A CFD approach to investigate the fuel spray characteristics for castor oil biodiesel in a constant volume chamber

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Abstract

Biofuels derived from various sources show great potential to replace the conventional diesel fuel, as they are much cleaner and renewable source of energy unlike the fossil fuels. However, biofuels possess different physiochemical properties as compared to the diesel fuel. They have high viscosity and surface tension which affects fuel atomization resulting in adverse effect on engine performance. Hence, this research was focused on investigating the fuel spray behaviour of castor oil biodiesel and its blends with the diesel fuel. Fuel spray was modelled using discrete phase model in Ansys Fluent where the basic conservation equations of mass, momentum, and energy were solved using Lagrangian/Eulerian multiphase formulation. Several sub models were coupled with the simulation like drop breakup, drop collision, dynamic drag, and turbulence model. Penetration length (PL), spray cone angle (SCA), Sauter mean diameter (SMD) were studied at two different injection and back pressures. Results revealed that higher injection pressure caused longer PL, higher injection velocities and smaller SMD, while increasing ambient pressure decreased PL, SMD and increased the rate of deceleration. Castor oil biodiesel (BD20) showed greatest PL and SMD because of higher viscosity and surface tension as compared to diesel and (BD10) fuel. The study will help us in optimizing fuel injection parameters for the use of biodiesel in diesel engines enabling to shift to a renewable energy source for the transport industry.

Key words: *Biodiesel, Penetration Length, Spray cone angle, Sauter mean diameter*

Introduction

Nowadays, biofuels attract many engine manufacturers as an alternative fuel in place of diesel because of their biodegradable nature, they are clean and renewable source of energy. Biodiesel have excess of oxygen that enhances combustion and reduce the particulate matter and soot emissions [1]. Biofuels usually have higher fuel viscosity and surface tension that affects fuel injection process and spray quality when used in a diesel engine. Spray characteristics act significantly on combustion process that defines the thermal efficiency of an engine. In order to use biofuels or their blends in diesel engine it is necessary to study the fuel spray and mixture formation characteristics that will give us better insight to the performance and emission properties. Wang et al. [2] experimentally studied the spray behaviour of palm oil and cooked oil and found that greater cone angle and larger drop size are observed for biodiesels as compared to diesel fuel. AK Agarwal et al. [3] studied spray behaviour of Karanja biodiesel at various injection pressures and injection timings for a multi hole injection nozzle. Lee et al. [4] investigated the macroscopic spray properties of biodiesel and its blends obtained from soybean and canola oil. Macroscopic spray properties include penetration length and spray cone angle that can be observed in figure 1. PL is the distance covered from the tip of the nozzle to the farthest distance the fuel has reached and SCA is the angle between the two lines starting from the nozzle tip and passing through the periphery of spray till the half of penetration length. Sauter mean diameter comes under the category of microscopic spray properties, it is the ratio of drop volume to its surface area.

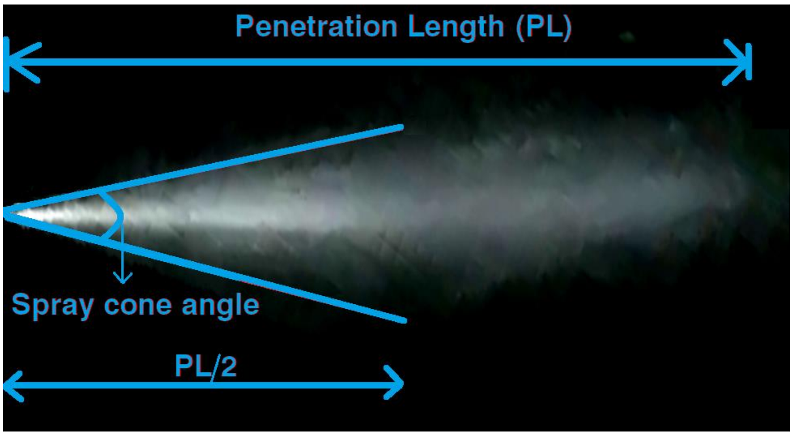

Figure 1. Macroscopic spray properties.

Effect of viscosity and surface tension on fuel spray properties of castor oil, neem oil and sunflower oil was revealed by Das et al. [5]. Biofuels that are being produced from edible sources are less likely to be used on a commercial scale; that is why biofuels derived from nonedible sources are more popular and beneficial. Consequently, researchers have sought non-edible feedstock options, and one such option is castor oil plant. Castor seeds are known to be poisonous for both humans and animals because of the presence of toxic protein ricin. However, it is eliminated after extraction of oil from seeds [6]. One of the major parts of castor oil is ricinoleic acid (12-hydroxy-cis-9-octadecenoic acid). It is a type of hydroxylated fatty acid which is the reason for specific features of the castor oil and the biodiesel produced [7]. Castor Methyl Esters (CaME) has high flash point, density and a very high viscosity and lubricity. Castor oil plant has gained significant attention because of its low production cost and its ability to develop under tough climates. Castor oil biodiesel has high oxygen content and cetane number that improves the ignition quality and helps in achieving complete combustion [8]. Azad et al. [9] revealed that literature available on engine performance, emissions and spray properties for castor biodiesel is quite rare. More research related to the spray properties and engine performance using castor oil biodiesel is required before producing it on a commercial scale.

Methodology:

Fuel spray is a complex phenomenon as it involves several processes occurring at the same time starting from the in-nozzle cavitation and turbulence followed by the external flow turbulence, liquid breakup and drop collision. For the spray simulation, several sub models were coupled together as seen in figure 2 below. Lagrangian/Eulerian multiphase formulation was used in ANSYS FLUENT in which fuel is injected in the form of particles into a gas phase (Air) inside the injection chamber. Particles were tracked using Lagrangian methodology while air inside the chamber was modelled using Eulerian approach. Transport equations of mass, momentum and energy were solved for gas phase. Particles were tracked by their trajectory calculations and its properties were updated as it passed through the gas phase.

Single hole nozzle was used for spray simulation as shown in figure 3a. Nozzle length is 1.4mm while the nozzle hole diameter is 0.290mm. Computational domain used for the study is shown in figure 4a. Length of the cylinder is 180mm and the diameter is 150mm.

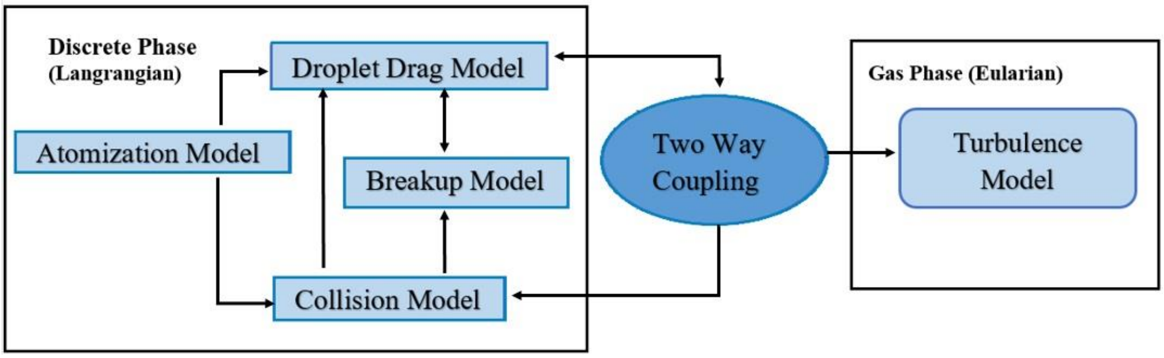

Figure 2. Numerical model interaction diagram for spray simulation.

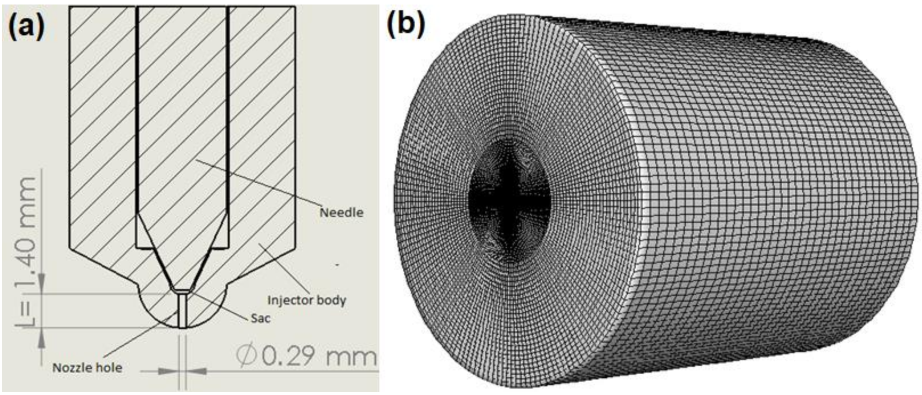

Figure 3. a) Injector nozzle, b) Computational domain

Governing equations:

Equations 1 and 2 are the continuity and momentum equations respectively. These were used for the transfer of mass and momentum between the fuel jet and the air inside the chamber. Turbulence of the gas phase was modelled using realizable k-ε model. It is a modified form of k-ε model that works well for high pressure flows similar to fuel spray phenomenon. Equation 3 and 4 are the transport equations for the realizable k-ε model.

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \rho \vec{v}}{\partial x} + \vec{\nabla}.(\rho \vec{v} \vec{v}) = -\vec{\nabla}(p) + \vec{\nabla}.(\bar{\tau}) + \vec{F} \tag{2}$$

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_j)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon - Y_M + S_k \tag{3}$$

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial(k)}{\partial x_j}\right] + \rho C_1 S_\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + (\varepsilon\nu)^{0.5}} + S_\varepsilon \tag{4}$$

Table 1. Fuel Properties [10].

Property	Diesel	BD10 (10%Biofuel & 90 % Diesel)	BD20 (20%Biofuel & 80 % Diesel)
Density kg/cm^3	837.9	849.1	859.5
Kinematic Viscosity cSt	2.42	3.14	3.73
Calorific value MJ/kg	44	43.59	43.44

Table 2. Injection parameters and boundary conditions

Parameter	Quantity
Injection Pressure	500,1000 bar
Injection Temperature	300 K
Ambient pressure	5 & 10 bar
Chamber Temperature	600 K
Mass flow rate	0.003 g/s
Injection Duration	1.5 ms
Chamber length	180 mm
Chamber diameter	150 mm
Nozzle diameter	0.290 mm

Validation:

The spray model is validated with the experimental study of Jing [11] and then the validated model was used for simulations according to our injection and ambient conditions. Figure 4a shows the comparison of simulated and experimental results for PL of diesel at 500 and 1000 bar injection pressure and 30 bar ambient pressure. Figure 4b shows the validation of SMD at various injection pressures. Minor differences might be related to the mesh related errors or due to the implication of boundary conditions that were not known form the literature.

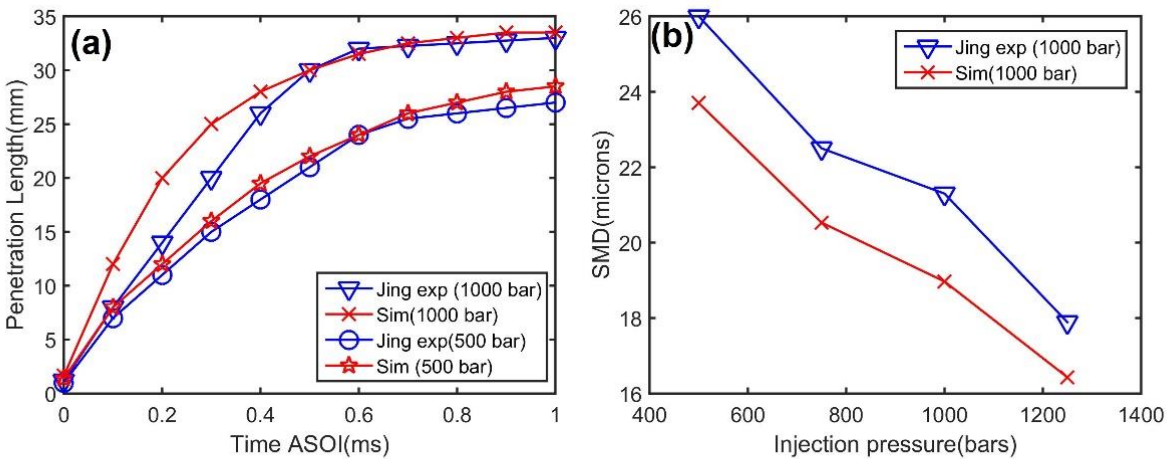

Figure 4. Comparison of simulated and experimental results [11] for a) PL and b) SMD respectively.

Results:

The validated model was used to study the PL, CA and SMD at two injection and ambient pressures for biodiesel and diesel fuel. It can be observed that higher injection pressure causes greater PL as the fuel is injected with greater force, it covers more distance. BD20 had the greatest PL because it has higher viscosity and density as compared to BD10 and diesel fuel as shown in figure 5. Viscous fuel was less affected by drag force due to which breakup process was reduced and higher density caused greater momentum due to which fuel would penetrate farther. Greater ambient pressure decreased PL due to higher amount of drag offered to the incoming fuel jet at higher ambient pressures. Its effect was more prominent at the later stages of spray. At initial stage, injection pressure defined the fuel spray behaviour because it was greater than the ambient pressure. PL contours at 1000 bar injection and 5 bar ambient pressure can be observed in figure 6.

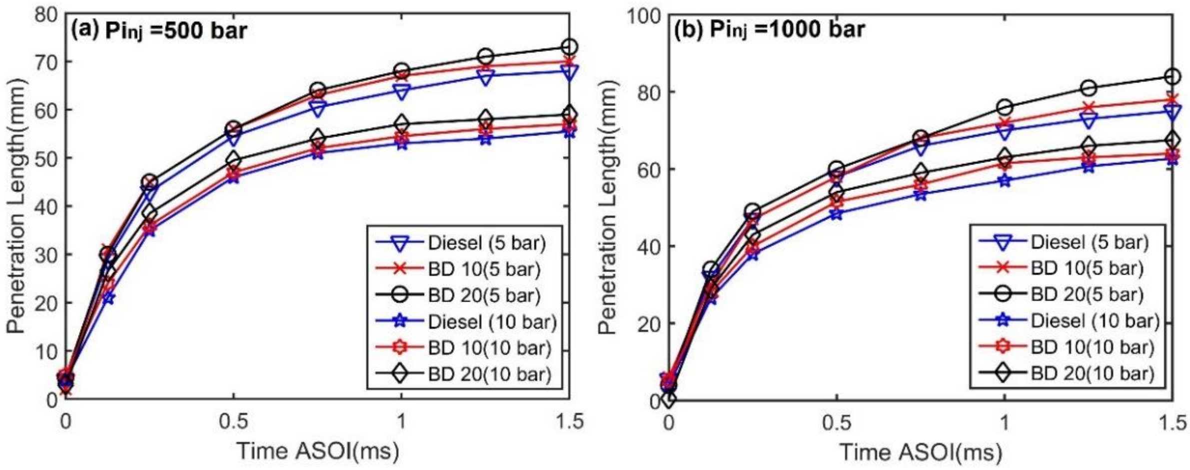

Figure 5. Penetration Length at Injection Pressure of a) 500 bar and b) 1000 bar respectively.

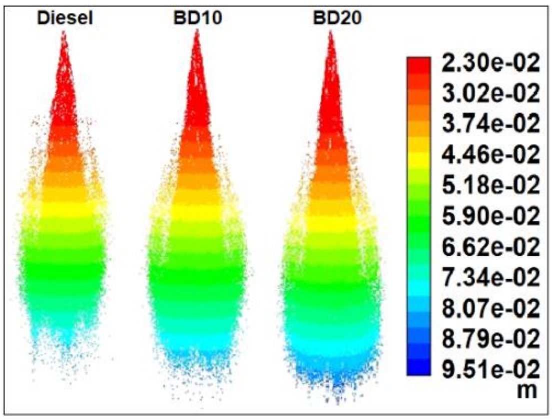

Figure 6. Penetration length contours at 1000 bar injection pressure.

Sauter mean diameter is one of the key parameters in defining fuel spray quality. Figure 7 shows that higher injection pressure caused small drop diameters because of the greater amount of turbulence induced at higher injection velocities. Increased amount of turbulence enhanced the brake up phenomena and small drop diameters were achieved. Increasing ambient pressures also decreased drop diameters as the amount of drag offered to the fuel jet was increased causing the formation of small drop diameters. BD20 had the greatest drop diameters as it was the most viscous and less likely to disintegrate as compared to the BD10 and diesel fuel. Diesel being the least viscous showed the smallest drop diameters.

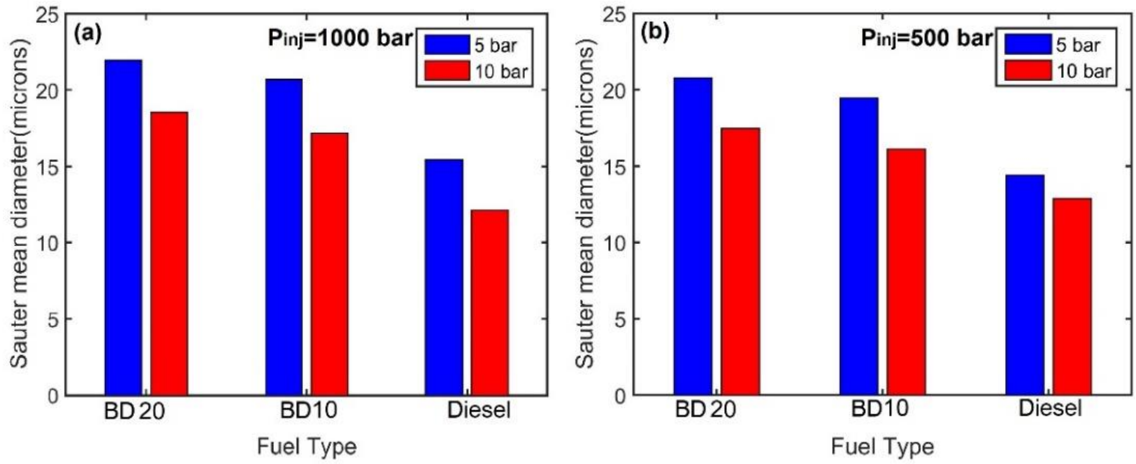

Figure 7. SMD for various fuels at a) 500 bar and b) 1000 bar injection pressure.

Greater cone angles were observed at higher ambient pressures because it retards the axial movement of fuel jet and caused it to expand radially. Cone angle was not much affected by the injection pressure. Diesel being the least viscous showed the smallest drop diameters that spread readily compared to the larger drops, hence, causing greater cone angles. Least cone angles were observed for the BD20 fuel, because of higher viscosity as observed in figure 8.

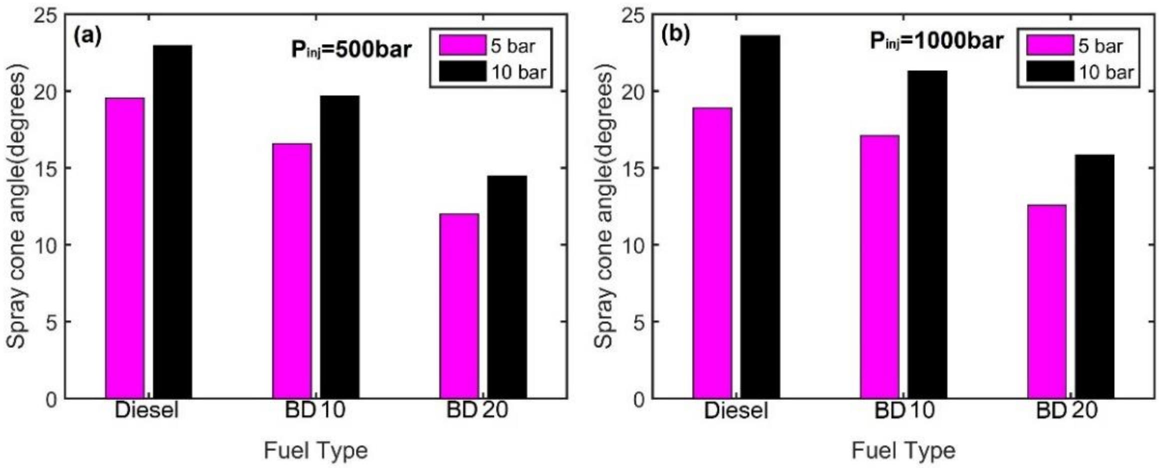

Figure 8. Spray cone angle for various fuels at a) 500 bar and b) 1000 bar injection pressure.

Conclusions

Spray properties of BD10 was closely related to diesel than BD20. Slight difference was due to high viscosity and density of biofuels due to which longer PL, greater drop diameters and smaller cone angles were observed. Increasing injection pressure decreased SMD but increased PL. Higher ambient pressures decreased PL and SMD while the cone angle was increased. Castor oil biodiesel can prove to be effective alternative fuel as it can grow in adverse climatic conditions and have low production cost. The only issue is high viscosity which can be reduced by making blends with diesel fuel. For further studies several additives like n-pentanol, ethanol, and diethyl ether can also be added to the blends for reducing viscosity and enhancing engine performance.

Nomenclature:

ρ : Density

u_i: Velocity in direction i

$\bar{\tau}$: Shear Stresses

$\vec{F}$: Body Force

k : Rate of production of kinetic energy

k_t : Rate of production of kinetic energy because of Turbulence

μ : Viscosity

μ_t : Turbulent Viscosity

G_k: Production of k_t

Y_M : Fluctuating dilation factor

σ_k, σ_ε : Turbulent Prandtl numbers for k and ε

S_e , S_k ,S_ε: User-defined source terms

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