**Spray Behavior of a GDI Injector at Constant Fuel Injection Pressure and Varying Engine Load**

Nikhil Sharma, Chetankumar Patel, and Avinash Kumar Agarwal*
Engine Research Laboratory, Department of Mechanical Engineering
Indian Institute of Technology Kanpur, Kanpur-208016, India

**Abstract**

In order to meet stringent emission norms, it becomes necessary to understand the behavior of atomized fuel spray droplets of a GDI engine. An experimental study was carried out to find droplet size and velocity distributions using phase droplet interferometry (PDI). Experiments were performed in ambient condition using a gasoline direct injection (GDI) injector at a fixed fuel injection pressure (FIP) of 80 bar. Two fuel injection quantities of 12mg and 20mg per injection were compared for spray droplet size and velocity distributions. Shadowgraphy of the spray plume was performed with the help of a high speed CCD camera to determine primary and secondary spray breakups. Experiments were performed 30 mm downstream of the GDI injector nozzle. Maximum spray droplet velocity distribution was found to be almost similar at same FIP, irrespective of fuel injection quantity. The three channels measured the droplet velocity distributions in mutually orthogonal planes. Increasing the fuel injection quantity while keeping constant fuel injection pressure, didn’t make noticeable difference in velocity or diameter distributions. It was observed that lower fuel injection quantity exhibited larger droplet surface area in contact with ambient air at constant pressure therefore it led to superior fuel-air mixing.

**Keywords:** Gasoline direct injection, spray, atomization, droplet size distribution, and droplet velocity distribution.

*Corresponding author: akag@iitk.ac.in*
Introduction

Atomization is a complex phenomenon. As the liquid is injected from a nozzle, it is atomized and vaporization of the liquid fuel takes place [1]. As depicted in figure 1, the atomization process can be divided into two parts: primary breakup and secondary breakup. Primary breakup is dependent on the internal geometry of the nozzle, which dictates the spray structure. Secondary breakup is influenced by the interference of spray by the surrounding air. This is the secondary breakup zone, where the spray ligaments get converted into spherical droplets. Understanding primary and secondary spray breakup makes the foundation for atomization process. Combustion characteristics of a gasoline direct injection (GDI) engine are closely related to the fuel distribution in the engine combustion chamber. The liquid and vapor phases exist simultaneously in the engine combustion chamber.

The atomization of a fuel breaks larger spray droplets into smaller droplets as the spray emerges from the injector. As the number of droplets increases due to droplet breakup, the contact surface area between fuel and oxidizer (atmospheric air) increases. This reduces the hydrocarbon emissions as the combustion tends to be relatively more complete. Combustion of fuel takes place following spray atomization, spray dispersion, fuel vaporization and fuel-air mixing processes. Atomization of fuel directly affects engine’s brake thermal efficiency and pollutant emissions. The objective of this study was to investigate ways of controlling combustion process in order to optimize engine performance and reduce engine-out emissions.

GDI spray characteristics are being investigated by several researchers as they affect the engine performance [2-6]. Huang et al. [7] investigated effect of fuel temperature on gasoline spray characteristics. High speed shadowgraphy was done to find spray characteristics. They reported that fuel temperature changed spray evaporation as well as spray breakup mechanism. Park et al. [8] investigated macroscopic spray characteristics such as spray tip penetration, spray width, and microscopic spray parameters such as overall Sauter mean diameter (SMD) and mean droplet size in a GDI engine for gasoline (G100), bioethanol (E100), and gasolineblended bioethanol (E85). Fuel properties such as surface tension, density and kinematic viscosity increased as the blending ratio of ethanol increased in a gasoline-ethanol (gasohol) blend. They reported that G100 exhibited largest droplet size distribution amongst G100, E100, and E85. This was due to higher kinematic viscosity and surface tension of G100 compared to other test fuels.

Spray characteristics of a group-hole nozzle were compared with a single nozzle-hole injector [9]. Both sprays had similar spray tip penetration and dispersion under identical operating conditions. However, spray emerging from a group-hole nozzle was comparatively more stable than that from a single-hole nozzle. The spray droplet velocity range for both conditions was 60-90 m/s. SMD of group-hole nozzle was smaller than the single-hole nozzle spray droplets.

Four different GDI injectors with either different hole arrangement or hole numbers were investigated by Kim et al. [10]. As the fuel injection pressure was increased, the droplet size distribution decreased. In another study, Romunde et al. [11] used a multi-hole injector to investigate spray evolution process in a spark ignition direct injection engine under different ambient conditions. They reported that spray tip penetration increased as the ambient pressure decreased. Spray tip penetration was also found to decrease as the ambient temperature decreased.

Experimental Setup and Methodology

Phase Doppler Interferometry (PDI) instrument (Artium, PDI-300 MD) was used in this experimental study to find the droplet size and droplet velocity distributions of a gasoline spray emerging from a GDI injector under different operating conditions.

Figure 2: PDI experimental setup

The experimental setup is shown in figure 2 and the schematic of the experimental setup is shown in...
Detailed specifications of the instrument are given in Table 1.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Droplet size range</td>
<td>0.5 to 2000 μm</td>
</tr>
<tr>
<td>Estimated accuracy</td>
<td>± 0.5 μm</td>
</tr>
<tr>
<td>Estimated resolution</td>
<td>± 0.5 μm</td>
</tr>
<tr>
<td>Velocity measurement range</td>
<td>-100 to 300 m/s</td>
</tr>
<tr>
<td>Velocity accuracy</td>
<td>± 1%</td>
</tr>
<tr>
<td>Volume flux accuracy</td>
<td>± 15%</td>
</tr>
<tr>
<td>Receiver lens focal length</td>
<td>350mm</td>
</tr>
<tr>
<td>Transmitter lens focal length</td>
<td>500mm</td>
</tr>
<tr>
<td>Laser type</td>
<td>Diode pumped solid state (DPSS) laser</td>
</tr>
<tr>
<td>Wavelength of lasers</td>
<td>Blue: 491nm; Green: 532 nm; Yellow: 561nm</td>
</tr>
</tbody>
</table>

Table 1: Specifications of the PDI system

Figure 3: Schematic of the PDI experimental setup

Experimental setup (figure 3) consists of a power source, two transmitters, a receiver, three channel advance signal analyzers (ASA) and software for signal processing. Class 3B diode pump solid state (DPSS) lasers were used in this study. Two lasers (green: 532 nm and blue: 491nm) were enclosed in transmitter 1. One laser (Yellow: 561nm) was enclosed in transmitter 2. Each laser beam was split into two using a beam splitter. These six beams were then carefully aligned to merge at a pin hole (~100 μm or less), which is called ‘probe volume’. Receiver unit consists of a lens and three photo detectors for three different scattered light wavelengths. The function of receiver is to detect the Doppler signal produced, when fuel spray droplets pass through this probe volume. As the fuel spray droplets pass through the probe volume, a constructive and destructive interference pattern is created, which results in alternative dark and bright fringe formation. The focal length of the transmitter lens was 500 mm and the focal length of the receiver lens was 350 mm. An injector driver module (NI; Driven DI Driver 9411) was used to control the GDI injector. NI Driven direct injection driver system (DIDS-2012) consists of a micro-controller (NI-cRIO-9022) and a module (NI, 9411) to drive the GDI injector. For shadowgraphy, a high speed camera (Photon; Fastcam SA1.1) having 6,75,000 fps at minimum resolution (64x16) and 5000 fps at maximum resolution (1024x1024) was used to capture spray images. Two white light sources were used to illuminate the spray. The data acquired was ensemble for a time period of 40 seconds. However the results presented in this study are for a time period of 6 ms only. A pneumatically driven liquid pump was used to pressurize the fuel for direct injection inside the combustion chamber.

Results and Discussion

Experiments were performed in ambient conditions using a GDI injector at a fixed fuel injection pressure (FIP) of 80 bar. Two fuel injection quantities of 12mg and 20mg were compared for spray droplet size and droplet velocity distributions.

Macroscopic Spray Visualization

Figure 4 shows the spray plume of a GDI injector with a gap of 1ms. These images were captured at 1000 fps. Spray images from a GDI injector were captured using the high speed camera to estimate the position of spray breakup length. The injector was a six-hole injector therefore five spray plumes need to be removed from the image frame for any meaningful measurement. A
cap was put on the injector such that only single plume emerges out of the injector, without interacting/interfering with the cap and measurements were made 30 mm downstream of the injector nozzle hole in all experiments. The probe volume diameter was ~100μm, through which fuel spray droplets of this single spray plume pass.

**Figure 5:** Spray measurement direction and location

**Droplet Velocity Distribution v/s Pulse Time**

Spray droplet velocity distribution variation can be divided into several sub-sections. These are: injection delay, detection time, head and tail sections. Injection delay is the time difference between the starting of energizing the injector solenoid and the start of actual injection. Detection time is the time interval between the start of injection and initial velocity signal of the spray droplets detected by the system. Head section is the zone after the signal detection where fuel droplets are ensemble in a particular region. This region has droplets with significant velocity. Tail section is the zone where velocity is relatively lower and remains almost constant with time.

**Figure 6:** Variation of droplet velocity with pulse time for channel ch-1 for 12 and 20 mg fuel injection quantities

Figure 6 shows the variation of channel 1 spray droplet velocity distribution with pulse time for 12 mg and 20 mg fuel injection quantities. For 12 mg fuel injection quantity, head section was observed for 2 ms and after 2 ms, the tail section started. As the fuel injection quantity was increased to 20 mg, head section duration increased and tail section duration decreased for the same fuel injection pressure. For the same fuel injection pressure, channel 1 velocity was same as that of channel 2, irrespective of the fuel injection quantity. All velocity components of channel 1 were in positive direction. Lower head section indicated that the fuel droplets evaporated earlier, which was desirable. Lower head section was achieved at lesser fuel injection quantity at same FIP. In another study, it was reported that as the FIP increased, head section width also increased [3].

Figure 7 shows the variations in channel 2 velocity distribution of spray droplets with pulse time for 12 mg and 20 mg fuel injection quantities at 80 bar FIP. There was no significant difference in channel 2 droplet velocity distribution with increasing fuel injection quantity at the same fuel injection pressure. Also, no head section was observed in ch-2.

**Figure 7:** Variation of droplet velocity with pulse time for channel ch-2 for 12 and 20 mg fuel injection quantities

Figure 8 shows the variation of channel 3 spray droplet velocity with pulse time for 12 mg and 20 mg fuel injection quantities at 80 bar FIP. There is no significant difference in channel 3 droplet velocity with increasing fuel injection quantity at the same fuel injection pressure. Also, no head section was observed in channel 3 velocity distribution. Higher numbers of spray droplets were observed in case of higher fuel injection quantity though. Channel 2 and 3 also exhibited some negative droplet velocities as well. Negative droplet velocities in case of channel 3 were higher than that from channel 2 however no negative droplet velocity was seen in chan-
nel 1. These negative velocities were obtained due to recirculation zones created, when atomized fuel droplets interacted with the ambient air, which was quiescent. This was also dependent on FIP and fuel quantity injected. Negative droplet velocities are desirable because they make the fuel-air mixing process more efficient.

**Droplet Velocity Distribution v/s Droplet Diameter**

Figure 8: Variation of droplet velocity with pulse time for channel ch-3 for 12 and 20 mg fuel injection quantities

Figure 9: Variations in spray droplet diameter distributions with droplet velocity at 12 mg and 20 mg fuel injection quantities

Figure 10: Number of droplet velocity counts for channel 1 at 12 mg and 20 mg fuel injection quantities

Bulk of the droplet count was concentrated near the origin and these decreased as the droplet velocity reduced. For the same FIP, lesser fuel injection pressure gave better fuel-air mixing. Negative droplet velocities were lesser for channel 1 and so were the droplet count.

**Droplet Velocity Distribution v/s Droplet Count**

Figure 10 shows number of counts at a particular velocity for two fuel injection quantities for channel 1. It is observed that for higher fuel injection quantity, number of droplet counts through the probe volume were lower as compared to lower fuel injection quantity.

Figure 11: Number of droplet velocity counts for channel 2 at 12 mg and 20 mg fuel injection quantities

Figure 11 shows number of droplet counts at a particular velocity for two fuel injection quantities for channel 2. Channel 2 showed lower number of droplet counts
for lower fuel injection quantity compared to higher fuel injection quantity. The velocities were uniformly distributed in both negative and positive direction for both fuel injection quantities.

**Figure 12:** Number of droplet velocity counts for channel 3 at 12 mg and 20 mg fuel injection quantities

Figure 12 shows number of droplet counts at a particular velocity for two fuel injection quantities for channel 3. Higher fuel injection quantity has significantly higher droplet velocity than lower fuel injection quantity for channel 3. In this case also, velocity counts were almost uniformly distributed in both negative and positive side, similar to channel 2.

**Figure 13:** Number of droplet counts v/s droplet diameter for channel 1 at 12 mg and 20 mg fuel injection quantities

Figure 13 shows number of droplet diameter v/s droplet counts for two fuel injection quantities. It was observed that number of droplets for lower fuel injection quantity were higher than higher fuel injection quantity. Since the fuel injection pressure was same, peak of maximum droplet diameter was ~7 μm. The smaller diameter droplets have relatively higher surface area/ volume therefore they have faster evaporation characteristics.

**Table 2:** Various definitions of mean diameters [12]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Common Name</th>
<th>Definition</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_{10}</td>
<td>Arithmetic Mean (Length)</td>
<td>( \sum N_i D_{10} ) / ( \sum N_i )</td>
<td>Comparison</td>
</tr>
<tr>
<td>D_{20}</td>
<td>Surface Mean (Surface Area)</td>
<td>( \sum N_i D_{20}^{1/2} ) / ( \sum N_i )</td>
<td>Surface Area Controlling</td>
</tr>
<tr>
<td>D_{21}</td>
<td>Length Mean (Surface area length)</td>
<td>( \sum N_i D_{21} ) / ( \sum N_i )</td>
<td>Absorption</td>
</tr>
<tr>
<td>D_{30}</td>
<td>Volume Mean (Volume)</td>
<td>( \sum N_i D_{30}^{1/3} ) / ( \sum N_i )</td>
<td>Volume Controlling (Hydrodynamics)</td>
</tr>
<tr>
<td>D_{31}</td>
<td>Length Mean (Volume length)</td>
<td>( \sum N_i D_{31}^{1/2} ) / ( \sum N_i )</td>
<td>Evaporation, Molecular Diffusion</td>
</tr>
<tr>
<td>D_{32}</td>
<td>Sauter Mean (Volume-surface)</td>
<td>( \sum N_i D_{32}^{3/2} ) / ( \sum N_i )</td>
<td>Mass Transfer Reaction</td>
</tr>
<tr>
<td>D_{43}</td>
<td>Herdan Mean (De Brouckere or Herdan) (Weight)</td>
<td>( \sum N_i D_{43}^{4} ) / ( \sum N_i )</td>
<td>Combustion Equilibrium</td>
</tr>
</tbody>
</table>

There are several definitions of mean diameters, which are used in engine parlances and have their own im-
importance in one way or the other. These mean diameters and their definitions are given in Table 2.

Different mean diameters for the gasoline sprays are shown in Figure 15. All the mean diameters for larger fuel injection quantity (20 mg) were relatively larger than lower fuel injection quantity (12 mg). SMD was ~34μm for 20 mg and ~29μm for 12 mg fuel injection quantity. Arithmetic mean diameter was observed to be ~10 μm for 20 mg fuel injection quantity and ~9 μm for 12 mg fuel injection quantity.

Conclusions
1. Maximum spray droplet velocity of gasoline fuelled GDI injector for channel 1 was ~60 m/s and maximum velocity for channel 2 and 3 were ~18 m/s. Bulk droplet velocity count was concentrated near the origin. Majority of droplet velocity count were distributed on the positive side of the x-axis in channel 1. However, for channel 2 and 3, velocity counts were uniformly distributed on both positive and negative sides of the origin on the x-axis.
2. Maximum spray droplet velocity was same at same FIP, irrespective of the fuel injection quantity injected. Head section for the fuel injection quantity of 20 mg was higher than fuel injection quantity of 12 mg.
3. Droplet count for 12 mg fuel injection quantity was higher than 20 mg fuel injection quantity. SMD was observed to be ~34μm for 20 mg and ~29μm for 12 mg fuel injection quantity. Arithmetic mean diameter was observed to be ~10 μm for 20 mg fuel injection quantity and ~9 μm for 12 mg fuel injection quantity. Negative droplet velocities were observed for channel 2 and channel 3 however majority of the droplet velocities for channel 1 were positive.
4. For 12 mg fuel injection quantity, higher velocity counts were observed than 20 mg fuel injection quantity for channel 1. However, the trend for channel 2 and 3 were quite opposite.

Acknowledgments
Authors would like to acknowledge the research grant received from Committee for the Acquisition of Research Equipment (CARE), Indian Institute of Technology Kanpur, Kanpur, India and assistance of laboratory staff Mr. Roshan and Mr. Surendra Singh during the experiments at Engine Research Laboratory, IIT Kanpur.

References