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The Spray Nozzle Geometry Design on the Spray Behavior Including Spray Penetration and SMD Distribution

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ABSTRACT In general the nozzle design and the induction tunnel geometry will decide the performance of a fuel injection system. The performance of the spray atomization and subsequent impingement inside the induction tunnel will decide the combustion efficiency and exhaust emissions of a combustion system. In order to understand the fundamental spray atomization processes and the operating parameters on the spray behavior, a Laser Diffraction Particle Dynamics Analysis System (LDPDA) and a High Speed Optical Camera Recording System are set up for measuring the droplet SMD and analyzing the spray atomization behavior after injection. Three various type of injector are adapted in this research with varied operating modes for understanding their effects on the spray behavior. Results show the appreciated SMD detection with the spray tip penetration, the spay angle, and the spay velocity measurements. These results can be further investigated for the good insight of a nozzle design philosophy.

Keywords: spray atomization, spray penetration, SMD.

1. INTRODUCTION

The engine's performance and exhaust emissions are strongly related to the injector's design, the intake manifold geometry, and the spray atomization characteristics. The injection pressure can also alter the spray penetration, the spray velocity, and the spray breakup [1]. The nozzle’s orifice design can affect the droplets distribution within the spray cone region. In general, the nozzle orifice diameter and its L/D ratio are two important parameters on the nozzle design [2].

At the beginning of this research, the nozzle’s baseline measurements regarding the spray atomization will be first established for future comparisons. The nozzle’s injection pressure and fuel injection duration (FID) will be altered later for parametric study. Three different types of nozzle shown in Table 1 are tested. The first part of this research applies the Laser Diffraction Particle Dynamics Analysis System to measure the droplets size distribution at different spray penetration depths. Then the High Speed Optical Camera Recording System is used to acquire a good insight of spray atomization characteristics.
Table 1 Three nozzles’ specifications.

<table>
<thead>
<tr>
<th>Nozzle Hole Number</th>
<th>Nozzle A</th>
<th>Nozzle B</th>
<th>Nozzle C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole Diameter (μm)</td>
<td>382.25</td>
<td>278.375</td>
<td>293.9375</td>
</tr>
<tr>
<td>Distance Between Center of Holes (μm)</td>
<td>X</td>
<td>730</td>
<td>V:1020 H:665</td>
</tr>
<tr>
<td>L/D (Length/Depth) Ratio</td>
<td>0.1964</td>
<td>0.5263</td>
<td>0.8607</td>
</tr>
</tbody>
</table>

2. EXPERIMENTAL METHODOLOGY

The spray droplets’ size in this experiment is measured by the Laser Diffraction Particle Dynamics Analysis System which includes the light source, the detector, the sample diffraction unit, the data acquisition, and the analyzing system.

This facility applies the laser diffraction principle and the Mie theory. The Fraunhofer principle claims when the light pass through a particle the light will diffracted by a specific angle for different particle size so that the particle size distributions are relative to the strength of light detected at various angles. The Mie theory considers the light reflection, penetration, rebounding, and absorption effects so that the Fraunhofer principle is more completed.

By detecting the spectrum of certain wave length light’s reflection coefficient for a specific particle size, the droplet size determination can be calculated even for the submicron case [3]. This facility’s set up diagram is shown in Figure 1.

The flow field’s observation is accomplished by using the High Speed Optical Camera Recording System. By recording and analyzing the continuous spray injection motions, the spray cone angle, the spray penetration and the spray tip velocity can be calculated if the spray conditions are remained the same [4,5]. This system’s setup is shown in Figure 2.
After the two facilities are tested and adjusted the baseline injector nozzle will be tested for fuel injection duration (FID) between 2 ~ 5 ms under different operating conditions.

3. RESULTS AND DISCUSSIONS

3.1 Baseline Study

For the baseline case the fuel injection pressure is maintained at 2.5 kg/cm² and the nozzle operating voltage is kept at 12 volts. The injection duration is set to be 5 ms. In Figure 3, nozzle A is tested at the position 10 cm downstream of the nozzle exit. Result shows over 75% of droplets have SMD more than 800 μm which seems to be relatively too high for a gasoline fuel nozzle.
Figure 4 shows the SMD reduced from 800 μm at 5 cm downstream of the exit to 500 μm at 15 cm downstream of the exit. Since the fuel is injected into a testing chamber placed under standard atmosphere and temperature; thus, the droplet size should not decade as fast as spray into the combustion devices where the entrained flow usually have high temperature. As we know the spray atomization processes include the breakup, the evaporation, the coalescence, and the mixing with entrained flow. All these processes take times.

Figure 5 shows the continuous pictures of the spray from 0.5 ms to 4.5 ms. The spray angle is remained at approximately the same after 0.5 ms. Figure 5.d shows the leakage of fuel spray after the end of FID. This leakage actually is very important to determine a good/bad nozzle design since the leakage can cause severe smoke exhaust in a combustion device.

The cause of this leakage maybe blamed to the rebounding of the nozzle’s pin after the shut down of the electric-magnetic field. However, this topic needs further investigation for better understanding.

Figure 4  The measured SMD at different location downstream of the nozzle exit.

Figure 5  The spray penetration at various timing after the onset of injection.

3.2 Effects of Nozzle Design on Spray Behavior

The design of the fuel injector includes the nozzle geometry, the flow passage inside the nozzle, the electric-magnetic pin-valve assembly, and the flow filter. Three completely different fuel injectors design by German, USA, and Japan listed in order in Table 1 are tested here for comparisons. Figure 6 shows the spray penetration at the timing of 4.5 ms after the injection. Basically the three nozzles have axisymmetric pattern of spray atomization phenomena. Since Nozzle C has four holes so that the spray angle is larger compared to the other two nozzles. However, Nozzle B has two holes and smaller spray angle compared to Nozzle A which has single hole. It is not necessary that the more holes the greater spray angle can occur. The nozzle L/D ratio and the flow passage inside the injector can all affect the results.
Figure 6  Spray atomization behaviors at 4.5 ms after injection for various nozzles.

Figure 7 shows the history of spray penetration for all three nozzles. Nozzle B has the largest penetration and Nozzle C has the smallest one. It is still unclear why Nozzle B and Nozzle C have very close hole-diameters but the results of penetration are so different. Nozzle A has the largest hole diameter which indicates the original droplet leaving the nozzle exit should have better chance to have larger droplet size and thus deeper penetration (due to larger inertia). However, Figure 7 does not conclude in this way.

Figure 8 shows the history of spray injection velocity after the onset of injection. The similar results have been found compared to Figure 7 that the Nozzle B has the largest exit velocity 45 m/sec compared to Nozzle C’s 23 m/sec. At the beginning of injection the velocity is speeded up due to sudden expansion effect. When the droplets enter the entrained air the breakup and aerodynamic force quickly slow down the injection velocity. After approximately 0.8 ms of injection all three injection velocities reaches at a near constant level.

Figure 9 shows the history of spray angle for all three nozzles. At the beginning of injection Nozzle A (larger hole diameter) has larger spray angle compared to Nozzles B and C (about the same hole size). However, at the end of injection Nozzle A has constant spray angle, Nozzle B has reduced spray angle, and Nozzle C has minor increased spray angle.

At the later stage of injection the spray atomization and evaporation will decide the shape of spray since small droplets evaporate and only the large droplets left in the center line of injection. Thus, the measured spray cone angle can change very differently.
and larger initial spray injection velocity. The increased injection velocity can cause fast droplet breakup and tip penetration. In this figure it is also observed the increased open pressure can slightly increase the spray angle. This is because the higher the pumping pressure the more the sudden expansion effect takes place as fuel left the orifice.

3.4 Effects of Injector’s Operating Voltage on Spray Behavior

Figure 11 has the electric-magnetic operating voltage changed from 12.0 volts to 13.8 volts. The higher voltage actually can drive the nozzle to open earlier and reduced the time on delay of spray injection; however, the spray atomization characteristics is still remained about the same without significant variations.

Figure 9 History of spray angle for all three nozzles.

3.3 Effects of Injector’s Pumping Pressure on Spray Behavior

Figure 10 shows the effects of various pumping pressures on Nozzle C’s spray behavior at 4.0 ms after injection. Apparently the increased open pressure causes the earlier start of injection (less injection time on delay) and larger initial spray injection velocity. The increased injection velocity can cause fast droplet breakup and tip penetration. In this figure it is also observed the increased open pressure can slightly increase the spray angle. This is because the higher the pumping pressure the more the sudden expansion effect takes place as fuel left the orifice.

Figure 10 Effects of injection pumping pressure on the spray atomization.

Figure 11 Effects of electric-magnetic operating voltage on the spray atomization.
4. CONCLUSIONS

In this study the spray atomization phenomena are observed and measured by the Laser Diffraction Particle Dynamics Analysis System and the High Speed Optical Camera Recording System. Several injection operating conditions are varied on different type of nozzles. The major findings are summarized as follows:

1. The SMD at the nozzle exit is too high for Nozzle A.
2. The nozzle orifice diameter will affect the spray angle.
3. Increase of pumping pressure will enlarge the spray velocity, tip penetration, and the spray angle.
4. Increase of operating voltage will not improve the spray atomization behavior. Only the time on delay is reduced.

5. REFERENCES