An Analysis on the Suitable Injection Pressure of Diesel Injection with High Pressure

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Spray patterns were visualized by the shadowgraph method and droplet size and velocity were measured by using PDPA with the high pressure injection up to 2600bar. Spray pattern and spray characteristics such as penetration, spray width, spray angle, droplet size, injection duration, droplet velocity, etc. were investigated to determine a suitable injection pressure. Spray penetration, width, angle and velocity increased with a continuous increase in injection pressure in a high pressure region up to 2600bar. However, the rate of enhancement of the above spray characteristics declined rapidly once 2000bar injection pressure was reached. Also, injection duration and droplet size were generally decreased with an increase in injection pressure, but the rate of enhancement decreased abruptly after 2000bar. Consequently, spray characteristics were moderate over 2000bar. This means that a suitable injection pressure is around 2000bar.

1. Introduction

High pressure injection of fuel is an excellent method used to promote the atomization of fuel. Atomization by high pressure injection can reduce both particulate and fuel consumption, and can increase engine power. Injection timing could be delayed widely with the enhancement of combustion and decrease the temperature of combustion gas. This results in reduction of NOx . To investigate the utility of high pressure injection, Kate 1), Yawata 2), G. Stump 3) and D.A Pierpont 4) clarify that spray characteristics are enhanced continuously under 2000bar.

It is anticipated that spray and combustion characteristics will be enhanced to some degree once injection pressure is increased to high, but it is expected that there will be a suitable injection pressure or a moderating enhancement ratio from the viewpoint of the rate of enhancement of spray characteristics. Also, if injection pressure becomes ultra high pressure, the spray from the nozzle converts to a critical state, indicating that there is a limit to the enhancement of spray characteristics or that the spray characteristics may be reversed.

A higher pressure injection system is more costly due to the difficulty in control ability and durability. Therefore, it is necessary to find suitable data indicating appropriate injection pressure when producing high pressure fuel injection methods. Because of the difficulty involved in inventing ultra high pressure injection equipment necessary to analyze the pressure, studies on high pressure injection have been localized under 2000bar until now.

In this study, a suitable injection pressure is investigated from a free spray pattern injected into the air.

Ultra high pressure injection equipment, which is able to reach over 4000bar, has been developed to investigate a suitable injection pressure.
Spray was visualized, and droplet size and injection duration were measured up to 2600bar to investigate a suitable injection pressure, as an aspect of the enhancement rate of spray characteristics.

2. Testing device and testing method

2.1 Testing device

2.1.1 Ultra high pressure injection equipment (UHPIE)

The UHPIE must be able to maintain ultra high pressure. As high as possible control of injection pressure, injection timing and injection pattern, as in an actual engine, should be controlled in the UHPIE.
Considering the above concepts, single shot UHPIE was developed and shown in Fig. 1.

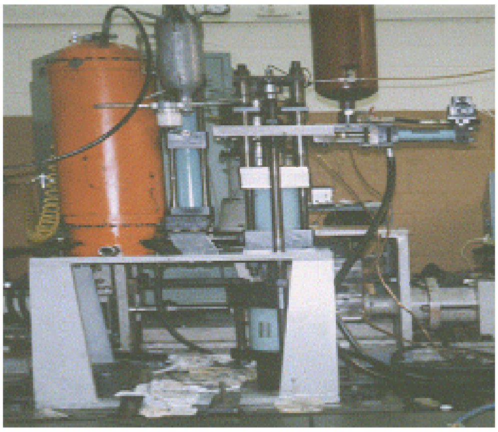

Fig. 1 Photograph of high pressure injection system.

UHPIE consists of a 1st stage compression component, a 2nd stage compression, returning component and an injector. A detailed description of the ultra high pressure injection equipment is as follows.
1st stage compression component : the equipment, which pressurizes the fuel supplied to the plunger, consists of a fuel tank and a pressurizing cylinder that pressurizes the cylinder without bubbles.
A 200bar booster cylinder was used for the 1st fuel pressurizing.
The hydraulic pump was used to control the 1st pressurizing of the fuel.
2nd stage compression component : the equipment, which repressurizes the fuel using the 1st stage compression component, consists of a N_2 gas bomb, a high pressure accumulator including operating oil, a stopper and a plunger pump.
Inert N2 gas was used for pressurizing the operation oil and preventing self-ignition by mixing operating oil with air.
Plunger velocity can be changed by pressure control of the operating oil and its pressure is controlled by the regulator.
The high pressure accumulator has a 30 liter container big enough for preventing rapid pressure drop, when a large quantity of operating oil is sent to the plunger driving cylinder.
The diameter of the plunger driving cylinder is 140mm in diameter.

In case the working fluid pressure is 80bar, The maximum design compression pressure of fuel that can be applied by the plunger driving cylinder of the plunger is 12000bar.
An actual and repeatable injection pressure with this equipment is around the cylinder toe tappet or plunger pump, which is maintained to transfer enough kinetic energy to free the plunger pump and decrease the driving time variable.
The plunger is used in commercial type PE-P, and the plunger diameter is 12mm while the effective stroke is 5mm.
Injection quantity can be controlled by using the control rack position changer.
The plunger barrel is held by a plunger holder of ϕ65mm and the delivery valve is installed at the upper side of the holder.
The inlet port and air drain holes are used to deliver the pressurized fuel to the plunger barrel and to remove the bubble respectively installed at the side of the holder.
Returning component: This equipment consists of the returning hydraulic cylinder, the plunger driving cylinder and the hydraulic pump. The return cylinder of ϕ160mm is installed at the base of the driving plunger cylinder, which is operated by the hydraulic oil pump. The operating plunger cylinder causes the return cylinder to move back to the end of the rod.
The stopper comes up to the end of the rod and locks it. And the returning cylinder pulls down the rod to restore it to the initial position.
Injector: The multi hole injector (DLL-s type) using direct-injecting diesel engine was modified. The modified injector consists of a nozzle holder, nozzle, pressure spring, needle lift sensor and a screw to control the spring tension. The opening pressure of the nozzle is adjusted by the controlling tension of the pressure spring.
To measure the needle lift, a pressure pin through the center of the pressure control screw can adjust the sensor mounted top of the injector. The hole diameter is 0.23mm, the injection angle is 150°, the needle lift length is 0.3mm and it has five holes.

2.1.2 Analysis system of spray characteristics in high pressure

The testing device for measuring the spray characteristics in high pressure is shown in Fig. 2.
The testing device consists of ultra high pressure injection equipment (UHPIE), a visualization system, a Phase Doppler Particle Analyzer (PDPA), data acquisition and a control systems.
A high speed camera (Cordin 350), is capable of 35000f/s and is used for measuring spray characteristics such as spray tip penetration, spray width and spray angle.
The halogen lamps (650w×2) were used for a light source. Semi-transparent paper is installed between the camera and the light to prevent direct exposure of light.

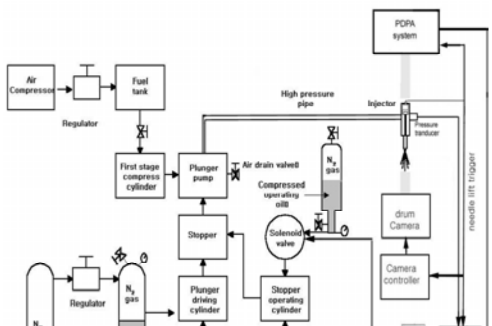

Fig. 2 Schematic diagram of testing device.

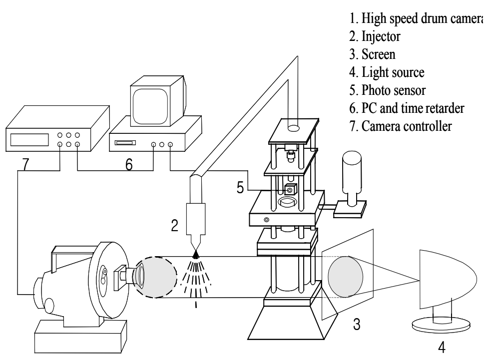

Fig. 3 Visualization system for high pressure spray.

The schematic diagram for spray visualization is shown in fig. 3.
Droplet size was measured using PDPA. PDPA consisted of a fiber driver, a transmitter, receiver, a signal analyzer and a PC. An Ar-ion laser was used for a light source.
A Piezo type pressure transducer, which is able to measure up to 10000bar, is mounted to measure injection pressure in the fuel supply line in front of the injector.
Needle lift length is measured by the capacity type gap sensor (VE-231), which has a measuring range of 0-2mm.
Data of fuel injection pressure and needle lift signal are converted through the A/D converter and analyzed in the PC.

2.2 Testing method

The purpose of this study is to analyze spray characteristics on free conditions.
Experimental variable one is injection pressure. Injection pressure was changed from 1000bar to 2600bar with step by step. The opening pressure of the injector was fixed at 500bar.
Spray was visualized using the shadowgraph method. Droplet size was measured at 60mm from the nozzle tip.

3. Spray characteristics in high pressure region

3.1 Spray behavior

Fig. 4 shows the visualized photograph up to the 2600bar with the lapse of time.
The fuel sprays show that the shape of spray at the beginning was straight, smooth, and the desired shape for all injections. Spray edges become dull and these sprays become shaky due to the time lapse, tendencies that were increasing during higher conditions. It is expected that shaky sprays are responsible for the reaction between air and progressing affects of injection.
As the injection pressure increases, the above aspects become greater because the shaky sprays are widening due to the higher injection pressure.
An amount of droplets, which are spread from the surface of the spray to the axis and radius directions, were increased with higher injection pressure, and the same tendency is repeated in high pressure injections. However, it is shown that droplets spread to the axis and radius directions were not increased remarkably over 2000bar.
The data were analyzed with visualized photographs as shown in Fig. 4.

3.2 Spray tip penetration and droplet velocity
Figure 5 shows the spray tip penetration by the time lapse at high pressure injection.

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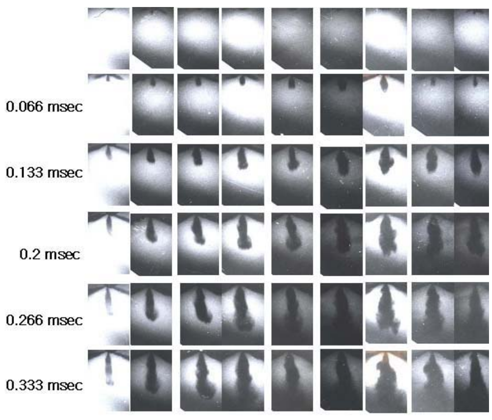

Fig. 4 Photograph of spray behavior.

Spray tip penetration was increased continuously by the time lapse and also by higher injection pressure. But the increasing rate is moderated by increasing injection pressure and it is decreased remarkably over 2000bar injection pressure.
Namely, when 1800 bar penetration is reached, it is increased 62.6% in comparison with 1000 bar at time 0.26ms following injection.
If injection pressure becomes higher such as up to 2000bar, penetration becomes increased by 15% as compared with 1800bar. However, when injection pressure is set to 2600 bar, the increasing rate of penetration is only 4.2%.
Spraying energy is increased due to increasing injection pressure, but it's reduced with decreasing droplet size as will be mentioned in section 3.4. Both effects on spray tip penetration offset each other. It is thought that the increasing rate of penetration is moderate over 2000 bar injection pressure according to the above result.
In other words, as shown in figure 6, it means maximum velocity is increased by increasing injection pressure, but the spray tip penetration is increased only faintly over 2000 bar injection pressure due to the decrease of kinetic energy by atomization of droplets.

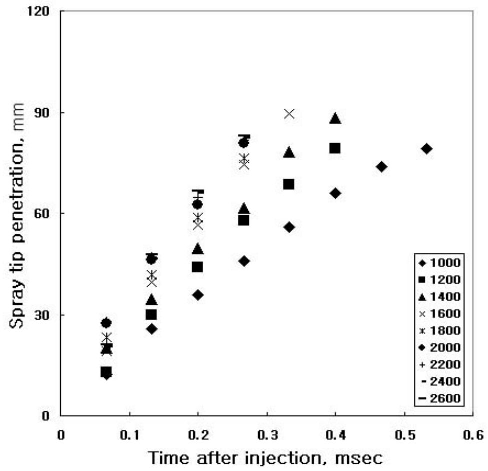

Fig. 5 Spray tip penetration.

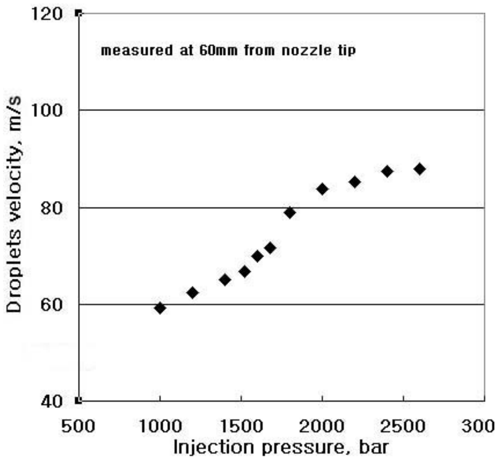

Fig. 6 Droplets velocity.

3.3 Spray width and spray angle

Figure 7 shows the sprays width by the time lapse of each injection pressure. At the beginning of the injection, spray width is increased with an increase in injection pressure until 2000bar, but if injection pressure becomes much higher, the spray width is decreased quite dramatically. However, the increasing rate of spray width is increased by the time lapse with high pressure. The increasing tendency of spray width is similar to the injection pressure after 0.2ms. However, the increasing rate of spray width is moderate when the injection pressure gets to over 2000bar with an 8% ratio increase. The mutual reaction between air and fuel is increased by increasing droplet velocity and by increasing injection pressure, as was mentioned in Fig. 6. Atomized droplets are spread far away to the radius direction. Spray widths are increased by increasing injection pressure.
For example, if the increasing ratio is set to 2000bar from 1000bar, the ratio of spray increase is remarkably about 232%. At the 2600bar, it is increased by about 240%.
But if the increasing ratio of spray width up to 2600bar is just 2.4% as compared with 2000bar, the spray angle and spray width shown in figure 8 are decreased by the time lapse for each injection pressure and then converged after a while.
If injection pressure is on low range, the spray angle is bigger at the beginning of the injection. The spray angle is increased by increasing injection pressure.

The changes of spray angle between the beginning and the end of the injection are quite different. But as injection pressure becomes higher, those results become smaller. Spray angle is increased due to increase of spray width with increase of injection pressure and it is shown that increasing rate is decreased remarkably over 2000bar. Spray angle is increased about 7° and 8° by increasing injection pressure from 1000bar to 2000bar and 2600bar.

3.4 Drop size (SMD)

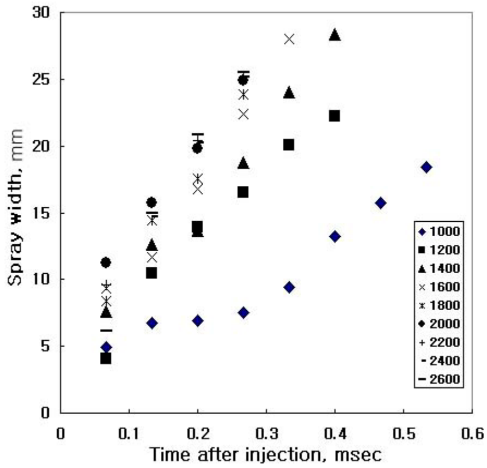

Fig. 7 Spray width.

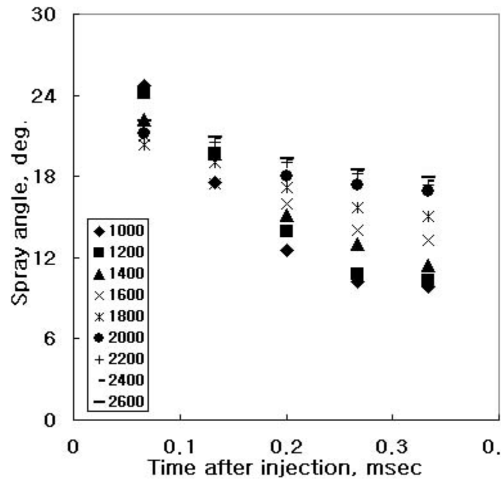

Fig. 8 Spray angle.

Figure 9 shows the droplet size for the injection pressure by SMD. Droplet size is decreased continuously as injection pressure becomes high pressure. But the decreasing rate of droplet size is decreased by increasing injection pressure, and droplet size becomes almost the same size when injection pressure is over 2000bar. Droplet size is decreased and the decreasing rate is moderated. This is caused by the mutual reaction between air and droplets due to the continuous increasing droplet velocity for the increase of injection.

When injection pressure becomes high pressure from 1000bar to 2000bar, droplet size is decreased remarkably from approximately 11.5 μm to approximately 7.34 μm, but when it is over 2000bar, droplet size becomes approximately 7 μm.

This means that the degree of vaporization of fuel by the surface that is contacted between air and fuel and enhancement of combustion characteristics is limited.

3.5 Injection duration

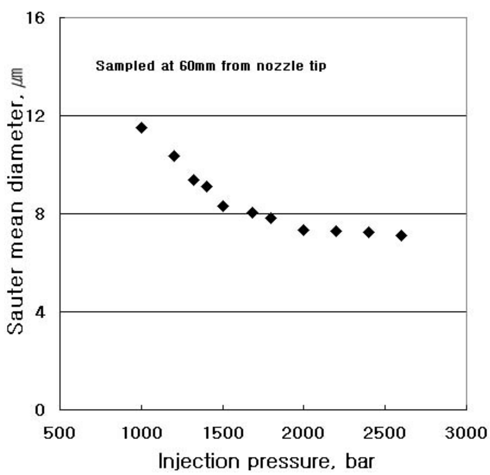

Fig. 9 Droplets size.

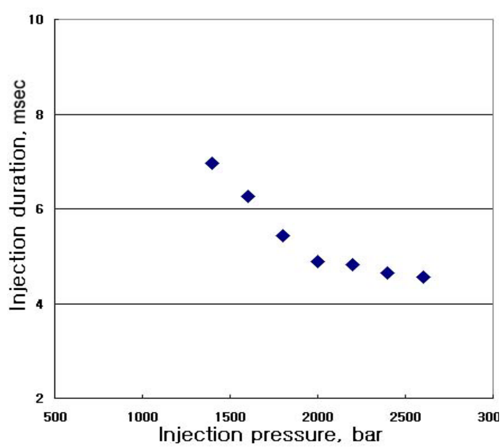

Fig. 10 Injection duration versus injection pressure.

Figure 10 shows the injection duration for the high pressure injection. Injection duration is the same value of needle lifting duration because the injection duration is the same value of needle valve opening time. Furthermore, injection duration is generally decreased by the increasing flow due to the increase of injection energy. Injection duration is decreased linearly until 2000bar and decreased moderately up to 2000bar.

As is well known, when a fluid is passing through the bended channel, cavitation occurs and this tendency becomes greater by increasing the bended angle and the velocity of fluid ejected from this passage. The cavitation causes the reduction of the passage area and the decreasing flow rate. Therefore, there isn't much difference in injection duration over 2000bar due to the decreasing flow rate per unit time caused by the decrease of passage area and side loss with cavitation occurred by the 70° bended angle of the nozzle hole and the increase of fluid velocity by injection pressure, while the fuel is ejected through passage.

Takedo[7] & Kato[1] clarified that injection duration is also decreased with an increase in injection pressure. CO and smoke was decreased by increasing injection pressure.

It is thought that this is caused by the decrease of injection duration, atomization and enhancement of fuel distribution for the increase of injection pressure. As mentioned before, although injection pressure becomes higher, injection duration, droplet size and penetration are not much different over 2000bar injection pressure.

This shows indirectly that the effect of decreasing exhaust gas such as CO or smoke hasn't been developed much over 2000bar injection pressure.

3.6 A suitable injection pressure

Figure 11 shows the enhancement ratio of spray characteristics such as spray tip penetration, spray width, droplets size, and injection duration. As shown in this figure, the above characteristics increase generally with an increase of injection pressure. However, it is also shown that enhancement rate of spray characteristics become moderate over 2000bar injection pressure. When injection pressure becomes higher from 2000bar to 2600bar, spray tip penetration and spray angle are enhanced by approximately 4.2%, on 1° degree of spraying angle respectively. Droplet size is enhanced marginally around 2.1% and injection duration is decreased around 4.2%.

As mentioned above, it is known that penetration, atomization, distribution of fuel and injection duration are not enhanced remarkably in high pressure regions over 2000bar.

This means that the most suitable injection pressure is around 2000bar from the view-point of enhancement rate of spray characteristics. Injection spray in engines is an impinging spray against piston head and cylinder wall. Combustion depends on this phenomenon.

It is a necessary systematic analysis of impinging spray and combustion characteristics in high pressure range to analyze which is the most suitable injection pressure.

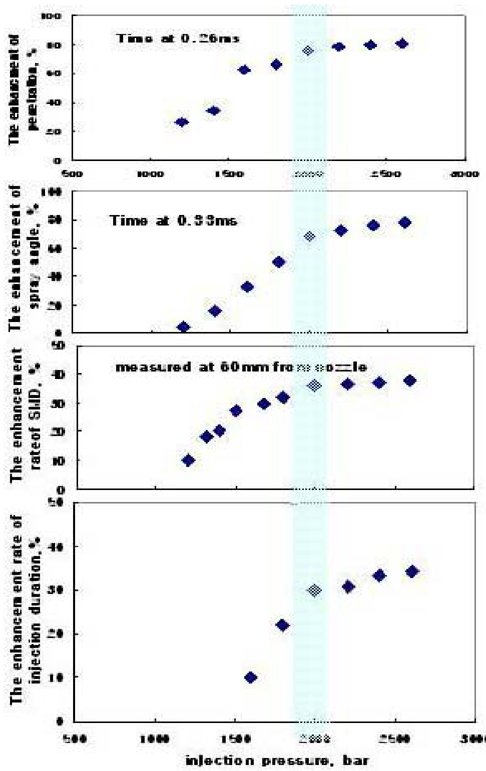

Fig. 11 Spray Characteristicses versus injection pressure.

4. Conclusions

From the analysis of spray characteristics by different injection pressures in ultra high pressure, the conclusions are as follows:

1. An ultra high pressure over 4200bar is achieved by developed HPIE, and a foundation is established to analyze spray characteristics in high pressure regions.
2. Spray spreading is increased to the axis and the radius direction of spray with an increase of injection pressure to high pressure, and spray behavior patterns are similar to those over 2000bar.
3. Spray tip penetration, spray width and angle are enhanced continuously with an increase of injection pressure to high pressure up to 2000bar, but the enhancement is remarkably moderate over 2000bar.
4. Droplet velocity is increased continuously up to 2000bar but enhancement ratio is decreased conspicuously over above injection pressure.
5. Droplet sizes are decreased generally with an increase in injection pressure, but the enhancement doesn't improve much over 2000bar and droplet size becomes about 7 ㎛.
6. From the above results, the most suitable injection pressure is around 2000bar based on the view-point of the enhancement rate of spray characteristics. This result comes from the analysis of the free spray characteristics. Impinging spray characteristics and combustion characteristics are required in high pressure for the future.

5. Acknowledgement

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6. References

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