In-Nozzle Flow and Spray Characteristics for Mineral Diesel, Karanja, and Jatropha Biodiesels

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Abstract

Superior spray behavior of fuels in internal combustion engines lead to improved combustion and emission characteristics therefore it is necessary to investigate fuel spray behavior for new alternative fuels. This study discusses the evolution of the in-nozzle orifice parameters of a numerical simulation and the evolution of spray parameters of fuel spray in a constant-volume spray chamber during an experiment. This study compares mineral diesel, biodiesels (Karanja-and Jatropha-based), and their blends with mineral diesel. The results show that mineral diesel provides superior atomization and evaporation behavior compared to the biodiesel test fuels. Karanja biodiesel provides superior atomization and evaporation characteristics compared to Jatropha biodiesel. The qualitative comparison of simulation and experimental results in tandem shows that nozzle-hole design is a critical parameter for obtaining optimum spray behavior in the engine combustion chamber.

Keywords: Cavitation; Primary atomization; Injector nozzle hole; Biodiesel; Viscosity.

1. Introduction and Background

Diesel engines are one of the most important prime movers for mobility and decentralized power generation and are characterized by heterogeneous combustion [1]. Heterogeneous combustion leads to formation of soot and NO_x in the combustion chamber. The fuel injection system, which is the heart of the engine, plays a pivotal role in the fuel-air mixing processes inside the combustion chamber. The fuel injector is an important component of fuel injection equipment (FIE) and delivers fuel in atomized form into the combustion chamber at very high injection pressures [2]. The main role of the injector is to inject and subsequently atomize the fuel in the engine combustion chamber. Superior atomization leads to the formation of fine fuel droplets (μm range) inside the engine combustion chamber [3, 4]. The large number of fuel droplets in the combustion chamber results in higher fuel surface area availability for air-fuel interactions, leading to better air-fuel mixing and combustion. Fuel atomization behavior depends mainly on parameters such as nozzle diameter, injection pressure, ambient conditions, nozzle geometry etc. Fuel atomization also depends on fuel properties such as viscosity, density, surface tension, vapor pressure, etc. [5]. OEMs design the injector for mineral diesel, which has a relatively lower viscosity and density compared to biodiesel. Injector effectiveness is greatly influenced by the largely different fuel properties of biodiesel. There is a need to more completely understand these influences.

Alternative fuels like biodiesel have received significant global attention in the last couple of decades due to their enormous potential as a partial substitute for mineral diesel. Biodiesel is available in many parts of the world. It is produced from vegetable oils/animal fats using a transesterification process. Biodiesel contains a high oxygen content (~11%), leading to direct reduction in particulate emissions in engine exhaust [6]. Sulfur and aromatics are almost negligible in

biodiesel. However, its higher viscosity can cause some issues in fuel injection equipment because of reduced fuel mass flow rate at the nozzle exit. Higher fuel viscosity and the presence of traces of glycerol in biodiesel may also cause higher wear in injector nozzles. Several researchers have investigated the effect of nozzle parameters on fuel injection [7-10].

Benajes et al., 2004 [11] studied the injection rates for two nozzle hole geometries (cylindrical and conical). They characterized the behavior of injector nozzles by measuring non-dimensional parameters such as Reynolds number (Re), cavitation number (K), and discharge coefficient (C_d). They observed that cavitation occurs in both nozzle types; however, the conical nozzle had a lower tendency to cavitate as compared to the cylindrical nozzle. They reported that C_d was higher for the conical nozzle, as well. They also observed that higher fuel injection pressure and Re leads to chaotic flow patterns in the cylindrical nozzle, while this is not the case in the conical nozzle. Payri et al., 2004 [12] carried out a computational study to determine the influence of cavitation on the nozzle hole internal flows and spray characteristics. They concluded that cavitation increases the spray cone angle and nozzle exit velocity. In a cylindrical nozzle, cavitation starts at the inner sharp corner of the nozzle. As soon as the injection pressure builds up, cavitation extends towards the nozzle exit, which correspondingly results in increased spray angle. Once cavitation reaches the nozzle exit, this phenomenon is called super-cavitation. Once super-cavitation is achieved, the spray angle becomes independent of the fuel injection pressure [13]. Payri et al., 2005 [14] also investigated the effect of nozzle geometry on spray characteristics by measuring the spray momentum flux. They characterized two injector nozzles; cylindrical and conical, using two spray parameters, such as mass flux and momentum flux. They reported that cavitation occurs when mass flow collapses in the cylindrical nozzle. They also reported that there was no cavitation in the conical nozzle, even under extreme pressure conditions. Suh and Lee, 2008 [15] studied the atomization characteristics of diesel, which is affected by in-nozzle cavitation. A flow visualization system was used for observing the cavitation, while atomization

characteristics were evaluated using a droplet analysis system. Diesel spray atomization was characterized for different L/D ratios of the nozzle orifices. It was reported that cavitation, as well as a higher length of nozzle orifice, both lead to increased spray atomization of the fuel. Payri et al., 2008 [16] proposed a model for liquid phase fuel penetration based on nozzle flow parameters and then investigated the effect of nozzle geometry on liquid phase fuel penetration under evaporative conditions.

Som et al., 2011 [17] studied the effect of nozzle hole geometry on spray, combustion, and emission characteristics of mineral diesel. Using the computational fluid dynamics (CFD) software CONVERGE [18], they investigated the combustion process resulting from coupled injector flow and spray simulations. Their results showed that the vaporization rate and fuel-air mixing reduced when conical and hydro-grounded nozzles were used. They reported higher pre-mixed combustion and reduced diffusion combustion for the conical nozzles, as compared to cylindrical nozzles. They also concluded that there is a trade-off between conical and hydro-grounded nozzles because conical nozzle leads to the highest soot production, whereas NO_x production was highest for the hydro-grounded nozzles.

The literature clearly shows that there have been extensive studies on characterizing the nozzle flow and ensuing spray of mineral diesel. Som et al., 2010 [19] performed a study comparing the injector flows and spray characteristics of biodiesel and mineral diesel. They characterized the inner nozzle flow dynamics of the two fuels with the help of a mixture-based cavitation model. They reported that there was loss of flow efficiency, reduction in injection velocity, and lower turbulence levels for biodiesel. Less cavitation was observed with biodiesel compared to mineral diesel. Spray penetration was slightly higher with biodiesel; however, spray cone angle was higher with mineral diesel because of its superior atomization character. Battistoni and Grimaldi, 2010 [20] also studied diesel and biodiesel characteristics using simulation tools. They observed that biodiesel leads to a significantly higher fuel mass flow only if the nozzle design induces significant cavitation, which extends upto the exit section, and if

the injector needle is at high lift. If the internal nozzle shaping is able to suppress cavitation, the stabilized mass flows were very similar for both fuels. As long as the lifts are small and the flow is turbulent, diesel gave higher mass flows due to relatively lower friction along the needle seat and nozzle walls. However, these studies either focused on soy or on rapeseed-based biodiesels. Park et al., 2008 [21] investigated the effect of cavitation on the fuel flow and atomization characteristics for biodiesel with two different injector nozzle designs (different L/D ratios of the nozzles). They also reported that cavitation occurred along the internal wall of the nozzle hole due to its geometry. The mean droplet size of biodiesel was reportedly larger than diesel and droplet size became smaller with cavitation. A nozzle design with higher L/D ratio resulted in smaller droplet sizes. Suh et al., 2008 [22] performed experimental investigations on the cavitating nozzle flow characteristics using diesel and biodiesel. They performed the study for different nozzle geometries and confirmed that cavitation growth could not happen in tapered nozzles even at high fuel injection pressures. There are studies [23-27], which compare simulation results and experimental results for diesel and biodiesel sprays or their in-nozzle flow patterns. There is hardly any study reporting simulation of fuel flow in the injector's nozzle and evaluation of its effects on spray characteristics experimentally. Flow characteristics inside injector nozzle affects spray behavior in the combustion chamber. For employing alternative fuels for diesel engines and emission reduction, this study is essential.

The literature also indicated that there are limited (if any) studies on Jatropha- and Karanja-based biodiesel feedstocks. These feedstocks are important in the South Asian sub-continent, and numerous studies on their utilization in engines have shown good performance and emission characteristics [28]. Graboski and McCormick, 1998 [29] published an excellent review of the physical and chemical properties of mineral diesel and biodiesels from different feedstocks. They demonstrated that differences in the physical properties of these fuels can in fact be responsible for differences in performance and emission characteristics in an

engine. This motivates us to further our understanding of the nozzle flow and spray characteristics of Jatropha- and Karanja-based biodiesels.

The main theme of this study are 1) in-nozzle flow characterization carried out using simulations, and 2) the study of ensuing spray behavior carried out experimentally. The nozzle flow parameters were determined by performing in-nozzle flow simulations, since experimental studies to visualize flow inside a fuel injector are rather limited. These studies provided critical insights about the flow and turbulence characteristics for the fuels of interest. The simulation studies were followed by experimental visualization and quantitative spray characterization of these fuels. The simulation results were used for qualitative analysis and comparison with spray injection parameters obtained from experiments with diesel, Karanja biodiesel (KB100), Jatropha biodiesel (JB100), and their blends with diesel (KB5, KB20, JB5, JB20). The blending was performed on a volume basis and the physical properties of the blends were determined using linear blending rules for pure components. Results are reported in two different sections: 1) Karanja biodiesel and blends, and 2) Jatropha biodiesel and blends, compared to baseline diesel.

2. Simulation Methodology

Transient in-nozzle flow simulations were performed using FLUENT software. The software employs a mixture-based approach [19, 30-31], comprised of fuel in liquid phase, vapor phase, and a non-condensable gas phase. A no-slip condition between the liquid and vapor phases was assumed. The mixture properties were computed using Reynolds-averaged continuity and momentum equations. In order to account for large pressure gradients, the Re-Normalization Group (RNG) $k-\epsilon$ turbulence model was incorporated, along with non-equilibrium wall functions. Vapor generation and condensation were calculated using the simplified solution of the Rayleigh-Plesset equation [32]. Further details about the physical model and governing equations can be found in the referred study [32]. A production grade mini-sac nozzle used in this study is shown in Figure 1. The injector had six cylindrical nozzle orifices (each 169 μ m diameter), at an

included angle of 126° . The flow was assumed to be symmetric across all nozzle orifices, therefore only one orifice was simulated. The computational domain (single orifice) used in the simulations is indicated by a marked box. The sac region was characterized by tetrahedral elements, while other zones consisted of structured orthogonal grids. To ensure grid independence, a total of 220,000 cells were generated. The pressure values specified were at the inlet (1000 bar) and at the outlet (10 bar) boundaries, while symmetry conditions were employed to demarcate the 60° sector mesh. All other surfaces were specified as wall boundaries, with no slip between the fuel-air mixture and nozzle orifice walls.

Figure 1: Schematic of a six-hole production grade mini-sac nozzle. Only two holes are seen in this cross-section. Nozzle and needle regions are identified along with the computational domain used in simulations.

Needle lift and injection pressure profiles for simulations were taken from an experimental study by Kastengren et al., 2009 [33]. Figure 2a shows the needle lift configuration for fuel injection through nozzle holes. Figure 2b shows the fuel injection pressure during fuel supply through the nozzle holes.

Figure 2: Needle lift (a) and injection pressure profiles (b) of the injector used for the simulation.

3. Experimental Setup and Procedure

It is essential to characterize the fuel before spray investigations for its important physical, chemical and thermal properties. Kinematic viscosity of mineral diesel and biodiesels was measured using Kinematic viscometer (Stanhope-Seta: Setavis 83541-3) at 40°C. ASTM 445 test method was followed for viscosity measurement. Fuel density was measured using portable Density meter (Kyoto Electronics: DA-130N) following ASTM D4052 test method. ASTM D613 test method was used for cetane number determination. Cetane number tests were carried out at Indian Oil Corporation (R&D centre), Faridabad. Flash point test fuels were determined by ASTM 3828 test method using Automatic Flash Point Apparatus (Stanhope-Seta: 33000-0). Carbon residue of test fuels was determined using Carbon Residue Tester. Carbon residue indicates the tendency of the fuel to form carbonaceous deposits and ASTM D189 test method was used for its determination. Bomb calorimeter (Parr, USA; 6200) was used for determination of the calorific values of test fuels.

Figure 3: Schematic of the experimental setup

The constant volume spray chamber consists of four diametrically opposite glass windows, which enable optical access for spray illumination and visualization (Figure 3). A six-hole solenoid fuel injector (with 169 μm nozzle orifice diameter) was installed on the side flange of the chamber, in order to facilitate fuel injection into the chamber. The fuel injection equipment consists of a high pressure pneumatic pump (Maximator; G300 LVE), a common rail (DELPHI-TVS; Rail – 2.2 TML), high pressure fuel lines and an injector driver system (NI; CompactRIO-9022). Nozzle opening pressure of the solenoid injector was maintained at 1000 bar using high pressure pneumatic pump. The test fuels were supplied to the solenoid injector using a high pressure common-rail system. Two white light sources (NaBa Green; RDL 24W) were used to illuminate the fuel droplets in the spray chamber. A high speed camera (Photron; Fastcam SA1.1) was used to capture the light scattered by the fuel spray droplets in injection. Triggering pulse of fuel injector was synchronized with the camera to eliminate time delay between injection and images captured. During the experiments, temperature and pressure in the constant volume spray chamber were maintained at 25°C and 10 bar respectively. The spray chamber was pressurized with the help of nitrogen gas. The images were captured using high speed camera, and then analyzed using Matlab to determine the spray penetration length, spray cone angle and area.

The injection duration pulse was kept constant at 3 ms for all the experiments. One fixed frame (at 0.9 ms) was considered for the macroscopic analysis. The high speed camera was set at frame speed of 10000 fps, 1/10000 shutter speed (fps^{-1}) with 768 $\times$ 768 resolution. A similar type of study was performed at Engine Research Laboratory, IIT Kanpur by our group earlier in order to study the macroscopic parameters of injection (Agarwal et al., 2013 [28]). However experiments were performed for a mechanical injector with 220 bar fuel injection pressure.

This study included comparison of spray results obtained from these experiments with the injector nozzle hole simulation results for mineral diesel, Karanja biodiesel and blends, and Jatropha biodiesel and blends. Simulation results were

obtained for fuel velocity and vapor fraction profiles inside the injector nozzle hole. In the present study, experimental work was carried out at an ambient pressure of 10 bar. This was done for the sake of comparison with simulation study which was also done at 10 bar ambient pressure. The images captured were used to evaluate macroscopic spray parameters. Figures 4 and 5 show the spray evolution for diesel, Karanja biodiesel, Jatropha biodiesel and their blends with time. Spray visualization images provide qualitative information about the spray evolution pattern for these test fuels.

Figure 4: Growth of fuel spray with respect to time for diesel, Karanja biodiesel and its blends (t=0 is start of injection)

Figure 5: Growth of fuel spray with respect to time for diesel, Jatropha biodiesel and its blends (t=0 is start of injection)

Macroscopic Spray Parameters

Spray tip penetration: The spray tip penetration was calculated by joining a line from the tip of the injector orifice to the farthest point where spray diminishes (Figure 6a).

Spray cone angle: The spray cone angle was created by the tip of the injector orifice and the tangent drawn to the spray boundary (Figure 6b).

Spray area: The area covered by spray droplets within the spray regime is known as spray area. The spray area was calculated using the total area of image pixels in the spray boundary region (Figure 6c).

Figure 6: Macroscopic spray parameters measurements showing (a) spray tip penetration, (b) spray cone angle, and (c) spray area.

Agarwal et al., 2013 [34] reported the influence of ambient pressure on the spray evolution of diesel and biodiesel blends. They reported that spray penetration length decreased with increasing ambient pressure (from 1 to 9 bar), while the spray cone angle and spray area increased. The dimension of the nozzle holes in the experiments is same as that used in the simulations. The simulations were carried out to provide insights into the flow development of these test fuels. The results reported in this study provide valuable insights about in-nozzle flows and turbulence characteristics, which were not previously available for the biodiesels used in this study.

4. Results and Discussions

4.1 Fuel Characterization

Karanja and Jatropha biodiesels, and mineral diesel were used as base fuels in this study; therefore, their physical properties are important and are shown in Table 1.

Table 1: Physical properties of test fuels

Fuel	Kinematic viscosity @ 40°C (mm ² /s)	Density @30° C (kg/m ³)	Calorific value (MJ/kg)	Flash point (°C)	Cetane number	Carbon residue (% wt)	Latent heat of Vaporization (kJ/kg)
Diesel	2.78	831	43.8	50	51	0.01	250
JB100	6.87	897	37.9	187	49	0.05	320
KB100	5.65	860	38.5	175	50	-	210

Karanja (KB100) and Jatropha (JB100) biodiesels have higher flash point temperatures compared to mineral diesel; therefore, blends of these biodiesels with mineral diesel would also have higher flash point temperatures compared to mineral diesel. The higher flash point indicates that it would be relatively safer to store biodiesel blends compared to mineral diesel. Calorific values of Karanja and Jatropha biodiesels were also lower compared to mineral diesel. The lower calorific value of biodiesel results in a higher volumetric flow rate compared to mineral diesel for the same engine power output. Biodiesel fuel contains oxygen, which results in a higher degree of combustion completion inside the engine combustion chamber. Biodiesels are derived from a vegetable oil feedstock using a transesterification process. Transesterification reduces the viscosity of vegetable oils by at least an order of magnitude, and the biodiesels thus produced have viscosities comparable to mineral diesel. As a result, these modified fuels could be used in certain unmodified internal combustion (IC) engines as 100% biodiesel, or in most engines as blends with mineral diesel. However, the slightly higher viscosity and gum-forming tendencies of biodiesel may cause higher wear of fuel injection equipment (FIE) components [29]. Vapor pressure was determined from the experimental measurements of the fuel properties and it was found to be 1000 Pa for both biodiesel feedstocks.

4.2 Simulation and Experimental Results of Fuel Sprays of Mineral Diesel, Karanja Biodiesel and Blends

Figure 7 shows the results obtained by simulating the vapor fraction contours for the diesel, Karanja biodiesel, and blend fuels at peak needle-lift. It was observed that all test fuels were present in liquid form upstream of the orifice hole. As soon as fuel entered the orifice hole, the cavitation phenomenon was clearly observed, with increasing regions of vaporization shown in red. For diesel, KB5, and KB20, cavitation inception occurred at the inlet to the orifice and continued through the nozzle exit.

Figure 7: Vapor fraction contours in the nozzle hole for diesel, KB5, KB20, and KB100.

Most of the cavitation occurred towards the upper edge of the orifice. For KB100, cavitation inception occurred at the inlet to the orifice but extended only for a short distance. It was observed that most of the biodiesel (KB100) was present in liquid phase and it was injected into the combustion chamber in liquid phase. This was mainly due to Karanja biodiesel having a higher viscosity than mineral diesel, which tended to inhibit cavitation inception. This is consistent with previous results reported by Som et al. 2010 [19] and Battistoni et al. 2010 [20].

Figure 8: Velocity contours in the nozzle hole for diesel, KB5, KB20, and KB100.

Figure 8 shows the velocity contours in the nozzle hole for diesel, Karanja biodiesel and blends. It can be observed that the fuel velocity in the nozzle is highest for diesel and this is also shown in Table 2, which lists the results for the various parameters in these simulation runs.

Table 2: Simulated parameters for diesel, Karanja and Jatropha test fuels

Simulated Parameter	Diesel	KB5	KB20	KB100	JB5	JB20	JB100
Quasi-steady mass flow-rate (g/s)	7.2317	7.2511	7.2697	8.0510	7.2446	7.2945	8.0498
Exit velocity (m/s)	411.0	409.0	408.0	386.0	409.4	396.2	382.6
Density at nozzle exit (kg/m ³)	774	780	786	900	780	860	910
Turbulent Kinetic Energy (m ² /s ²)	2748	2828	2896	3131	2861	3091	3596
Turbulence Dissipation Rate (m ² /s ³)	5.4E+9	5.5E+9	5.5E+9	5.6E+9	5.5E+9	5.8E+9	6.2E+9
T (s) [TKE/TDR]	5.09E-7	5.14E-7	5.26E-7	5.59E-7	5.20E-7	5.33E-9	5.80E-7
Discharge Coefficient (C _d)	0.682	0.681	0.681	0.732	0.681	0.683	0.738
Area Coefficient (C _a)	0.90	0.91	0.93	1.00	0.91	0.93	1.00

Fuel density and viscosity play a critical role, and are also primary factors controlling the flow through the injector. Diesel has a relatively lower viscosity compared to other test fuels, which results in higher velocity. As biodiesel content in the test fuel increased from 5% to 100%, exit velocity decreased (Table 2). Higher spray velocity is desirable for superior combustion since it enhances fuel atomization in the combustion chamber [3,4]. Due to cavitation at the nozzle exit for diesel and its blends with Karanja biodiesel, the density of the fluid mixtures at the nozzle exit were lower (Table 2). However, for Karanja biodiesel (KB100), the density at the nozzle exit was equal to the liquid density, due to the absence of vaporization at the nozzle exit, as seen in Figure 7. Cavitation at the nozzle exit led to a reduction in the fuel mass flow rate entering the combustion chamber (Table 2). According to Figures 7 and 8, atomization is expected to be superior for mineral diesel, which progressively worsened with increasing biodiesel content in the test fuel.

Figure 9: Velocity contours at the exit of the nozzle hole cross-section for diesel, Karanja biodiesel, and blends.

Figure 9 shows the velocity contours of the diesel, Karanja biodiesel and blends at the exit cross section of the nozzle hole. The fuel present in the periphery of the cross section of the hole would have lower velocity due to the boundary layer. Note that the high velocity zone was highest and most symmetric in diesel; therefore, it was expected that the fuel spray would have a lower spray cone angle. Karanja biodiesel had the smallest zone with the highest velocity, also located eccentrically, suggesting that this would lead to a higher cone angle for KB100. The conditions of the fuel velocity inside the hole can significantly affect macroscopic parameters in the engine combustion chamber. These observations can only be verified by spray chamber experiments. If the exit velocity and region of higher exit velocity is higher, then one would expect the near field spray cone angle to be lower but the far field spray cone angle would indeed be higher. This is due to the fact that higher relative velocity between liquid and gas phases results in a higher degree of shear between the two phases that basically promote breakup of the liquid jet as per the Kelvin Helmholtz instability mechanism. Enhanced shear and breakup would result in higher momentum exchange with the ambient air, thus higher degree of spray spreading and increased spray cone angle would be observed. Since the spray cone angle measured here is averaged and is not near-field or far-field, it is difficult to draw clear conclusions. However, it is observed that fuels with higher velocity and larger extent of high velocity actually lead to lower cone angles.

Table 3 shows the experimental results of macroscopic spray parameters such as spray tip penetration, area, and cone angle. These experiments were carried out in the constant volume spray chamber under simulated non-evaporative engine conditions, typical of the end of the compression stroke, except for temperature and turbulence.

Table 3: Spray parameters for diesel, Karanja biodiesel, and blends

Fuel	Spray tip penetration (cm)	Spray area (cm ²)	Spray cone angle (degree)	Reduction in cone angle (degree)
Diesel	9.91	31.45	19.30	
KB5	10.15	28.66	18.55	0.75
KB20	10.87	31.86	19.26	0.04
KB100	12.19	32.62	20.98	-1.68

For diesel, the spray tip penetration length was 9.91 cm, which becomes 10.15 cm for KB5, 10.87 cm for KB20, and 12.19 cm for Karanja biodiesel (KB100). This trend was consistent with the in-nozzle quasi-steady mass flow rate calculations shown in Table 2. Spray area was observed 31.45 cm², 28.66 cm², 31.86 cm² and 32.62 cm² for diesel, KB5, KB20, and KB100 respectively. Similarly, spray cone angles were observed as 19.3°, 18.55°, 19.26° and 20.98° for diesel, KB5, KB20, and KB100, respectively. KB5 showed the lowest values of spray area and spray cone angle among the four fuels which was followed by diesel fuel, however, spray tip penetration length was lowest for diesel. The values of the three spray parameters were highest for KB100. Due to the 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, which results in a lower spray penetration for diesel. This expectation is consistent with the experimental measurements shown in Table 3. Since KB100 is completely in a liquid phase when entering the engine combustion chamber (Figure 7), the droplets of biodiesel having higher inertia would travel longer distances. Hence higher spray penetration, more spray area and wider cone angles were observed for Karanja biodiesel (KB100) compared to all test fuels. Since the fuel may not evaporate at the experimental temperature conditions of 25°C, it may just be a fluid mechanics effect governed by the flow inside the nozzle orifice. Therefore, one can expect a similar behavior showing relatively higher spray penetration and higher cone angle for Karanja biodiesel. The higher spray surface area can also be attributed to the fact that Karanja biodiesel evaporated less and more slowly than diesel spray due to the absence of cavitation at the nozzle exit (Figure 7). The blends followed an expected trend, i.e., increased biodiesel content in the test fuel led to an increase in spray penetration, spray area, and spray cone angle, except for KB5 which showed lower values of spray area and spray cone angle compared to diesel. Reductions in spray cone angles observed were 0.75°, 0.04° and -1.68° for KB5, KB20 and KB100 respectively compared to diesel (Table 3). KB5 showed lowest spray cone angle, which increased with increasing biodiesel blend concentration. This

increase in cone angle may be simply because of the resistance of air to the incoming fuel droplets. In case of diesel, higher spray cone angle is a result of its relatively higher evaporation compared to biodiesel.

4.3 Simulation and Experimental Results Using Fuel Sprays of Mineral Diesel, Jatropha Biodiesel and Blends

Figure 10 shows the results obtained by simulation of vapor fraction contours for the diesel, Jatropha biodiesel (JB) and blends at peak needle-lift. It was observed that all test fuels were present in liquid form upstream of the orifice hole. As soon as fuel entered into the orifice hole, cavitation phenomenon was clearly observed, with increasing regions of vaporization shown in red. For diesel and JB5, cavitation inception occurred at the inlet to the orifice and continued through the nozzle exit, similar to the observations made for Karanja biodiesel. Most of the cavitation occurred towards the upper edge of the orifice.

Figure 10: Vapor fraction contours in the nozzle hole for diesel, JB5, JB20 and JB100.

For JB20 and JB100, cavitation inception occurred at the inlet of the orifice but extended for only a short length. It was clearly observed that most of JB100 was present in liquid phase and the fuel injected into the combustion chamber was completely in liquid phase. This was mainly due to the fact that Jatropha biodiesel has a relatively higher viscosity than mineral diesel, which tends to inhibit cavitation inception. Due to cavitation at the nozzle exit for diesel and its minor blends with Jatropha, the density at the nozzle exit was lower for these fluid mixtures (Table 2). However, in the case of Jatropha biodiesel (JB100), the density at the nozzle exit was equal to the liquid density due to the absence of vaporized fuel at the nozzle exit. Cavitation at the nozzle exit led to the reduction in fuel delivery (fuel mass flow rate) into the combustion chamber, also shown in Table 2.

Figure 11: Velocity contours in the nozzle hole for diesel, JB5, JB20 and JB100.

Figure 11 shows the velocity contours for diesel, JB5, JB20, and JB100. It can be observed that the velocity was highest for diesel, followed by Jatropha biodiesel blends (Table 2). Diesel had the lowest viscosity, which resulted in higher nozzle exit velocity. As the biodiesel content increased from 5% to 100% in the test fuels, the exit velocity decreased (Table 2). According to the simulation results, atomization is expected to be better for diesel, and it worsened with an increasing blend of Jatropha biodiesel. Jatropha biodiesel has higher viscosity, which lowers the overall exit velocity of the droplets from the nozzle. However, lower blends of Jatropha biodiesel behaved quite similarly to diesel.

Figure 12: Velocity contours at the exit of the nozzle hole cross-section for diesel, Jatropha biodiesel, and blends.

Figure 12 compares the velocity contour at the exit of the nozzle hole cross-section for Jatropha biodiesel, blends, and diesel. Compared to diesel, the velocity profile of Jatropha biodiesel and blends had a significantly lower exit velocity at the nozzle exit. The lower exit velocity led to less atomization and evaporation of the fuel in the combustion chamber. Similarly, macroscopic parameters such as spray area and spray cone angle were reduced for Jatropha biodiesel and blends as compared to diesel. As the concentration of Jatropha biodiesel in the test fuel increased, spray characteristics became inferior. Different fuel properties lead to differences in spray behavior for biodiesel blends compared to mineral diesel. Biodiesel has relatively higher viscosity and density compared to diesel, which leads to lower nozzle exit velocity, and subsequently lower spray area as well as spray cone angle.

Table 4: Spray parameters for diesel, Jatropha biodiesel and blends

Fuel	Spray tip penetration (cm)	Spray area (cm ²)	Spray cone angle (degree)	Reduction in cone angle (degree)
Diesel	9.91	31.45	19.3	
JB5	9.98	29.54	17.17	2.13
JB20	10.37	30.77	17.74	1.56
JB100	11.11	32.38	18.27	1.03

Table 4 shows the spray tip penetration, spray area, and spray cone angle for Jatropha biodiesel and blends as compared to diesel. Due to the higher degree of cavitation for diesel and cavitation patterns reaching the nozzle exit, a higher degree of atomization was expected in the nozzle exit zone, which would result in lower spray penetration for diesel (9.91 cm) compared to the blends of Jatropha biodiesel. This is consistent with the experimental measurements for spray penetration length shown in Table 4. Since the fuel may not evaporate at the experimental temperature conditions of 25°C, it may just be a fluid mechanics effect governed by the flow inside the nozzle orifice. The higher heat of vaporization of Jatropha biodiesel and lower velocities of the peripheral contours of the nozzle cross sections (Figure 12) resulted in lower evaporation, deeper penetration, and wider spray cone angle. The higher spray surface area can also be attributed to Jatropha biodiesel's lower evaporation characteristics. The JB100 biodiesel blends followed an expected trend, i.e., increasing concentration of Jatropha biodiesel in the test fuel increased spray penetration, spray area, and spray cone angle. However, JB5 showed lower spray area and spray cone angle than diesel, unlike the spray penetration length.

4.4 Comparison of Karanja and Jatropha Biodiesels

The exit velocity, mixture density, and mass flow rates at the nozzle exit were quite similar for Karanja and Jatropha biodiesels. However, the vapor fraction results of Karanja (Figure 7) and Jatropha (Figure 10) biodiesels were significantly different. Atomization and vaporization characteristics were superior for Karanja biodiesel (KB100) since cavitation contours continued to the nozzle exit up to KB20, which was not the case with Jatropha biodiesel, where it continued up to the nozzle exit for JB05 only. The reason for this phenomenon may be the relatively higher viscosity of JB100 compared to KB100, which tended to inhibit cavitation.

From the present experimental spray studies, it can be seen that Karanja biodiesel may evaporate faster in the engine combustion chamber than Jatropha biodiesel. This can be extrapolated from the spray penetration, cone angle, and spray area plots for these two biodiesel fuels. Karanja test fuels had higher

relative velocity contours at the exit of the nozzle cross section compared to Jatropha test fuels (Figure 9 and 12). This is because Karanja biodiesel has relatively lower viscosity and density compared to Jatropha biodiesel (Table 1). Therefore, Karanja biodiesel seems to be a more promising biofuel compared to Jatropha biodiesel, as far as fuel-air mixing is concerned.

5% biodiesel blends behaved in a slightly different manner compared to higher biodiesel blends for both feedstocks. Currently no clear explanation can be provided for this phenomenon and the reason for this needs to be investigated in future studies. It should be noted that simulation results show the in-nozzle flow characteristics and experimental results show spray characteristics in spray chamber. The diameter of the injector nozzle used in the experiment is slightly different than the dimensions used in the simulation study. This leads to some variation in the experimental and simulation results.

5. Summary

In the present study, experimental results of macroscopic spray parameters were investigated and compared with results obtained from simulations for diesel, Karanja biodiesel and blends, and Jatropha biodiesel and blends. On the basis of our investigations, the following conclusions are made:

1. The physical properties of a fuel have a profound influence on nozzle flow and spray characteristics. Nozzle flow and spray characteristics of Jatropha and Karanja biodiesel were investigated in this study, which highlights that diesel shows superior atomization and evaporation characteristics in comparison to both Jatropha and Karanja biodiesels and blends.
2. Jatropha and Karanja biodiesels behaved markedly different from each other and as compared to diesel. However, lower biodiesel blends showed nozzle flow and spray characteristics closer to those of diesel than to corresponding biodiesels.
3. Qualitative insights can be drawn from simulation results, which helped further the understanding of fuel sprays penetration trends.

4. The cavitation, turbulence, and velocity of fuel at the nozzle exit are critical parameters. These parameters have a significant influence over the atomization and evaporation characteristics of the spray exiting the injector nozzles.
5. By comparing simulation results with experimental results, it was evident that the nozzle orifice design is an important parameter for obtaining optimum spray characteristics and subsequent engine performance and emission characteristics.

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