Investigation of the relationship between liquid sheet characteristics and spray mean diameter

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Abstract

The atomization mechanism involves the formation of waves on liquid surface that will breakup into droplets. These phenomena are the development of waves on a liquid surface, the increase in their amplitude, and the loss of stability. An experimental study has been undertaken in order to measure liquid sheet characteristics and droplet diameter by visualization and image processing method. Finally, The influence of spray characteristics on spray mean diameter are analyzed experimentally. The motivation of this study is to visualize the spray structure of low-pressure diesel injection systems in an attempt to correlate the spray structure to the injection system performance and nozzle design.

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1. Introduction

The Environmental Protection Agency (EPA) and California’s Air Resources Board (CARB) have proposed severe regulations for reducing the exhaust emissions from mobile IC engines. It will not be easy to reach these low emissions levels for diesel engines. A modern diesel engine has been modified to incorporate advanced air and fuel management systems to enable it to be used with advanced emission controls (including DOCs, NOx absorber catalyst and DPFs)\[1\]. NOx reduction system needs rich or stoichiometric operation periodically to reduce NOx\[2\]. It was proposed that a rich air fuel ratio in a diesel engine was realized by post fuel injection, or supplemental fuel injection into the exhaust gas or smokeless low temperature combustion with massive EGR\[3\]. In-pipe post injection is favored at higher load operation because in-cylinder injection tends to increase exhaust temperature and may exceed turbocharger temperature limits\[4\].

This paper describes spray characteristics of nozzle designed for external fuel enrichment system. Optical diagnostics were applied to investigate the spray characteristics. The main focus of this work was to characterize the sprays of an injector that has been proposed for use in external fuel enrichment system. Another objective of the investigation was to provide experimental data for validating simulation results, and the data can be used to provide more detailed information about the spray structure and atomization mechanisms.

2. Experimental apparatus and procedure

Spray characteristics are generally measured by considering the macroscopic and microscopic structure of the spray. In this study, the macroscopic structure of the spray, such as spray tip penetration and cone angle, was measured conventionally by high-speed photography, and the microscopic structure of the spray, such as the droplet size distribution was measured by shadowgraphy.

2.1 Spray visualization system

The processes of the sprays were observed by direct photography using an high speed video camera with illumination from the xenon lamp. A white background illumination is used to obtain high contrast images of the spray. Images are acquired at a grabbing rate of 10,000~20,000 fps, and with an exposure time of 10μs.

The high-speed camera has 256 by 512 pixels with 256 levels of gray scale resolution. The captured images of the spray were then directly downloaded from the camera’s RAM to the PC.

Figure 1 shows a schematic diagram of the arrangement of the visualization system. Qualitative and quantitative analysis of the spray is carried out by the transmitted light illumination technique. Camera and light source are on opposite sides of the object (spray or drop). The screen shows the dark form of the object in front of a light background. Microscopic visualization was applied to the sprays with the illumination by a spark light source, which had light duration of shorter than 100ns. In order to determine the size of the droplet on the image and whether they are in focus, calibration was preceded with reticles of known sizes.

An active high TTL command signal is provided to the metering valve driver. The driving pulse signal of solenoid valve is sent to a delay pulse generator and the delayed pulse signal was used as a trigger for starting the high-speed video camera or high resolution CCD camera.

<table>
<thead>
<tr>
<th>Table 1 Nozzle spec. and experimental conditions</th>
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<tbody>
<tr>
<td><strong>Nozzle Type</strong></td>
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<td><strong>Spray Geometry</strong></td>
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<tr>
<td><strong>Fuel supply pressure</strong></td>
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<td><strong>Injection duration</strong></td>
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<td><strong>Ambient gas condition</strong></td>
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Table 2 Physical characteristics of test oil

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<table>
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<tbody>
<tr>
<td>Cloud point (°C)</td>
<td>-20</td>
</tr>
<tr>
<td>Specific gravity at 15°C</td>
<td>0.822</td>
</tr>
<tr>
<td>Pour point (°C)</td>
<td>-30</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>85</td>
</tr>
<tr>
<td>Water content (ppm)</td>
<td>&lt;50</td>
</tr>
<tr>
<td>Distillation 5% max at 210°C</td>
<td>4.0</td>
</tr>
<tr>
<td>Distillation 5% min at 360°C</td>
<td>96</td>
</tr>
<tr>
<td>Viscosity at 40°C cSt</td>
<td>2.57</td>
</tr>
</tbody>
</table>

2.2 Fuel injection system

The injection system used in the experiments composed of low pressure pump which can raise the pressure up to 7 bar, filter, pressure regulator, injection unit. Nozzle is opened and closed depending on the pressure. The injector creates a solid-cone spray. Table 1 describes specification of nozzle and experimental condition.

All experiments have been performed with ISO 4113 proof oil, which is used as working fluid instead of diesel because its properties are very similar to diesel fuel as about density and viscosity. It is suitable for all nozzle tests such as pressure, output and spray patterns.

Table 2 shows the physical characteristics of test fuel.

The aim of the measurement system is to characterize quantitatively the behavior of each spray. In order to determine the spray characteristics from time series images showing the development of the spray, spray images were captured by high speed camera. To investigate the whole injection process, a large number of images should be analyzed before statistical treatment.

3. Results and discussion

Figure 2 shows typical injection pressure trace under different supply pressure conditions. The different parts of the spray (leading edge, steady state and trailing edge) can be identified in the image series. In a pulsed spray, SMD varies throughout the duration of the spray. Successive measurements will show high SMD values at the leading edge (as fuel must be accelerated to its steady state velocity). This tends to decay the steady state SMD value once the spray has been fully established, then decays further in the tail end of the spray.

Figure 3 shows time series of the spray development for leading edge. Initial spray tip penetration increased with the supply pressure. The breakup of the

![Figure 2](image1.png)

**Figure 2** Typical injection pressure trace and parts of the spray

![Figure 3](image2.png)

**Figure 3** High-speed sequential images obtained under various supply pressure for leading edge
liquid sheet generated large number of droplets, with a large dispersing angle.

Figure 4 shows ensemble averaged RMS macroscopic images under different supply pressure conditions. Figure 5 shows spray dispersion angle acquired from figure 4, using Gaussian blur, Canny edge detection, and Hough transforms. As supply pressure increases, the dispersion angle is increased, and spray symmetry improved obviously.

For analyzing the break-up frequency of liquid sheet, spray tip penetration, and spray velocity, we applied linear array image analysis technique developed by Jeffey and Siebers with line-scan image[5], but we used time series image with high-speed camera.

During an injection event, 256x256 pixels 8bit gray time-series images were acquired at every 50μs. After normalizing the image to remove effects of spatial variations in light intensity, sequential images contain time for a period of 7.2ms (50μs x 1440frames) are loaded PC memory by 3D matrix form that dimensions are 256(width) x 256(height) x1440(time-series). We shifted the dimensions this matrix, and averaged width dimension(radial direction of spray) data to get 2D matrix data. Using this matrix data, a pseudo line-scan images of an injection were created that were 1440 pixels wide and 256 lines height. In addition, the image contained the spatial variation of light intensity of the spray as a function of time.

As shown in this figure, the spray is varied with injection pressure periodically because of instabilities of liquid sheet.

Figure 6 shows part of pseudo line-scan spray images of single injection. The images are oriented so that the vertical axis is the distance from nozzle tip(y). The horizontal axis is time (t) with the origin at the start of injection at the right. Areas of high intensity in the image represent regions of high droplet concentration, while areas of low intensity in the image represent non-attenuated light (i.e., no spray, liquid sheet). The bottom of images have low intensity because liquid sheet is developed near the nozzle.

At the figure 6 (a), the lines from the lower left to upper is the spray tip penetration as a function of time. In the center region, the slope of left line is initial sheet growth velocity, and slope of right line is terminal velocity before disintegration. From this result, we found that the initial velocities are faster than terminal velocities for all the conditions of the steady state of the spray.

The results of the spray tip penetration measurements from figure 6 using the image processing technique are presented in Figure 7. As increase of supply fuel pressure, penetration length is increasing. The first liquid sheet generated at injection start and the second liquid sheet are collided. Thus, reacceleration point is...
exist near 2.5ms after start of injection. This sheet-to-sheet interaction phenomena are also appeared for steady spray period.

To get liquid sheet disintegration frequency, the intensity of horizontal line profiles are transferred to the frequency domain by Fast Fourier Transformation (FFT). Figure 8 shows the results of Fast Fourier transform in amplitude spectrum at different supply pressure.

For all conditions, the disintegration frequencies are almost same. This means that supply pressure between 4bar and 7bar had no effect on sheet disintegration frequency.

Figure 9 shows the effect of supply pressure on the averaged initial and terminal velocities of liquid sheet. Initial velocities is increased linearly from 4bar to 6bar.

Figure 10 summarizes the measured SMD for different supply pressures at 30ms after the start of injection. Injection flow rates of solid cone spray shape are concentrated in the center region. Therefore, this figure indicates that SMD is decreased as the injection pressure increases. As a result of this improved atomization performance, the SMD is decreased by approximately 26% from 4bar to 7bar at the center position.

4. Conclusions

A detailed spray characterization study has been performed for a low-pressure diesel injection system that is intended for use in a fuel enrichment system. The influence of fuel supply pressure on spray behavior and development has been analyzed experimentally. The conclusions are summarized as follows:

(1) The different parts of the spray (leading edge, steady state and trailing edge) can be identified in the image series and injection pressure data.

(2) As supply pressure increases, initial spray tip penetration increased. The breakup of the liquid sheet generated large number of droplets, with a large dispersing angle. The dispersion angle is widened and spray symmetry is improved obviously.

(3) Using linear array image analysis technique, spray tip penetration length, liquid sheet disintegration
frequencies, and mean velocities of liquid sheets can be obtained.

(4) Since the first liquid sheet generated at injection start and the second liquid sheet are collided, reacceleration point is exist near 2.5ms after start of injection.

(4) For our experimental conditions, the supply fuel pressure had no effect on sheet disintegration frequency.

(5) Initial velocities of liquid sheet is increased linearly from 4bar to 6bar supply pressure. At 60mm from nozzle tip, the SMD is decreased by approximately 26% from 4bar to 7bar at the center position.

Acknowledgement

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References

5. Jeffrey D. Naber and Dennis L. Siebers, SAE Technical paper series, 960034
Figure 6 Pseudo line-scan images of the penetration spray obtained with the high-speed camera

Figure 7 Influence of the supply pressure on the spray penetration

(a) 4bar
(b) 5bar
(c) 6bar

Figure 8 Effect of supply fuel pressure on the initial and terminal velocity of liquid sheet

(a) 4bar
(b) 5bar
(c) 6bar