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Experimental and Numerical Investigation of Spray Characteristics of Butanol-Diesel blends

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Abstract

Spray characteristics are among the most important factors that affect compression ignition (CI) engines' performance and emission levels. Flow visualisation and optical diagnostics have been widely employed in previous and current research as methods for controlling the combustion processes. This paper investigates the spray visualisation of butanol-diesel blends to determine spray characteristics such as spray penetration (S) and Average Sauter Mean Diameter (ASMD) using Ansys Forte under different ambient pressures and temperatures. The spray results showed that the spray penetration length is decreased as a result of the increased ambient pressure, while it is increased as a result of increased injection pressure of all test fuels**.** An increase in ambient temperature caused pure diesel penetration to become longer and wider, while butanol-diesel blends penetration becomes shorter. The ASMD of the butanol-diesel blend is higher than that of pure diesel at all operating conditions.

1 Introduction

The growing number of alternative fuels such as alcohol has led to an increased interest in studying the spray and combustion characteristics of these fuels. These alternative fuels can be used alone or mixed with diesel fuel in different ratios. Flow visualisation and optical diagnostics should be employed to help understand the combustion processes. Complete combustion is assisted by maximising the contact the injected fuel has with the available air. Since design and fabrication of an engine with an optical window is a costly and complex option, visualisation techniques have been applied in modified engines with optical access [1, 2] and in a constant volume chamber (CVV) at similar conditions to a real engines [3]. In addition, these visualisation techniques can be used to investigate a wide range of operating conditions and different alternative fuels used later. Some studies have also used a CVV at ambient conditions [4, 5] and made use of software (Forte or KIVA) to simulate the results for a wider range of operating conditions. Investigating, operating conditions can be expensive if carried out experimentally, so effective software can contribute to a saving in both cost and effort. The software can be set for different injection systems and optimal operating conditions. The key parameters for the visualisation technique can be classified into classes of parameter: (1) macroscopic parameters such as spray penetration can be determined through direct visualisation methods. A charge-coupled device (CCD) is commonly used in research labs for taking spray images [6]. (2) The microscopic parameters such as droplet size and ASMD can be measured using Particle Image Velocimetry (PIV). Moreover, there are many studies that numerically investigated spray behaviour. These studies used different software packages such Ansys Fluent and Ansys Forte to predict the spray characteristics. Agudelo et al. [7] studied spray behaviour by using the Kelvin-Helmholtz Rayleigh-Taylor (KH-RT) model in Ansys Forte. The simulation parameters that were used are three different injection pressures (400 bar, 500 bar, and 600) bar and three ambient gas pressures (1 bar, 10 bar and 20 bar). The model outputs were spray tip penetration, drop mean diameter and evaporation rate. These results have been validated with experimental data and good agreement obtained. Vijayraghavan and Rutland [8] investigated the effect of physical properties on spray models

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using Ansys Forte and for non-reacting spray simulations using the KH-RT model. Verma et al. [4] also studied the spray behaviour of gasoline fuel in DI engine using Ansys Forte at atmospheric conditions at an injection pressure of 100 bar and durations of injection of 0.88 ms and 2.4 ms. The result of the simulation had very good agreement with experiments at the same conditions. This paper investigates the spray characteristics of a butanol-diesel blend experimentally and numerically in Ansys Forte to measure spray penetration length (S) and ASMD under various ambient pressures and temperatures.

2 Experimental Apparatus

2.1 Spray Test Setup

The spray test was carried out on a CVV at atmospheric pressure and room temperature (30 ºC). An air-driven high-pressure fuel pump was used in the fuel injection system, where the fuel was pressurised in a common-rail system and injected using a solenoid Delphi-type injector with six holes (each 0.198 mm in diameter). A Photron (CCD) camera was used to capture the spray blend images. The camera has a resolution of 1024×1024 pixels and the shutter speed and frame rate were fixed at 1/5,000 s. The camera was synchronised with the injector by using same triggering signal. A Nikon AF Micro-Nikkor lens with a focal length of 60 mm and a maximum aperture of f/2.8D with filter size 62 mm was connected to the camera. An LED light was used for illuminating the fuel spray on each window to ensure constant background light for the camera. The spray characteristics of neat diesel (D) and 20% butanol 80% diesel (B20D80) fuel blends were investigated. Two injection pressures were used 300 bar and 500 bar. Fig. 1 shows the schematic of the CVV with the fuel injection setup.

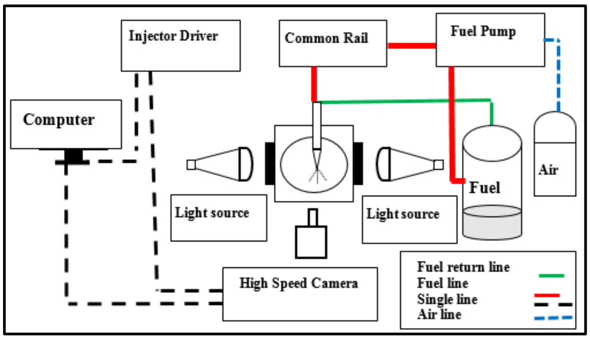

Figure 1. Schematic of CVV with fuel injection system.

2.2 Simulation of Spray Visualisation

2.2.1 Spray Model

Ansys Forte was used to simulate fuel injection with the RNG k-ε turbulence model and an independent spray breakup model proposed by Alaina [9] called the gas jet model. The multi-component vaporisation model solves unsteady vaporisations of single and multi-component fuel droplets with consideration of both normal and flash-boiling vaporisation conditions. The spray was modelled by using an Eulerian-Lagrangian approach and also incorporating multicomponent fuels. The initial spray conditions at the nozzle exit were determined through the specification of a discharge coefficient and the KH/RT breakup model was used for droplet breakup. Distribution of droplet size at the nozzle exit was specified using a Rosin-Rammler distribution. Velocities of primary parcels (blobs) were calculated as a function of the measured injected-mass flow rate profile. The gas jet model uses a correlation from classical gas-jet model theory to model the drops' relative axial velocity [10]. The gas-jet model was applied with an advanced KH-RT hybrid break-up model. Droplet collisions were modelled using the radius of influence (ROI) collision model.

2.2.2 Spray Simulations

The simulation cases were carried out in a 45-degree sector of the diesel engine (Fig. 2). Non-reactive, low pressure conditions were used since they allow calibration of the model for predicting correct spray dynamics. The chamber was initialized with air at ambient pressure of 1 bar and a temperature of 30°C. A single-hole injector with hole diameter of 0.198 mm was used for the simulation at 300 bar injection pressure. The default values for the model constants were used. Moreover, the spray model parameters for KH size and the time constant were set to 1 and 40 respectively; RT size time and distance constants were 0.15, 1 and 1.9 respectively. Gas entrainment constant for the unsteady gas-jet model was 0.5. The nozzles have a coefficient of discharge of 0.7.

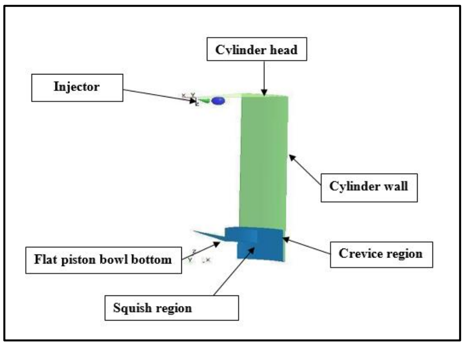

Figure 2. 45 degree sector of engine with injector

3. Result and Discussion

3.1 Spray Characteristics

Figure 3 compares the spray images of D and B20D80 for different injection pressures and times after start of injection (ASOI). It is clearly seen that the spray penetration is increased as a result of increased injection pressure of all test fuels. Adding butanol to diesel resulted in increased spray penetration length due to the low viscosity and high surface tension of butanol. Fig. 4 shows the spray images of neat diesel fuel at 300 bar injection pressure and ambient pressure and temperature (1 bar and 30 ºC)). Surrogate composition was used for diesel (nC_7H_{16}) species' (n-Tetradcane) physical properties.

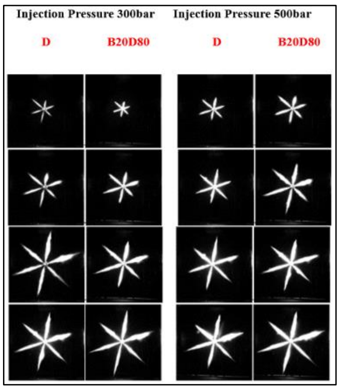

Figure 3. Spray images of test fuels. Rows are (top to bottom) ASOI: 0.5 ms, 0.75 ms, 1 ms, and 1.5 ms.

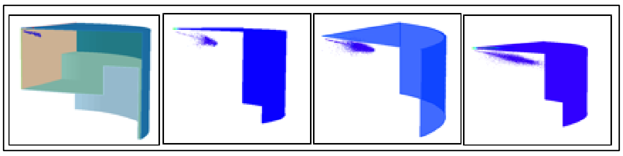

Figure 4. Spray images of diesel at 300 bar injection pressure, ambient conditions using Ansys Forte. Images (left to right) after ASOI: 0.5 ms, 0.75 ms, 1 ms, and 1.5 ms.

The spray patterns for the simulations are qualitatively similar to the experiments. For a quantitative measure, a good match in the liquid penetrations was found as seen in Fig. 5.

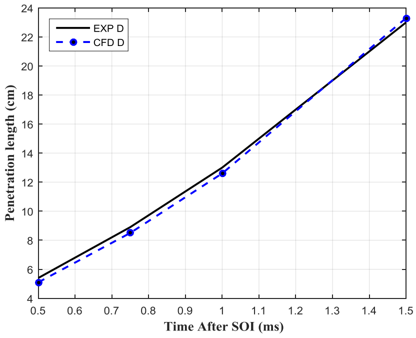

Figure 5. Spray penetration of diesel at ambient conditions.

Figure 6 presents the impact of the ambient pressure on the spray penetration length of diesel (D), l0% butanol-90% diesel (B10D90) and 20% butanol 80% diesel (B20D80). The spray penetration of all test fuels is decreased with increasing ambient pressure (the pressure inside the chamber) because of insufficient radial momentum to overcome penetration resistance and the effect of the pressure difference across the sheet. As a consequence, the spray shoulders become strongly curved and the spray collapses into a form that can ultimately become narrow. The region of spray tip penetration of neat diesel becomes longer and wider as a result of ambient temperature increases, due to the lower in-cylinder gas density at higher temperatures (Fig. 7). However, for butanol-diesel blends, the results were reversed due to the high heat of vaporisation of butanol being more than double that of diesel (Table1) so penetration length will be shorter and plumes will be narrower.

Properties	D	Butanol
Density (kg/L)	0.82-0.85	0.810
Viscosity (mm^2/s) at 40 ºC	1.9-4.1	2.22
Surface tension (mN /m)	23.8	24.2
Latent heat (MJ/kg) at 25 ºC	270	582

Table 1. Fuel properties.

Figure 8 and Figure 9 present the ASMD of the test fuels under different ambient pressures and ambient temperatures predicted via Ansys Forte. It is clear from Fig. 8 that the ASMD decreases with an increase in the ambient pressure for all test fuels. The ASMD difference among the test fuels is mainly due to the differences in their viscosity and surface tension. A higher viscosity leads to a lower fuel jet velocity, leading to larger droplet size. A lower surface tension makes the spray easier to break up into small droplets. In contrast, no significant difference in the ASMD was found when ambient temperature increased.

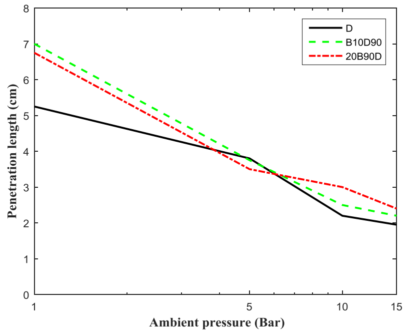

Figure 6. S of different ambient pressures.

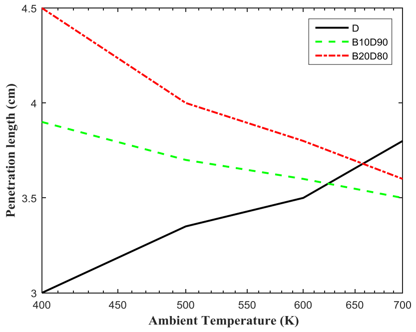

Figure 7. S of different ambient temperatures.

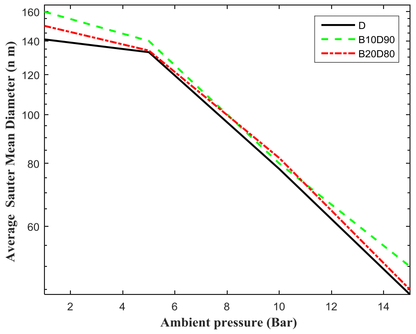

Figure 8. ASMD under different ambient pressures.

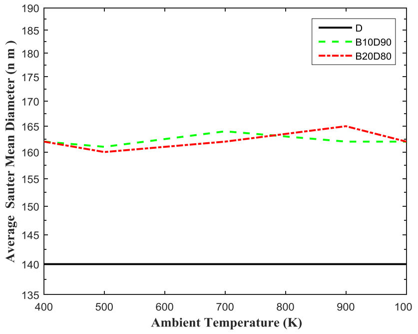

Figure 9. ASMD under different temperatures.

4 Conclusions

- The spray penetration (S) length is decreased as a result of increased ambient pressures of all test fuels**.**
- The spray penetration (S) length is increased as a result of increased injection pressures of all test fuels**.**
- Increased ambient temperature causes the spray penetration of pure diesel to become longer and wider. In contrast, the penetration of butanol-diesel becomes shorter.
- The ASMD of the butanol-diesel blend is higher than pure diesel.

5 Acknowledgment

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