penetration that provided important insight into the spray breakup and atomization process.

Keywords– Biodiesel, spray tip penetration, spray cone angle, Weber number, Reynolds number, spray characteristics

1. INTRODUCTION

Macroscopic spray characteristics such as spray penetration, spray cone angle and droplet size distribution are critical parameters that influence the in cylinder air/fuel mixture and combustion process of the internal combustion engine. The spray performance is influenced by a large number of parameters including the fuel pressure, fuel temperature, ambient pressure, ambient temperature, fuel properties and nozzle geometry [1]. For a direct injection diesel engine, the atomization performance of its fuel is very important because of its close relationship with the engine efficiency and pollutant emissions. In practical applications, the combustion efficiency is strongly influenced by the fuel vaporization rate and the vaporization characteristics which are heavily dominated by the fuel spray atomization since the total surface area becomes larger and interacts actively with ambient gas.

Hiroyasu [2] has investigated both the macroscopic and microscopic spray characteristics of the diesel spray under various conditions, providing a set of empirical formulations that describe the spray penetration and spray cone angle, Sauter mean diameter. Wei Zeng et al. [3] studied the macroscopic characteristics for direct injection multi hole sprays using dimensional analysis. Weber number, Reynolds number and air to liquid density ratio were used to represent the four primary forces that are known to influence the spray. The effect of fluid property was described for gasoline, methanol and ethanol fuels.

*Received by the editors May 11, 2014; Accepted May 20, 2015.
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Wei Zeng et al. [4] investigated the spray structural changes and vaporization processes for flash boiling multi hole spray over a broad range of superheated conditions using Mie scattering and laser induced exciplex fluorescence optical technique. The fuel property effects were examined by characterizing n-hexane, methanol and ethanol fluids over a wide range of conditions consistent with that found in spark ignition direct injection engine. The macroscopic spray structure was quantified using spray penetration, spray plume width and normalized distance between spray plumes. The study provides insight to the primary mechanism responsible for observed spray transformation under flash boiling conditions. By increasing the fuel temperature or decreasing the ambient pressure it has been proven that resulted in flash boiling sprays or superheated sprays are able to improve the evaporation of fuel spray tremendously and increase spray angle for rapid fuel- air mixing.

Ainul Ghurri et al. [5] studied the effect of injection pressure and fuel type on the spray tip penetration and spray cone angle of spray injected into atmospheric chamber. The experiment was performed by a common rail type high injector for the diesel engine at the injection pressure of 400-1000 bar and four different fuels. The result showed that the biodiesel content increased the spray tip penetration and decreased the spray angle. The correlation of spray tip penetration was expressed for each region before and after breakup time in terms of injection pressure, fuel viscosity and time after start of injection.

Ryan and Bagby [6] found that reduction of viscosity for neat soyabean oil by heating resulted in increase in the spray tip penetration. They suggested that the chemical changes that occur during the injection process could account for the opposite spray characteristics of several vegetable oils including neat soyabean oil. For the application of rubber seed oil, one of the typical inedible vegetable oils, as a diesel fuel substitute / extender for diesel engine, the variation of spray angle with liquid viscosity was measured by Pereva and Dunn [7]. It can be seen from this study, the spray angle decreases as the viscosity of liquid fuel increases, and only half of the value of spray cone angle of diesel fuel was obtained for rubber seed oil in this work due to the high viscosity.

Abdul Adam bin Abdullah [8] studied the effect of kinematic viscosity of straight vegetable oil on fuel injection spray characteristics using constant volume high pressure spray chamber. Straight vegetable oil spray tip penetration measured shortest and narrow cone angle compared with biodiesel and diesel spray, these are due to the high level of kinematic viscosity inside straight vegetable oil compared to biodiesel and diesel fuel. Straight vegetable oil at high ambient temperature produce similar spray structure as diesel spray due to kinematic viscosity level of straight vegetable oil decreased with increased of fuel temperature.

The use of edible vegetable oils such as sunflower, rapeseed oil and soybean oil for fuel purposes may directly affect the economy, i.e. it may increase the price of cooking oils. In order to avoid the consequence, it is essential to use non-edible oils for biodiesel production. Rubber seed oil, Jatropha oil, Neem oil, Karanja oil and Linseed oil are examples of non-edible oils. Among these Jatropha oil is a promising fuel and is derived from seeds of Jatropha curcas plant. This plant can survive in adverse condition and requires very little water for irrigation and can grow in any type of soil. Dedicated jatropha plantation can give a seed yield of 0.8 kg/m^2. Jatropha seeds contain approximately 30-40% oil by weight and it is an odourless, colourless and slow drying oil. The main issue with jatropha is that seeds are toxic and the press cake cannot be used as animal feed. Jatropha oil cannot be used for any nutritional purpose without removing its toxic contents, therefore it a good alternate fuel.

In this research work spray atomization is studied near nozzle tip to examine the effects of injection pressure on spray characteristics such as spray cone angle and spray tip penetration using dimensionless numbers (Reynolds number, Weber Number and $\rho_{a/}\ \rho_l$) under non evaporating conditions in a constant volume chamber. The correlation between these dimensionless numbers for determining spray characteristics have been formulated for various injection pressures (180- 230bar). These correlations provide important insight for spray breakup regimes and can be used for developing spray model.

Spray tip penetration (spray length) is the distance between the injector tip and longest spot in the spray image and is obtained using graphical tool of Image j software. Spray cone angle is 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 injector tip and is obtained by drawing appropriate lines in the captured images using graphical tool as shown in Fig. 1.

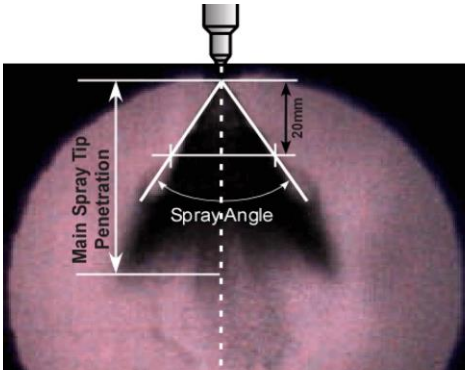


Fig. 1. Definition of spray tip penetration and spray cone angle

2. EXPERIMENTAL SETUP

The fuel is supplied from the fuel tank to the fuel injector using a simple mechanical fuel pump, with a fuel injection pressure from 180-230 bars. The experimental setup for investigating the biodiesel spray is shown in Fig. 2. The experimental conditions are shown in Table 1.The fuel injector used in the experiments is a mechanical injector with single hole nozzle, the hole diameter is 0.231 mm and length to diameter ratio to the nozzle orifice is 2. Using this spray injection system the fuel was injected into the glass chamber (40x40x5 cm) and spray was filmed with a digital camera (Nikon D200). The pressure and temperature inside the chamber are 1 atmosphere and 27- 30^{0}C. Two sides of the chamber are transparent to make the inside observable. The camera was placed at a distance of 65 cm from the spray chamber wall and about 20 mm from the top of the chamber. The injection duration was 1.2ms. The macroscopic characteristics such as spray cone angle and spray penetration were measured from the images captured by high speed digital camera. In the present study Jatropha oil methyl ester (JOME) and diesel are used as test fuels. The properties of test fuels are shown in Table 2.

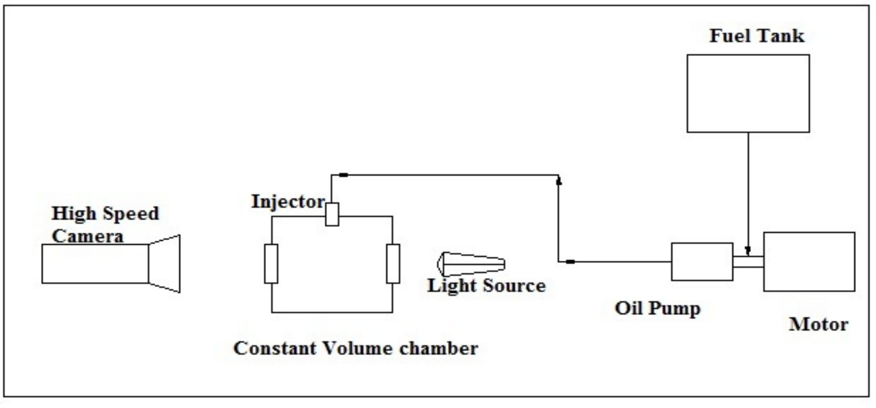


Fig. 2. Experimental setup

Table.1. Experimental conditions.

Injection parameters	Quantity
Chamber pressure (bar)	1.013
Injection duration (ms)	1.2
Chamber temperature (K)	300
Nozzle diameter (mm)	0.231
Air temperature (K)	300
Injection pressure (bar)	180,200,210,230
Fuel temperature (K)	300
Surface tension of diesel (N/m)	0.024
Surface tension of biodiesel (N/m)	0.028

Table. 2. Properties of mineral diesel and Jatropha oil methyl ester

Property	Diesel	Jatropha oil	Jatropha oil methyl ester	ASTM standard values
Density (kg/m^3)	840	917	875	875-900
Calorific value (MJ/kg)	44	39	42	118
Flash point (^0C)	71	229	158	100-170
Viscosity (40^0C)	3.4	35.38	4.27	1.9-6.0
Cetane number	48-56	23-41	51-52	48-70

a) Reynolds and Weber numbers dependence

The breakup process and spray characteristics can be analyzed using Weber number ($We = \rho_l d u^2/\sigma$), Reynolds number ($Re = \rho du/\mu$) and air to liquid density ratio (ρ_a/ρ_l). ρ_l and ρ_a are the densities of a liquid and surrounding air kg/m^3, d is the nozzle diameter mm, u is the jet velocity through the nozzle m/sec, σ is the surface tension N/m, μ is the viscosity of liquid Nm/sec^2. These dimensionless parameters ideally comprehend the effects of ambient pressure, fuel pressure, nozzle diameter, fuel temperature, fluid properties. The Weber number represents the ratio of inertia force to surface tension force, Reynolds number represents the ratio of the inertia force to viscous force and air to fuel density ratio is used to study the effect of drag force.

3. RESULTS AND DISCUSSION

Fuels used for this investigation are JOME and diesel. The spray images of diesel and JOME captured by digital camera are shown in Figs. 3 and 4. These images are interrogated for spray tip penetration and spray cone angle. Every image was masked to select the area of interest and background was filtered, after this, image was calibrated for user defined coordinates in order to calculate the spray characteristics.

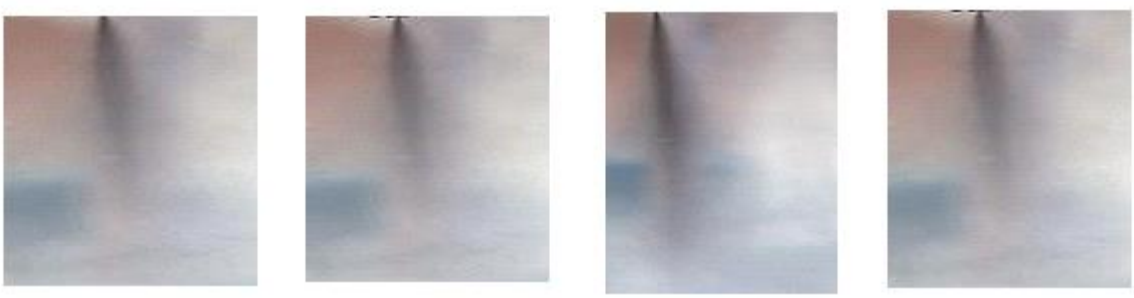


Fig. 3. Images of diesel spray development (injection pressure 180,200,210 and 230 bar), ambient pressure 1bar and ambient temperature 300 K)

Fig. 4. Images of biodiesel spray development (injection pressure 180,200,210 and 230 bar), ambient pressure 1bar and ambient temperature 300 K)

a) Weber number and Reynolds number effect on macroscopic spray structure

Figures 5 and 6 illustrate the effect of Reynolds and Weber numbers on spray characteristics. For ambient and fuel injection pressure conditions (180, 200, 210 and 230 bar) evaluated, the Reynolds number varies from 15,000 to 20,800 and the Weber number varies from 29, 0000 to 45, 0000. The viscous and surface tension forces primarily depend on fuel type and fuel temperature. The inertia force primarily depends on the fuel injection to ambient pressure and the fuel viscosity. As the change in surface tension force is considerably smaller compared to the changes in both the inertia and viscous force, this analysis focuses on describing the influence of the inertia and viscous forces on the macroscopic spray characteristics.

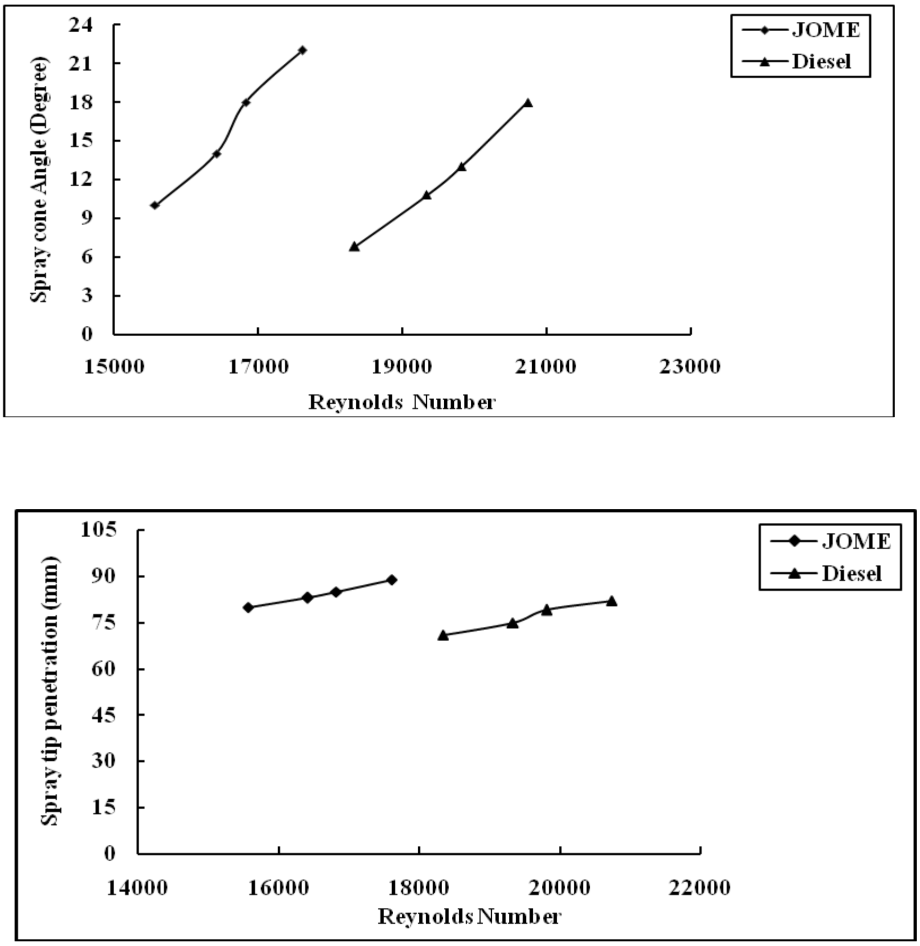


Fig. 5. Spray cone angle and spray tip penetration versus Reynolds number for various injection pressures (180,200,210 and 230 bar)

For the lower values of Reynolds number and Weber number, the region is characteristics of small inertia forces due to low injection pressure with large viscous forces due to low fuel temperature. These conditions provide a relatively small spray momentum where a weak interaction between fuel particles and air is anticipated. In general, the macroscopic spray parameter increase in a linear fashion with increasing Reynolds number. This behavior is attributed to change in injection pressure and constant air to liquid density ratio. The high injection pressure tends to have wider spray dispersion, due to stronger interaction between the liquid and surrounding air in the chamber.

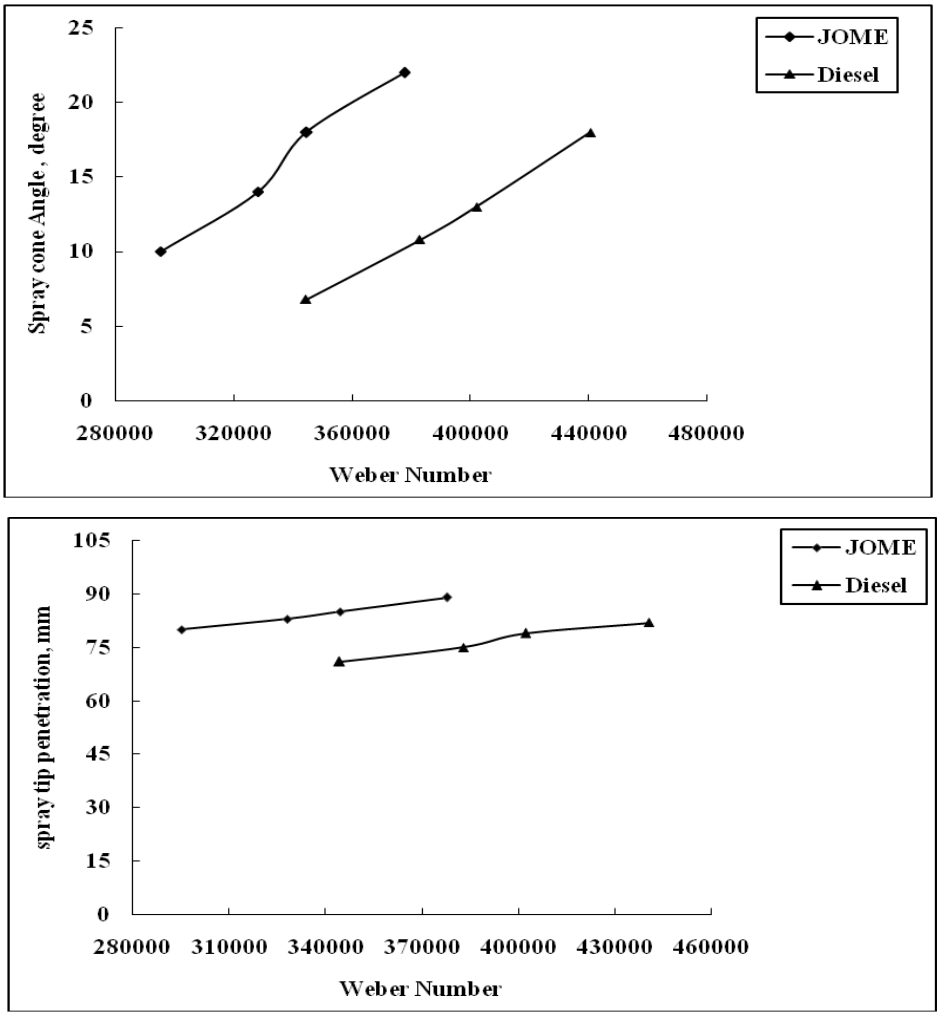


Fig. 6. Spray cone angle and spray tip penetration versus Weber number for various injection pressures (180,200,210 and 230 bar)

The fuel injection pressure has significant effect on spray tip penetration and spray cone angle. For the same test conditions, the spray effects on spray tip penetration of JOME is slightly higher than the diesel and the differences in the penetration between diesel and JOME is very small, such small differences are also observed in the spray cone angle for JOME and Diesel.

b) Correlations between spray characteristics and dimensionless number

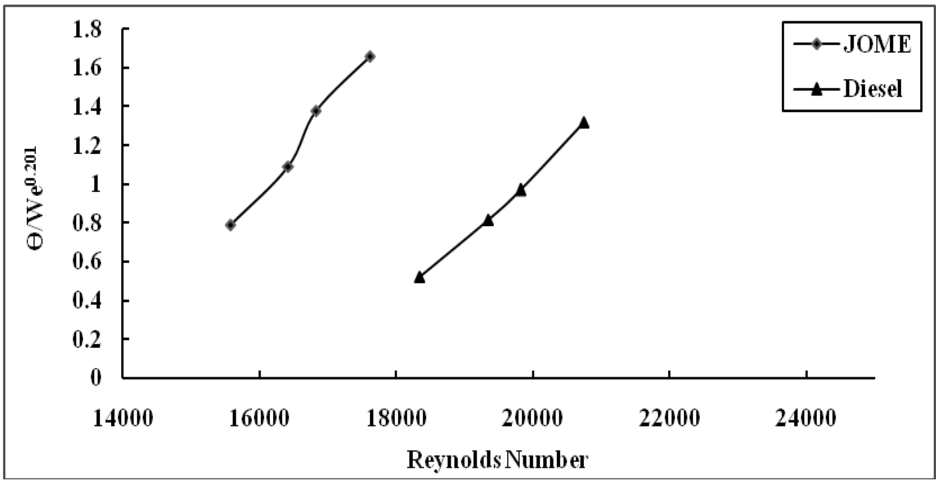
Figures 5 and 6 illustrate the spray angle and spray tip penetration versus Reynolds number and Weber number. The data were compared for 1.2ms. The high injection pressure tends to have wider spray dispersion, so it tends to have higher values of Reynolds number and Weber number. When comparing these data at constant air to liquid density ratio ($\rho a_{/} \rho_l$), strong correlations are obtained for both spray cone angle and spray tip penetration as described by the following equations.

$$\theta \propto We^{0.201} \quad (1)$$

$$S \propto We^{-0.195} \quad (2)$$

Where Θ is the spray cone angle and S is spray tip penetration.

The expressions (1) and (2) provide a quantification of the inertia effect on spray cone angle and spray tip penetration. To isolate the Weber number effect from other dimensionless numbers, the spray cone angle and spray tip penetration are divided by expressions (1) and (2) respectively. Figure 7 shows the correlations between the new dependent variables that represent the spray cone angle and spray tip penetration compared to Reynolds number.



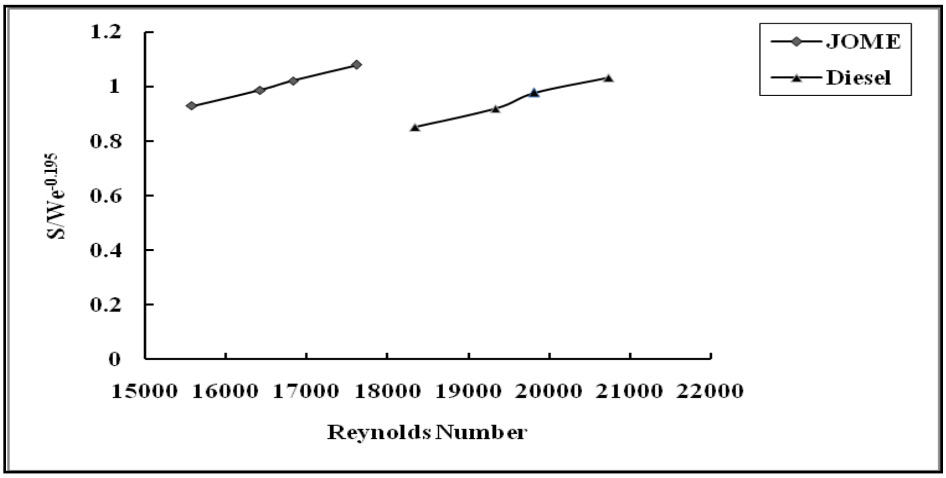


Fig. 7. Θ/ $We^{0.214}$ and S/$We^{-0.195}$ versus Reynolds number

Correlation is obtained using experimental data to study the effect of air to liquid density ratio on the spray tip penetration and spray cone angle and given by the equations

$$\theta \propto \left(\frac{\rho_a}{\rho_l}\right)^{-0.309} \quad (3)$$

$$S \propto \left(\frac{\rho_a}{\rho_l}\right)^{0.38} \quad (4)$$

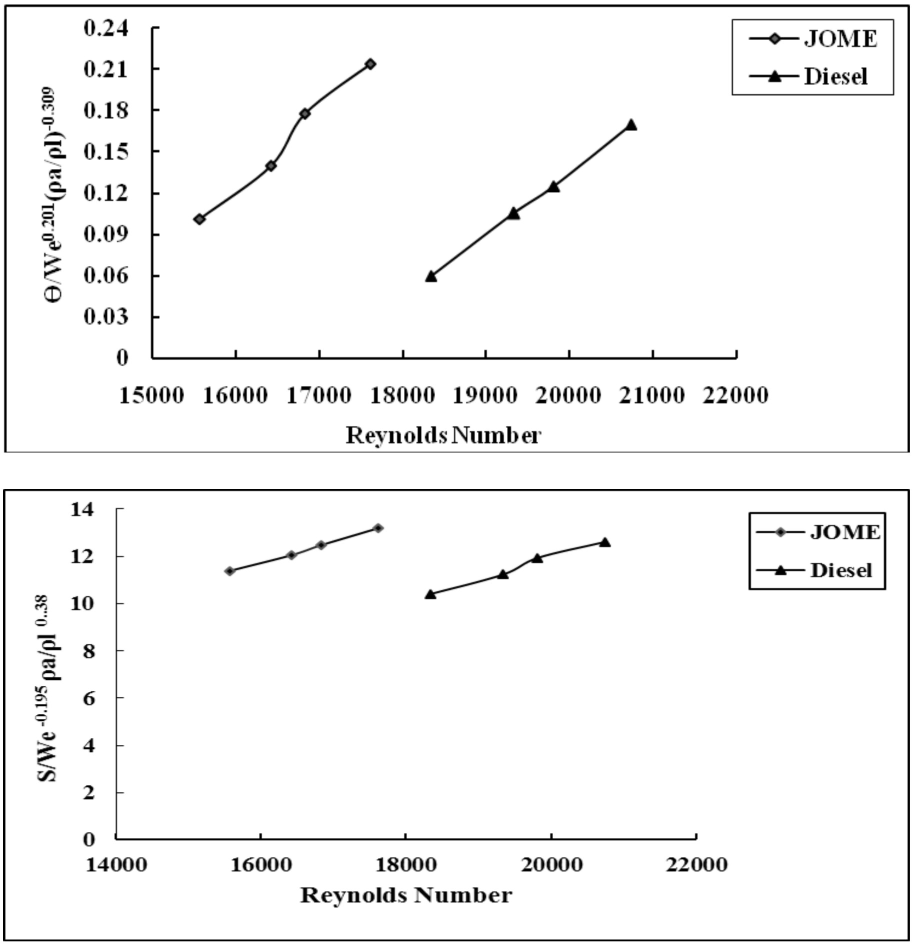


Fig. 8. Effect of dimensionless numbers on spray cone angle and spray tip penetration

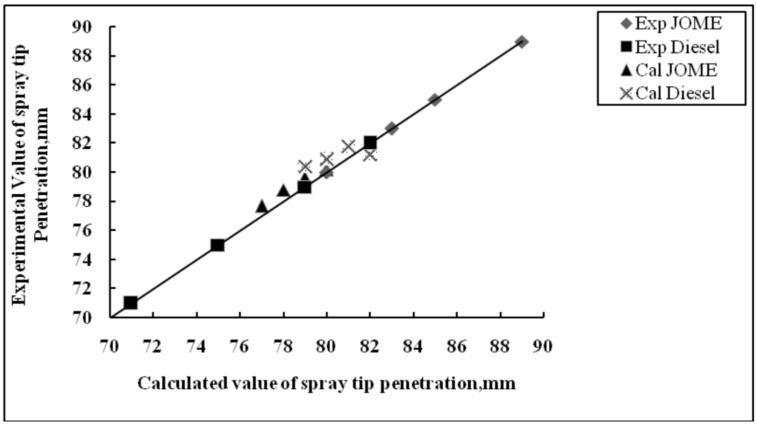
Combining expressions (1)-(4), the spray cone angle and spray tip penetration is represented by two new variables that comprehend the Weber number effect and air to liquid density effect; namely $\Theta/We^{0.201}(\rho_a/\rho_l)^{-0.309}$ and $S/We^{-0.195}(\rho_a/\rho_l)^{0.38}$ respectively. These new variables are plotted for all injection pressure conditions evaluated in the study and are shown in Fig. 8. These plots illustrate the quantified effect of viscous forces on spray cone angle and spray tip penetration, when Reynolds number is larger than 20800, indicating limited effect of the viscous forces on the spray cone angle and spray tip penetration. For lower Reynolds numbers, increasing viscous force leads to reductions in spray cone angle and spray tip penetration. Therefore the viscous effect plays a more important role on spray macroscopic characteristics for lower Reynolds number conditions. This is in agreement with the findings reported by Zeng et al. [5]. Correlations were developed to comprehend the effect of all three dimensionless numbers on spray cone angle and spray tip penetration and are shown in Eqs. (5)-(8). For each spray parameter, two equations are provided to distinguish between Reynolds number regimes.

$$\Theta=1.81We^{0.201}(\rho_a/\rho_l)^{-0.309}Re^{-0.262},\ Re<20800 \quad (5)$$

$$\Theta=0.126\ We^{0.201}(\rho_a/\rho_l)^{-0.309},\ Re>20800 \quad (6)$$

$$S=1.02\ We^{-0.195}(\rho a/\rho_l)^{0.380}Re^{0.252},\ Re<20800 \quad (7)$$

$$S=6.19We^{-0.195}(\rho a/\rho_l)^{0.380},\ Re>20800 \quad (8)$$



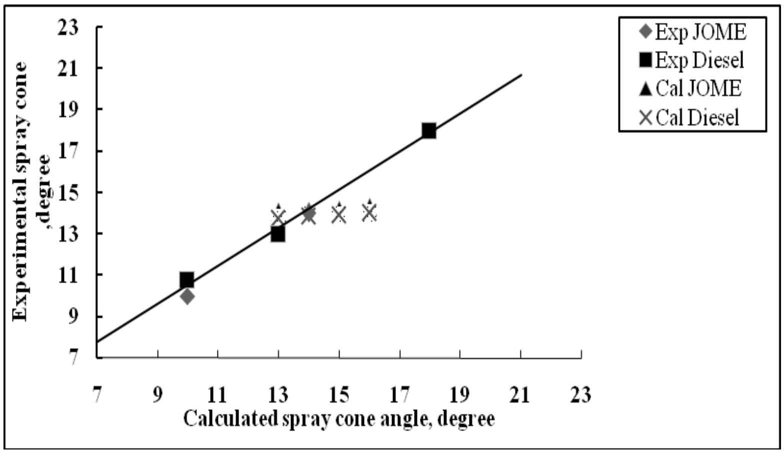


Fig. 9. Comparision between calculated and measured spray cone angle and spray tip penetration

Figure 9 describes the calculated versus measured spray tip penetration and spray cone angle, providing an assessment of variance associated with these correlation. Spray tip penetration increases with increase in injection pressure for biodiesel as a fuel, because the increase in fuel viscosity prevented the breaking of spray jet, resulting in an increase in the size of the spray droplets. Also, viscosity and surface tension are higher for biodiesel than those of diesel fuel as the spray continued droplets around the border become smaller and diffused easily leading to reduction in spray angle. The spray pattern is also affected, since a dense and viscous fuel tends to induce a longer spray penetration and with a narrower spray angle. The uncertainty of the measured and experimental value of diesel and biodiesel as shown in Fig. 9 are 2.60% and 1.56%, respectively.

c) Correlations for spray macroscopic characteristics

The dimensionless analysis reported in this study comprehends the effect of fuel injection pressure, ambient pressure, fuel properties on fuel spray for a single hole nozzle. For the test fuels and injection pressure conditions, Weber number varies from 29,0000 to 45,0000, Reynolds number varies from 15,000 to 20,800 and air to liquid density ratio of diesel is 0.00132 and for JOME is 0.00138. The analysis yielded dimensionless correlations for spray penetration and spray cone angle characteristics at 1.2ms injection duration based on the regions of these three dimensionless numbers.

These correlations quantify the effects of primary forces on spray tip penetration and spray cone angle for direct injection single hole nozzle. Strong correlations are observed between these two spray parameters and Weber number which was attributed to a higher amount of inertia effect compared to surface tension effect. The Weber number has more effect on the spray tip penetration and spray cone angle, compares to the Reynolds number contribution. The inertia force and air drag force are more important factors compared to the viscous force and surface tension forces. The formulations could be used to generate generic spray models which express the physical mechanism explicitly independent of the test conditions and fuels used.

4. CONCLUSION

Dimensionless analysis was applied for fuel spray in a constant volume chamber to investigate the macroscopic characteristics of DI single hole nozzle. Weber number, Reynolds number and (ρa/ ρl) were used to represent primary effect on spray atomization of JOME and diesel. The experiments were carried out for JOME and diesel fuel over a broad range of conditions, ensuring the dimensionless numbers cover a relatively large domain. For the various injection pressure conditions evaluated, the Reynolds number varies from 15,000 to 21,800, Weber number varies from 29,0000 to 45,0000, for the constant air to liquid density ratios of 0.00312(diesel) and 0.00135(biodiesel). The correlations between these dimensionless number and spray penetration and spray cone angle provide a fundamental understanding of spray characteristics.

Spray characteristics are primarily dependent on the competition among the four major forces acting on a liquid jet such as inertia force, surface tension force, air drag force and viscous force, which can be represented by a three-dimensionless number, Weber number, Reynolds number and (ρ_a/ρ_l). The good correlations between these three dimensionless numbers and spray macroscopic characteristics have yielded a set of general formulations. These formulations provide important insight into the spray breakup and atomization processes and could be used to generate generic spray models which express the physical mechanism explicitly, independent of the test conditions and fuel used.

Acknowledgement: We thank the management of Sri Venkateswara College of Engineering for providing us with the necessary experimental setup to perform this research work.

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