Comparison of Gasoline and Butanol Spray Characteristics in Low Pressure Port Fuel Injector

Balram Sahu, Shamit Bakshi*, A. Ramesh
Department of Mechanical Engineering
Indian Institute of Technology Madras 600 036, India

Abstract
Butanol is a very attractive renewable fuel and is used as a substitute of gasoline or as a blend with gasoline. Butanol and gasoline sprays are different because of their physical properties. The present work attempts to characterize these fuel sprays in terms of penetration and spray angle. Single-hole and two-hole plate type injectors were selected for the study. Experiments were performed for 2-4 bar injection pressures at 5 ms injection duration. Shadowgraphy technique was used to visualize the fuel spray. A high power LED is used as a backlight and spray evolution images were acquired by a high speed CMOS camera. Acquired images were processed to quantify spray parameters. It was observed that gasoline sprays has shorter break-up length and atomizes faster compared to butanol. Gasoline sprays has higher spray angle and spray penetration than butanol spray for two-hole injector but in case of single-hole injector it varies with pressure. While comparing volume of fuel injection, gasoline has higher volume injected per pulse. These results may be useful for guiding in modification of injectors and strategies while using butanol as a fuel in place of gasoline.

*Corresponding author: shamit@iitm.ac.in
**Introduction**

Depletion of reserved petroleum resources is a serious issue which leads to energy crises and increase in crude oil price. In recent years bio-alcohol came as an alternate solution because of its renewable and clean emission characteristics. Ethanol and Butanol are widely used alcohols and can be produced from various biomass such as sugarcane, barley straw, wheat straw, corn fiber, switchgrass, agricultural waste etc. Butanol seems more attractive than ethanol due to its higher heat of combustion and lower latent heat of vaporization which is closer to gasoline. Another reason is, ethanol is water affinitive which makes it corrosive and more prone to separation from ethanol-gasoline blends. Table 1 shows the physical properties of gasoline, butanol and ethanol.

Port fuel injector is a promising technology for accurate fuel metering, targeting, atomization and fast transient response. Designing or modifying a mixture preparation system for a new fuel is a very challenging task and requires detail information like dead time of injector, flight duration of spray to reach inlet valve, spray angle and droplet size for a given pressure. Mixture formation process significantly affects the engines performance and emissions [2]. Anand et al [3] studied the effect of injection pressure on multi-hole PFI injectors and found increase in spray tip penetration and spray angle with increase in injection pressure but the difference in penetration for higher injection pressure is less. In another study [4] they reported the spray characteristics of ethanol-gasoline blends on a multi-hole PFI injector. They did not report any major difference in spray tip penetration but the spray angle was higher for the ethanol. In similar experiments with multi-hole PFI injector Padala et al [5] reported higher penetration for gasoline than ethanol.

**Experimental Setup**

**Injector and Injection System**

Single hole and two hole plate type port fuel injectors were selected for the study. The injector orifice diameters were measured by Coordinate Measuring Machine and found to be 474 micrometer for single hole injector and 274 micrometer for two hole injector. The orifices of two hole injector are separated by 450 micrometer. Figure 1 shows close-up image of injector orifice. A commercial fuel pump was used to pump the fuel to injector, pressure and fuel flow rate were regulated by pressure gauge and needle valve. The pressure was maintained constant during entire injection duration. The injection pulses were generated by a programmable microcontroller and these pulses were further amplified to 12V to actuate the injector.

**Optical System**

Shadow imaging technique was used to visualize the spray. All the experiments were conducted in a quiescent optical chamber, left and right face of the chamber has optical access. A high power LED light is used as a backlit; a diffuser was placed between LED light and glass chamber to uniformly illuminate the entire spray. Spray evolution images were acquired by a high speed CMOS camera (Photron FASTCAM SA4) at speed of 7200 fps. The acquired image size is 448×1024 pixel with 8 bit gray scale resolution. For measuring spray penetration and cone angle Nikon 50 mm lens was used, which give 11×11 cm field of view. Camera was synchronized with the injection pulses. Figure 2 shows the schematic of experimental setup.

**Experimental Condition**

All the experiments were performed at atmospheric pressure and ambient temperature condition. Gasoline and Butanol were used as test fuel. The injection pressure was 2, 3 and 4 bar at 5 ms injection duration. The injector was operated at a speed of 10 Hz, the time elapsed between two injection signal allow the spray to completely settle down and transfer the data from camera memory to computer.

**Image Processing**

The acquired images were post-processed in matlab to get required information like spray tip penetration and spray angle. The spray tip penetration was defined as the distance from nozzle tip to the point (along centre line) where 99% spray area is inside similarly spray angle was defined as angle between two lines where 90% spray area is inside. Figure 3 shows the definition of spray tip penetration and spray angle. Similar definition was adopted for spray angle measurement in [4, 6]. In order to extract useful information from the image, the spray has to be subtracted from background. The subtracted image has a very big size which makes it computationally heavy and also has non uniform illumination therefore region of interest (ROI) was cropped. Then 8 bit ROI images were segmented to single bit binary image using Otsu’s algorithm. Parallel line scanning technique is used to quantify penetration and cone angle. Figure 4 shows the flow chart of penetration measurement.

**Result and Discussion**

**Volume of fuel Injected**

The amount of fuel volume injected was calculated by dividing the average amount of fuel injected over 1000 cycle to its density. This procedure was repeated for all injection pressure and different electronic pulse duration. As expected the amount of fuel
volume injection increases linearly with increase in injection pressure and injection duration. The effect of increasing pressure on the amount of fuel injection seems very less for small injection duration and difference increases with higher injection duration. This may be because of time required to open and close the orifices which is same for all injection pressure and fuels.

Gasoline has higher volume flow rate than butanol, possibly because of its lower viscosity. Figure 5 and 6 shows the amount of fuel volume injected by single hole and two hole injector respectively.

Spray structure

Figure 7(a), 7(b) shows the development of gasoline and butanol sprays for single hole injector and Figure 8(a), 8(b) for two hole injector at 3 bar injection pressure and 5 ms injection duration. These sprays are very thin and less spread. Figure 9 and 10 compare of spray tip penetration for single hole and two hole injector respectively. The difference in penetration between gasoline and butanol is negligible for single hole injector but it is quite significant for two hole injector. Two hole injector has a steeper penetration than single hole injector. At near injector tip liquid sheets are observed for butanol sprays whereas gasoline sprays are atomized and has droplets. The reason may be higher viscosity of butanol which is approximately 4.5 times higher than that of gasoline. It seems that viscous forces predominate the inertia forces which avoid it to collapse instantly. Liquid sheets formed by two hole injector has a peculiar characteristics, these types of sheets are generally formed when two liquid jets impinge on each other. Figure 11 shows the development and breakup of liquid sheet formed by two hole injector at 2 bar injection pressure. These sheets collapse instantaneous-ly and do not appear for high injection pressure. The difference in penetration between 3 and 4 bar is less as compared to 2 and 3 bar injection pressure. At low injection pressure spray has less momentum thus the velocity is easily reduced by drag. Figure 12 and 13 shows the effect of injection pressure on the penetration of spray for single hole and two hole injector respectively. At first spray tip is visible out of nozzle at 1.6 ms after start of injection (electronic pulse) and it stops after some delay. Table 2 summarizes delay between hydraulic and electronic pulse for 5 ms injection duration for both the injector and fuel. Figure 14 represents it pictorially. Figure 15 shows the beginning of gasoline spray from single hole injector. There are two distinct ligaments; the smaller ligament may be because of fuel trapped in sac volume and injected earlier than main spray, the second ligament which is head of main spray has bigger size and look like a mushroom. It was observed that after stop of hydraulic pulses some fuel drops falls from two hole injector. Figure 16 shows one such image. The injection velocities were calculated from the slope of penetration curve and it is found between 12 to 30 m/s for two hole injector and it goes up to 35 m/s for single hole injector.

Spray Angle: Spray angles were measured for fully developed sprays.

Single hole injector: Spray angle varies from 1 to 11 degree for the butanol sprays whereas it’s almost constant for gasoline. Butanol sprays are very thin at low injection pressure and forms sheets for higher injection pressure which cause irregularity in spray angle.

Two hole injector: Gasoline sprays are well atomized and spread more whereas butanol sprays forms sheets which confine it to narrow region thus the gasoline has slightly higher sprays angle for all the pressure.

Nomenclature

G-Gasoline
B-Butanol
ASOI- After Start of Injection

References

Table 1. Fuel Properties [1]

<table>
<thead>
<tr>
<th>Properties</th>
<th>Gasoline</th>
<th>Butanol</th>
<th>Ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg/m³] (20°C)</td>
<td>729</td>
<td>809</td>
<td>794</td>
</tr>
<tr>
<td>Viscosity [cP] (25°C)</td>
<td>0.4–0.8</td>
<td>3.64</td>
<td>1.08</td>
</tr>
<tr>
<td>Surface tension [mN/m] (20°C)</td>
<td>25.8</td>
<td>25.4</td>
<td>22.4</td>
</tr>
<tr>
<td>Energy density [MJ/kg]</td>
<td>44</td>
<td>37</td>
<td>29</td>
</tr>
<tr>
<td>Boiling point [°C]</td>
<td>30–190</td>
<td>117.2</td>
<td>78.5</td>
</tr>
<tr>
<td>Latent heat of vaporization [MJ/kg] (25°C)</td>
<td>0.364</td>
<td>0.43</td>
<td>0.902</td>
</tr>
</tbody>
</table>

*For current study gasoline density is taken as 760 kg/m³.

Figure 1. Injector orifices size.

Figure 2. Schematic of experimental setup.
Figure 3. Definition for spray tip penetration and spray angle.

Figure 4. Flow chart of spray tip penetration measurement.
Figure 5. Volume of fuel injected per pulse of single hole injector.

Figure 6. Volume of fuel injection per pulse of two hole injector.
Figure 7. Development of gasoline (a) and butanol (b) spray for single hole injector at 3 bar injection pressure and 5 ms injection duration.
Figure 8. Development of gasoline (a) and butanol (b) spray for two hole injector at 3 bar injection pressure and 5 ms injection duration.
Figure 9. Comparison of spray tip penetration for single hole injector at different injection pressure and 5 ms injection duration.

Figure 10. Comparison of spray tip penetration for two hole injector at different injection pressure and 5 ms injection duration.
Figure 11. Development and breakup of liquid sheet formed by two hole injector at 2 bar injection pressure.

Figure 12. Effect of injection pressure on development of spray for single hole injector, Gasoline spray (a) and Butanol spray (b).

(The images (a) and (b) are not in the same scale)
Figure 13. Effect of injection pressure on development of spray for two hole injector, Gasoline spray (a) and Butanol spray (b).

(The images (a) and (b) are not in the same scale)

Table 2. Delay between hydraulic and electronic pulse.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Injector</th>
<th>Start of hydraulic pulse, ms</th>
<th>End of hydraulic pulse, ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butanol</td>
<td>Single hole</td>
<td>1.6</td>
<td>8.4</td>
</tr>
<tr>
<td>Gasoline</td>
<td>Single hole</td>
<td>1.6</td>
<td>8.4</td>
</tr>
<tr>
<td>Butanol</td>
<td>Two hole</td>
<td>1.6</td>
<td>7.77</td>
</tr>
<tr>
<td>Gasoline</td>
<td>Two hole</td>
<td>1.6</td>
<td>7.77</td>
</tr>
</tbody>
</table>

Figure 14. Pictorial representation of delay between hydraulic and electronic pulse.
Figure 15. Beginning of gasoline spray in single hole injector.

Figure 16. Dripping of fuel drops after end of injection in two hole injector.

Figure 17. Comparison of spray angle for single hole injector.

Figure 18. Comparison of spray angle for two hole injector.