EXPERIMENTAL STUDY OF THE EFFECTS OF NOZZLE HOLE GEOMETRY FOR A DI DIESEL ENGINE

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ABSTRACT Spray tip penetration and spray angle for one main injection were measured at the atmospheric condition with the fuel injection pressure of 270bar, 540bar and 1080bar postulating not only idle condition mode but also that of some emission modes of a common rail DI diesel passenger car to investigate the effects of different nozzle hole geometry of conventional cylindrical one and those of elliptical ones. Injection period represented by injector drive pulse was fixed at 1ms and time after injection start was varied to investigate the possibility of good spray characteristics with the elliptical geometry nozzle hole compared to that with conventional cylindrical one. From the results of this study, it is shown that spray tip penetration becomes shorter and spray angle becomes wider with the elliptical geometry nozzle hole due to the fast break up of a fuel liquid column. It is also shown that more homogeneous fuel-air mixture, which means better atomization, can be realized with the elliptical geometry nozzle hole than with the conventional cylindrical one through the mean gray value of spray pixel.

Keywords: Common rail diesel engine, Spray penetration, Spray angle, Nozzle hole geometry, Fuel-air mixture

1. INTRODUCTION

Recently, diesel engines have been paid special attention to not only for commercial vehicles but also for RV, SUV, even for passenger cars globally due to their fuel application, fuel economy and higher efficiency, which means less emission of carbon dioxides compared to that of gasoline engines.

However, a few toxic substances such as NOx(nitric oxides), unburned hydrocarbon, carbon monoxide and PM(particulate matters) reduce the merits of diesel engines. In addition, emission regulation standard will be more stringent in the near future. For example European Unity introduced more severe emission regulation standard for diesel vehicles with EURO-5 emission regulations, which has half values of NOx and PM compared to those of EURO-IV emission regulations.

To solve the problem of toxic substances from diesel engines, especially for NOx and PM, many techniques have been applied to diesel engines. Exhaust gas recirculation(EGR) with turbo charger system[1] is now generally used for diesel engines to reduce NOx.

VGT(Variable geometry Turbocharger)[2] has been recently equipped for diesel engines of RV and passenger cars not only to reduce NOx but also to reduce PM through rapid air supply by preventing turbo lag.

Many after treatment systems have been developed to reduce NOx. SCR(Selective catalytic reduction) by ammonia(NH3) or urea injection showed that drastic NOx reduction for diesel engines for relatively low temperature conditions[3]. Nevertheless, SNCR systems using NH3 or urea are still under developing because of ammonia slipp[4]. In addition, it is very difficult to inject quantitatively NH3 or urea for the corresponding NOx concentration under the vehicle running conditions since NOx formation is very transient and dependent on injection pressure, injection quantity change rate, boost pressure, instant EGR rate and even on inlet air temperature to the engine. LNT(Lean NOx trap)[5] also showed NOx reduction effect for the after treatment systems of diesel engines.

Meanwhile PM reduction techniques have been also reported by many researchers. Not only for the common rail diesel vehicles but also for the conventional ones, DOC(Diesel Oxidization Catalyst) has also been used to reduce THC, CO and some SOF(soluble organic fractur) of PM. DPF(Diesel particulate Filter)[6] has been begun to equipped for diesel vehicles as EURO-5 has been in effective. DPF, however, also has some problems to be solved such as durability, thermal shock by pressure increase in DPF, oil dilution problem by after injection for regeneration of DPF.

Nakatani et. al reported that DPNR(Diesel PM and NOx Reduction) has good effect to reduce PM and NOx concentration simultaneously[7].

Simultaneous reduction of PM and NOx by combustion control through high pressure injection with common rail systems is considered to be one of the most effective key techniques since diesel combustion is highly dependent on homogeneous fuel-air mixture results from good atomization. From this point of view, piezo-actuated injector[8] is operated not only to elevate fuel injection pressure but also to make a sharp injector needle close. Piezo-actuated injector or more high pressurized injection systems for diesel engines, however, is not desirable in terms of cost. Meanwhile, combustion control through a good atomization with the change of nozzle geometry is one of the attractive techniques to reduce PM and NOx[9][11].

Some reported that there is a possibility of good atomization which leads to PM and NOx reduction for diesel engines[12][13].

In this study, therefore, spray penetration and spray
angle were measured and some spray images were observed to investigate the effect of nozzle hole geometry on spray characteristics for conventional cylindrical nozzle and for that of elliptical ones using a common rail diesel injection system.

2. EXPERIMENTAL SETUP

Figure 1 shows a schematic of nozzle used and Table 1 shows the specification of nozzle hole.

<table>
<thead>
<tr>
<th>Injector</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Circle</td>
<td>ellipse</td>
<td>←</td>
<td>←</td>
</tr>
<tr>
<td>Nozzle dia. (mm)</td>
<td>d1(major)</td>
<td>0.565</td>
<td>0.682</td>
<td>0.702</td>
</tr>
<tr>
<td>d2(minor)</td>
<td>0.565</td>
<td>0.569</td>
<td>0.543</td>
<td>0.539</td>
</tr>
<tr>
<td>Nozzle hole area(mm²)</td>
<td>1.00</td>
<td>1.22</td>
<td>1.20</td>
<td>1.22</td>
</tr>
<tr>
<td>No. of holes</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection system</td>
<td>Bosch common rail system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection pressure(bar)</td>
<td>270, 540, 1080</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection duration(ms)</td>
<td>1ms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ambient gas condition</td>
<td>Atmospheric condition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>Light diesel(KS #2)</td>
<td></td>
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</tr>
</tbody>
</table>

Fuel was supplied from fuel tank then injected for 1ms into the atmosphere after pressurized at the high pressure pump of a Bosch common rail system used for commercial RV cars. Common rail system was driven by a 3.7kW of DC motor.(OTIS LG Co., model KM105HK1) Air bleeding was done before the injection start to remove air in the fuel supply pipe and common rail. Fuel injection duration was controlled using common rail injection driver system(TEMS Co., model TDA-330). Spray images were taken by digital camera(Nicon Co., model D70s) through synchronized stroboscope with injection start.(SUGAWARA Co., model PS-240A) Electronic microscope was used to measure the diameter of each nozzle. Injected fuel quantity was measured using electronic balance(CAS Co., model MW-120). Some captured spray images were processed by the personal computer to measure spray tip penetration, spray angle and fuel-air mixing grade through the calculation of each spray pixel on certain axial line at each time passage after injection start.

3. RESULTS AND DISCUSSION

3.1 Fuel flow rate

For a diesel engine injector system fuel flow rate is one of the most important factors to be considered since this mainly determines maximum power performance at rated engine rpm. To investigate fuel flow rate experimentally fuel was injected to the atmosphere for 1 minute with the injection duration of 1ms. Measured fuel flow rates for each nozzle are shown in Figure 3. Note that nozzle cross sectional areas of B, C, D are almost the same. It is shown that flow rates with nozzle D has maximum flow rate among tested elliptical nozzles when the fuel injection pressure is greater than 550bar despite it has almost the same cross sectional area with the other elliptical nozzles. It seems that when the ratio of d1/d2 becomes larger the flow rates increases regardless of fuel injection pressure over the certain fuel injection pressure.

The flow rate of nozzle D is about 1.4times larger than that of nozzle A when it is evaluated under the same
sectional area of nozzle exit with $A$. This means that elliptical nozzle hole has a good potential to be applied to diesel injectors which can be used in common rail systems since nozzle hole diameter can be manufactured in far smaller size for the same flow rate which results in good atomization.

### 3.1 Spray Tip Penetration and spray angle

For diesel engine combustion, not only droplet size but also spray penetration and spray angle are very important since these are closely related to smoke formation and high concentration of CO. CO formation mechanism in a diesel engine is somewhat different from that in a spark ignition engine which uses gasoline or natural gas as a fuel. CO is mainly formed near the cylinder wall and lower part of piston bowl side because surrounding temperature is relatively low and fuel has less mixed with air in this region by fuel attachment or wetting compared to other regions in combustion chamber. Thus it is important to make fuel droplet smaller with rapid mixing into the surrounding gas composed of burned gas and fresh air to prevent fuel wetting or attachment. Figure 4 shows spray penetration tip length for each nozzle and Figure 5 shows spray angle for each nozzle respectively when the fuel injection duration is 1.0ms and time after injection start was changed from 0.5ms to 1.6ms. Fuel was injected to the atmosphere with the fuel injection pressure of 270bar which is corresponding to the pressure of idle running condition in passenger car diesel engines. Note that spray tip penetration and spray angle were measured both for the major axis and the minor axis. Penetration length and spray angle were derived from the method proposed by Kang and Bae[14].

It is obviously shown that conventional nozzle $A$ which has cylindrical geometry nozzle hole has the longest penetration compared to that of elliptical nozzles for the same fuel quantity with the smallest diameter, which means elliptical nozzles have a potential of good atomization hence results in short penetration and narrow spray angle. It is also shown that spray angle of cylindrical nozzle $A$ is narrower than that of other elliptical nozzles. These facts mean that elliptical nozzles have more potential for fuel atomization and fuel-air mixing than cylindrical nozzle.
The reason why elliptical hole nozzle has good spray characteristics can be explained as follows. When the fuel is injected from cylindrical nozzle the entire shape of spray become solid cone.

On the other hand, that from elliptical nozzle becomes ellipse shape. Moreover, ellipse nozzle has a possibility of being a rather sheet spray shape when the difference between the length of the major axis and that of the minor axis becomes large. This means that liquid column has more chance to be mixed with surrounding air in terms of the minor axis compared to that of cylindrical nozzle that has almost same distance between the center of liquid column and the edge of the liquid column. Thus, liquid column of the injected fuel from elliptical nozzle is not only well atomized but also well mixed with surrounding air which results in homogeneous fuel-air mixture.

Nozzle C and nozzle D have almost the same penetration length and spray angle, which results from the fact that their diameter is almost the same both for major axis and for minor axis. The penetration length and the spray angle of nozzle B are very similar to those of nozzle A. This may result from the fact that nozzle hole geometry of B is more close to cylindrical nozzle hole rather than elliptical one. Spray tip penetration by time after injection start seems to increase regardless of nozzle hole geometry. This may come from the fact that break up\[15\] occurs quite slowly due to low fuel injection pressure hence atomization become incomplete.

To investigate the effect of the fuel injection pressure on penetration length and spray angle by nozzle hole geometry, fuel was injected at the pressure of 540bar. Figure 6 and Figure 7 show spray tip penetration length and spray angle for fuel injection pressure of 540bar under the ambient gas condition is atmospheric.

It seems that spray tip penetration and spray angle pattern for each nozzle are different from those shown in Figure 4 and Figure 5. Penetration, especially, has little difference regardless of nozzle type except for certain range over time delay after injection start with nozzle C and nozzle D. This may be related to the fact that nozzle C and D have higher flow rate under the same time delay after injection start and fuel injection pressure compared to that
of nozzle A. Note that the injected fuel quantities were 26.7, 34.8, 39.5, 43.6 g/min in alphabetic order, respectively. Thus, the penetration length ratio of nozzle C and D to nozzle A becomes relatively longer compared to that of 270 bar since more fuel quantity causes retarded break up of fuel liquid column if all the other conditions are constant. Spray angle of nozzle C and nozzle D, whereas, show still similar tendency appeared in Figure 5, that is to say, spray angle of nozzle C and D is obviously wider than that of nozzle A. This means that elliptical nozzles have a possibility of good atomization than that of cylindrical one. Fuel-air mixture degree will be described later through the processing of mean gray level of pixel for each spray image.

Figure 8 and Figure 9 show penetration length and spray angle when the fuel is injected at 1080 bar under atmospheric condition. At this condition, the injected fuel quantities for each nozzle were 35.6, 47.2, 54.4, 60.4 g/min, respectively in alphabetic order. It is shown that penetration and spray angle pattern has the same tendency with the fuel injection pressure 270 bar and 540 bar for nozzle C and D. That is to say, penetration length is shorter and spray angle is wider than those of cylindrical nozzle A.

Whereas, it is interesting to note that nozzle B has longer penetration and narrower spray angle than those of nozzle A which implies that spray characteristics are not good even with elliptical nozzle B. This means that there exists certain ratio of d1/d2 to shorten break up length of fuel liquid column over the certain fuel injection pressure. In this study it seems that the certain ratio of d1/d2 is 1.2. Thus, to have a good spray characteristics using elliptical nozzle hole, it is important to determine the diameter of major axis and that of minor axis properly.

3.2 Spray images

Some spray images for nozzle A and nozzle D under the condition of fuel injection pressure of 1080 bar and the time delay after injection start of 1.4 ms are shown in Figure 10. It is interesting that the penetration length of for the major axis of nozzle D is shorter than that of nozzle A. It is shown that spray angle of the major side for nozzle D is wider from the start of the fuel injection. It is also shown that some light gray pixels or white pixels are easily to be seen
in the fuel liquid column of the nozzle D which represents good atomization and rapid entrainment of surrounding air. This phenomenon explains that the fuel liquid column of nozzle D has more chance to meet surrounding air since the distance from the center to the edge of fuel liquid column is much closer than that the case for nozzle A as described in the previous section. Thus, more amount of surrounding air is entrained even to the fuel liquid core then mixed with the fuel. These are well expressed in the time history of spray images shown in the Figure 11.

It is shown that fuel liquid column of nozzle C and D include light gray pixels from the early state from the fuel injection, whereas, fuel liquid column of nozzle A and B do not. It is interesting to note that the shape of liquid column of nozzle C and D have somewhat spring out profile from the fuel liquid column downstream. This is mainly results from the good atomization and good entrainment of surrounding air. Therefore, there is a possibility of NOx and PM reduction with these elliptical nozzles because homogeneous fuel-air mixture is easily obtained through good atomization and good entrainment of surrounding air. Therefore, there is a possibility of NOx and PM reduction with these elliptical nozzles because homogeneous fuel-air mixture is easily obtained through good atomization and good entrainment of surrounding air. Therefore, there is a possibility of NOx and PM reduction with these elliptical nozzles because homogeneous fuel-air mixture is easily obtained through good atomization and good entrainment of surrounding air. Therefore, there is a possibility of NOx and PM reduction with these elliptical nozzles because homogeneous fuel-air mixture is easily obtained through good atomization and good entrainment of surrounding air.

3.4 Mean gray level

Mean gray level of the liquid column for each nozzle is derived through the image processing for the purpose of investigating fuel-air mixture grade. Figure 12 shows mean gray level for each nozzle at the axial position of 75mm from nozzle exit when the fuel injection pressure is 1080bar.

Note that 0 means black color and 255 means white color. Thus, if the number is high it means good fuel-air mixture since the number of pure liquid column pixel is close to 0. From the mean gray level of local line which represents pixels including 2mm from liquid edge and entire mean gray level which include all pixels on the line of 75mm from the nozzle exit, it is shown that mean gray level of elliptical nozzle B, C and D are higher than that of cylindrical nozzle A both for local line and for entire line. This means that surrounding air is well entrained into the spray which results in early break up of fuel liquid column and homogeneous fuel-air mixture with the elliptical nozzle compared to that of cylindrical nozzle. Thus, as is described in the previous section, elliptical nozzle has good spray characteristics which can lead to not only the reduction of NOx, PM and CO but also better fuel economy.

4. CONCLUSIONS

The effects of nozzle hole geometry of conventional cylindrical nozzle and that of elliptical ones on spray characteristics were investigated experimentally under the various fuel injection pressures. The obtained results from this study can be summarized as follows.

1. Penetration length becomes shorter and spray angle becomes wider when the fuel is injected from elliptical nozzle hole of C and D regardless of the fuel injection pressure.
2. It seems that there exists a certain ratio of the major
axis to the minor axis to have a good effect for good spray characteristics. (In this study it was 1.2).

3. The values of mean gray level of elliptical nozzles are larger than that of conventional cylindrical one. This means that more homogeneous fuel-air mixture can be achieved by elliptical nozzles.

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6. REFERENCES