Spray Characteristic Analysis of Diesel Injector with Biodiesel

E. Deeparaj\textsuperscript{a}, B. Vivek\textsuperscript{a}, D. Gunasekaran\textsuperscript{a}, N. Satheeshkumar\textsuperscript{a}, M. Magudeswaran\textsuperscript{b}, S. A. Srinivasan\textsuperscript{b}  
\textsuperscript{a}Department of Mechanical Engineering, Maharaja Prithvi Engineering College, Avinashi, Tiruppur 641654, India.  
\textsuperscript{b}Department of Mechanical Engineering, Nandha College of Technology, Erode, Tamilnadu, India-638052.

Abstract

This paper focuses on the analysis of the effects of biodiesel fluid properties on spray and flow characteristics. Spray characteristics such as initial spray break-up, atomization, droplet size, spray angle, sauter mean diameter and spray tip penetration govern mixture formation in the combustion chamber. The spray parameters have direct influence on combustion, which in turn affects the engine performance and emission characteristics. To analyze the spray parameters, two-step simulation methodology is applied for the computation of the injector nozzle internal flow and the spray evolution. In the first step, the multiphase cavitating flow inside the injector nozzle is calculated by means of steady state CFD simulation at maximum needle opening condition. In second step spray analysis is carried out by multiphase particle tracking using Lagrangian spray calculation. Simulation is carried out with standard diesel, RME and DME in three nozzle diameters 0.15mm, 0.2mm and 0.3mm at injection pressures 800, 1200 and 1400 bar. Mass flow and velocity of fuel at the nozzle is strongly influenced by the change in fluid properties. Cavitations region in nozzle is strongly influenced by fluid properties rather than pressure. Simulation of spray analysis is carried out at non evaporating condition. Spray penetrations and Sauter mean diameter are the two main parameters considered for analysis and discussed.

Keywords: biodiesel, spray parameters, flow characteristics, combustion.

1. Introduction

First generation biofuels refer to biofuels made from sugar, starch, vegetable oils, or animal fats using conventional technology. Second and third generation biofuels are also called advanced biofuels. Second generation biofuels made from non-food crops, wheat straw, wood, energy crop using advanced technology. Algae fuel, also called algae or third generation biofuel is a biofuel from algae. Algae are feedstocks to produce biofuels using more advanced technology. On the other hand, an appearing fourth generation is based on the conversion of vegetable oil and biodiesel into bio gasoline using the advanced technology.

In Diesel engine the high compression pressure to ignite the combustible mixture due to high temperature in the combustion chamber. However, current diesel engine still suffered the emission problems such as nitrogen oxide (NO\textsubscript{x}) and particulate matter into the atmosphere. It is well known that the fuel-air mixture formation is responsible for ignition of diesel engines. The effective control mixture formation is important to improve the exhaust emission from diesel engine.

2. Direct Diesel Injection System

The main requirements of diesel injection system to meet the current and future emission norms include, deliver fuel at the correct time, deliver precise quantity of fuel and at a precise rate of injection. For liquid spray breakup, the jet atomization region is the region of interest in direct diesel injection. The jet atomization region is defined as the break-up consist of coherent liquid core, the droplets outer surface that begin at or very near the nozzle exit results in whose average diameter is much smaller than the nozzle diameter. Many jet atomization mechanisms have been proposed by researchers, classified them as aerodynamic surface wave growth, pipe turbulence, rearrangement of the cross sectional axial velocity profile of the jet, wall boundary layer exit velocity profile relaxation effect, cavitation, and liquid supply pressure oscillation. Cavitation occurs when the pressure in the hydraulic fluid reaches the saturation vapor pressure, and this is a much faster process than air release. Since the
pressure inside the bubbles is much lower than the pressure around the emerging jet, the bubbles gradually collapses as convected by the jet internal turbulence. This process causes perturbations to be formed on the surface of the jet, which lead to its disintegration and detachment of drops. In a diesel nozzle, cavitation is due to shear stress and there are two mechanisms; dynamically induced and geometry induced cavitation.

2.1 Nozzle Configuration

‘Orifice-Type Diesel Nozzles’ are used in directed injection diesel engines. Nozzle tip having smaller nozzle holes and low sac volume is critical for more accurate fuel quantity control and reduction of emissions in direct injection diesel engine. To achieve the low sac volume, minisac nozzle and VCO (Valve Cover Orifice) nozzle are used for direct injection diesel engine. A VCO nozzle is known to be effective for reducing HC emission and creating fine droplets.

2.2 Fuel Properties Affecting the Flow Characteristics

Properties affecting atomization based on the theory of atomization are evident that there are some key parameters, important for atomization and burning characteristics. These properties are viscosity, surface tension, density, latent heat of vaporization, thermal conductivity, specific heat capacity, boiling point and heat of combustion.

2.3 CFD Spray Modeling

The fuel spray represents a very important aspect of combusting systems, as the shape and composition strongly affects the ignition and flame propagation processes. Therefore, the simulation of mixture formation is a critical precondition for the further CFD calculation of combustion in IC engines. The first idea was to adopt a one-phase solver for the gas, in which the droplets were coupled as a carried property (Discrete Droplet Method, DDM). Spray parcels are therefore followed during their motion with a Lagrangian approach, while gas is modeled with a grid-based Eulerian RANS solver.

3. Spray Characteristics & CFD Spray Modelling

3.1 Problem Identification
In view of the rapid development of high-performance engines and fuel-injection systems with sophisticated functionality, adopting biodiesel blends is required to meet future emission regulation. In addition, there are a number of aspects to be considered in the development of dual fuel application. The main difference in physical properties of diesel and biodiesel is one of the major concerns in application of biodiesel in the existing system. The better understanding of behaviour of biodiesel with existing system helps in development. Based on the Literature Survey, the present focus is on the spray characteristics of biodiesel where investigations are in preliminary stages.

3.2 Objectives

The main scope of the paper is to understand the behaviour of diesel injection system with the application of biodiesel. The main aspect to be considered in injection process is injection spray characteristics.

i. Analyse the injection spray characteristics of biodiesel in the diesel injection system. The analysis includes investigation of atomisation efficiency, spray angles, spray penetration, cone angle and sauter mean diameter.

ii. Identify the physical property which influences the spray parameters and establish a relation.

iii. Identify the possible design solution to adopt biodiesel with conventional diesel based on investigation results.

Further scope includes the wear characteristics and deposition formation in nozzle geometry when biodiesel is used. This involves extensive test benches and accelerated test measures.

3.3 Mechanisms of Atomisation

The atomisation processes, can be divided into incomplete such as laminar flow and complete sprays such as cavitating flow. The detaching of the liquid core into ligaments or large droplets is called primary break-up, which involves the action of forces internal to the liquid jet. The liquid ligaments and large droplets will further break-up into small droplets due to the interactions between the liquid ambient gas or droplet collisions. The process of this further break-up is called secondary break-up. The atomization process depends mainly on the injection velocity in the nozzle hole.

3.4 Effects of Injection Velocity and Nozzle Shape on Atomization

Higher injection pressures combined with small nozzle hole diameters can provide better spray formation, better air entrainment, better air-fuel mixing, and more homogeneous mixture with lower equivalence ratio and fewer over-rich regions. The atomization can also be improved by enlarging the chamfer at the spray hole inlet, which also improved the fuel flow velocity at the spray hole outlet.

3.5 Spray Characteristics

3.5.1 Break-up length

The break-up length characterizes a point of discontinuity, where the spray changes from a densely packed zone of liquid, to a finely atomized regime of droplets. Researchers found that the break-up length decreased with an increase in injection velocity, finally reaching a constant value. The same technique was applied by Hiroyasu et al.,

\[ L_B = 7D_n\{1+0.4*r/D\}(P_s/p_l)^{2.05}(L/D)^{0.13}(p/p_g)^{0.13} \]

3.5.2 Spray Penetration
The maximum distance from the nozzle to the tip of the spray at any given time and is one of the most important characteristics of the combustion process. If the spray penetration is too long, there is a risk of impingement on the wall of the combustion chamber, which may lead to fuel wastage and the formation of soot.

\[
S = 3.07 \left( \frac{\Delta P}{\rho g} \right)^{1/4} \left( d_o t \right)^{1/2} \left( 294/T_\theta \right)^{1/4}
\]

3.5.3 Spray cone angle \([\theta_s]\)

The spray cone angle is defined as the angle formed by two straight lines drawn from the injector tip to the outer periphery of the spray at 60 degrees downstream from the nozzle. The definition of the spray angle and the spray penetration are dependent on each other. Therefore the spray angle can be defined as follows: [20]

\[
\theta_s = \tan^{-1} \left( \frac{A_p}{(S/2)^2} \right)
\]

3.5.4 Sauter Mean Diameter (SMD)

The SMD of a spray represents the diameter of the droplet that has the same volume to surface ratio as that of the total spray. It indicates the quality of the atomisation process. It is also the most useful value for determining the rate of evaporation. For a spray to have a fine droplet distribution there is a limit for fluid viscosity and also a lower limit for injection pressure. Higher fuel viscosity resulted in higher SMD as did lower injection pressure.

\[
SMD = 6156\mu^{0.385} S_t^{0.737} \rho_f^{0.737} \rho_a^{0.06} \Delta P^{-0.54}
\]

3.6 Nozzle Fluid Flow Domain

A single hole Sac nozzle is considered for flow analysis. Dimension details of SAC nozzle are given in Figure. The diameter of the nozzle hole is the variable in the analysis. The different diameter considered for analysis is presented in L/D ratio of nozzle hole considered is ~ 5 – 7, nozzle hole is provided with inlet rounding to increase the discharge coefficient of nozzle. In current study K factor considered is 0, where the diameter of nozzle hole at inlet and outlet are equal.

Spray chamber is designed as a cylindrical domain with 80mm diameter to a length of 150mm. Half cylinder is considered as a domain with symmetry surface to reduce the computational time.

3.7 Boundary Conditions: Flow Analysis

The main boundary conditions for flow analysis are represented by the pressure inlet, corresponding to the rail pressure, and the outlet, which should reflect the pressure value of the injection chamber refer Figure.2. At inlet section total pressure (stable) is applied corresponding to the rail pressure, the outlet selection should assure the injection chamber conditions in terms of static pressure.
4. Results and discussions

Simulations are carried out for nozzle diameters 0.15, 0.2, 0.3 with pressures 800, 1200, 1800 bar pressure with standard diesel, RME and DME. Cavitation mainly occurs in the upper part of the nozzle inlet, the computational result agrees well with the observational result in literatures. This confirms that the nozzle model can simulate cavitation. The diesel, RME and DME used in these experiments had different Reynolds. It can be said that through-cavitation occurs when fuel has a high Reynolds number.

Cavitation with fuel vapour production is visible in the upper edge of the nozzle entrance and it is transported downstream by means of flow. The smoothed volume fraction for cavitation of diesel, RME and DME in nozzle hole is shown in Figure 6, 7, 8. In comparison with diesel oil, DME has a large negative-pressure region at the nozzle inlet, causing the flow coefficient to drop. The effective nozzle hole diameter is reduced due to cavitation.

When compared with diesel, RME has less vapour pressure region and hence the flow is slightly less than diesel even the viscosity is very high compared to diesel. The result of simulation shows that the volume fraction, which indicates the effect of cavitation, is larger with DME than with other two fuels. The volume fraction also

---

### Table 1: Boundary condition for analysis

<table>
<thead>
<tr>
<th>Nozzle Diameter (mm)</th>
<th>Injection Pressure (bar)</th>
<th>Outlet Pressure (bar)/ Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>800, 1200, 1600</td>
<td>30 bar / N2</td>
</tr>
<tr>
<td>0.2</td>
<td>800, 1200, 1600</td>
<td>30 bar / N2</td>
</tr>
<tr>
<td>0.3</td>
<td>800, 1200, 1600</td>
<td>30 bar / N2</td>
</tr>
</tbody>
</table>

---

### Table 2: Fluid properties of diesel and bio-diesel

<table>
<thead>
<tr>
<th>Properties / Fuel Type</th>
<th>Diesel</th>
<th>Dimethyl Ether (DME)</th>
<th>Rapemethyl Ether (RME)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>825</td>
<td>668</td>
<td>870</td>
</tr>
<tr>
<td>Liquid dynamic Viscosity (Pa s)</td>
<td>0.0021</td>
<td>0.0001558</td>
<td>0.0039</td>
</tr>
<tr>
<td>Surface tension (N/m)</td>
<td>0.024</td>
<td>0.012</td>
<td>0.028</td>
</tr>
<tr>
<td>Vapour Density (kg/m³)</td>
<td>5</td>
<td>11.23</td>
<td>8.5</td>
</tr>
<tr>
<td>Vapour Dynamic Viscosity (Pa s)</td>
<td>10e-05</td>
<td>1.028e-05</td>
<td>10e-05</td>
</tr>
<tr>
<td>Saturation Pressure (Pa)</td>
<td>1000</td>
<td>892</td>
<td>892</td>
</tr>
</tbody>
</table>
indicates the length of cavitation which is larger for DME. The cavitating length of RME is similar to diesel, but the vapour fraction is less. Cavitation also occurs downstream of the nozzle inlet which does not have a significant change. DME maintains high pressure in the area downstream from the nozzle inlet. The pressure and velocity plot for 0.5mm diameter injector at 800 bar is presented in figure 3,4,5. DME has higher pressure in the nozzle hole, with lower pressure loss in the nozzle, than diesel oil. As a result, DME achieves higher nozzle outlet velocity than diesel oil. The high viscosity of RME causes a decrease of its discharge coefficient in turbulent flow, while its effect is overcome in cavitating conditions. The lower viscosity of DME causes higher velocity and higher volumetric flow rate, hence it can be seen from volumetric plot the mass flow is not very low when compared to the larger velocity difference of flow.

Figure. 3 Pressure and Velocity profile of diesel at 800 bar in 0.15mm Dia. nozzle
Figure 4: Pressure and Velocity profile of RME at 800 bar in 0.15mm Dia. Nozzle

Figure 5: Pressure and Velocity profile of DME at 800 bar in 0.15mm Dia. Nozzle

Figure 5: Pressure and Velocity profile of DME at 800 bar in 0.15mm Dia. Nozzle
4.1 Spray Penetration for Diesel and Bio Diesel

DME spray spreads widely with short penetration. Observing the spray in view of liquid and gaseous portion, the liquid portion of DME spray has shorter penetration than that of diesel. DME has a higher cone angle so the fuels spread immediately after injection.

The same reverse effect can be seen with RME. Even though the velocity of flow is less in nozzle the momentum of fuel droplets is very high when compared with diesel. This is because of large droplets and higher mass density. The sauter mean diameter for RME is higher when compared to other fuels because of higher surface tension at the same time the spray angle is also very narrow. As a result RME penetrates more when compared to diesel and DME. Maximum penetration of 350mm happens with 0.3m diameter nozzle at 1600 bar pressure.
Figure 10. Spray penetration at 1400 bar in 0.15mm Dia. Nozzle

Figure 11. Spray penetration at 1600 bar in 0.15mm Dia. Nozzle

Figure 12. Spray penetration at 800 bar in 0.2mm Dia. Nozzle

Figure 13. Spray penetration at 1400 bar in 0.2mm Dia. Nozzle
5. Conclusion and future work

The influence of using biodiesel fuels with the standard injection system has been studied in this paper. The three fuels RME, DME and Diesel used for simulation have present different physical properties has a direct effect on the working of the injection system and in that way, the injection process is affected. Two step modelling approach is adopted, first the flow analysis is carried out with cavitations condition and spray analysis is carried out with particle tacking using Lagrangian Particle transport model.

The mass flow rate simulations have pointed out that, due to its change in density and viscosity, biodiesel has a different mass flow. As a result of lower density DME has a lower mass flow rate when compare to diesel. Even though the RME has a higher density mass flow is less compared to diesel as a result of higher viscosity. The simulation shows that the sprays of RME have a lower velocity; the analysis showed that the density and viscosity affects the spray velocity and makes it higher for DME. Simulations of spray evolutions highlighted that surface tension affects significantly diesel spray penetration and cone-angle. Concerning the spray pattern, the analysis
revealed that RME has a longer penetration and a narrower angle, mainly due to the high density, viscosity and surface tension.

As the sprays are narrower, this leads to have a higher fuel mass fraction in the spray and this might affect the evaporation behaviour. RME has higher penetration when compared to diesel and DME. Analysis shows the influence of using biodiesel fuels in a standard injection system, slight differences can be adopted by changing the injection strategy can be developed to adopt range of fuels in the current system. In a macroscopic picture DME has more atomisation efficiency comparing with diesel and RME.

References