Atomization of High Viscosity Liquid by a Diesel Nozzle *

By Michihiko TABATA **, Masataka ARAI ***

and Hiroyuki HIROYASU ****

The purpose of this study is to clarify the effect of liquid viscosity on the Sauter mean diameter and the spray angle. The spray injected by a diesel nozzle of hole type was observed by the laser diffraction technique system and the direct photography method. The tests were carried out over a wide range of injection pressures and viscosities of glycerine solution at ambient pressure of 3 MPa.

With an increasing liquid viscosity, the spray angle decreases and the Sauter mean diameter gradually increases. With further increase of the viscosity, the Sauter mean diameter suddenly increases. There is an upper limit of the viscosity to be atomized as a spray of fine droplets. At a high injection pressure, the effect of viscosity on the Sauter mean diameter still remains but the viscosity has no effect on the spray angle.

Key Words : Internal Combustion Engine, Diesel Engine, High pressure Chamber, Viscosity, Spray, Sauter Mean Diameter, Spray Angle, Atomization

1. Introduction

The demand for middle distilled fuels is recently mounting and it expands into industrial areas. Then thermal and catalytic cracking processes that can produce much distilled fuels are increasingly adopted in the oil manufacturing in order to meet the increased demand on the distilled fuels. As the result, residual fuel reprocessed by such cracking processes will have higher viscosity and density, and lower stability than the same kind of the fuel used today (1)(2).

The residual fuel is originally the main fuel for diesel engines of ships or big plants. And recent use of the low quality residual fuel for such diesel engines is causing several engine troubles. These are connected with deterioration of the spray and combustion characteristics, elongated ignition delay, corrosion of piston and nozzle, etc (3)~(6). Because of the engine troubles caused by the residual fuel, previous studies on the diesel combustion of high viscosity fuel were mainly carried out based on engine tests. But it has been realized that a direct approach to correlate the spray characteristics to the combustion with the consideration of

viscosity would be much more fundamental.

The combustion process in a diesel engine involves many physical processes, such as injection of liquid fuel, mixing of fuel and air, ignition, spray combustion, etc. The aim of the injection is to atomize liquid fuel into a multitude of droplets and to supply it into high pressure and high temperature air in the diesel combustion chamber. In other words, the injection process plays the primary part in the formation process of a combustible mixture that controls the overall combustion process in a diesel engine.

Therefore accurate knowledge of the atomization process and the spray characteristics of a diesel spray is indispensable to a detailed analysis of diesel combustion. So, the study on the spray injected by a diesel nozzle has been performed by many engine researchers as a basic study of the diesel combustion.

The numerous atomization studies have generally been made on a liquid like the low viscosity fuel that is used presently in the diesel engine. As a result, correlations relating droplet size distribution to fuel properties and injection conditions have been established (7). However, for a highly viscous residual fuel oil that is now of growing interest to marine users of diesel engines, these correlations have not been obtained. Further most of the previous experimental works were carried out under an atmospheric ambient pressure condition. This is very different from a high ambient pressure condition of a diesel engine. So it would be difficult to consider that such experimental result can be applied to the diesel spray of the high viscosity liquid injected into the high ambient pressure air.

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** Graduate Student, Department of Mechanical Engineering, University of Hiroshima (Shitami Saijocho, Higashi-Hiroshima, 724 Japan).

*** Associate Professor, Department of Mechanical Engineering, University of Hiroshima.

**** Professor, Department of Mechanical Engineering, University of Hiroshima.

The objectives of this work are to study effects of liquid viscosity, injection pressure and diameter of nozzle hole on the mean droplet size and spray angle. Several kinds of glycerine water solutions were prepared to change the viscosity of liquid widely. The mean droplet size and the spray angle were measured over a wide range of the injection pressures (3 to 90 MPa), the liquid viscosities (1×10^{-6} to 120×10^{-6} m²/s) and the nozzle diameters (0.2 to 0.4 mm) under a high ambient pressure of 3.0 MPa.

2. Experimental apparatus

A schematic diagram of the experimental apparatus is given in Fig.1. This apparatus consists of a pressure vessel, an injection system, an injection nozzle and a measuring equipment for droplet size distribution of a diesel spray. All of the data reported here were obtained under an ambient pressure of 3.0 MPa and room temperature. For this purpose, a large cylindrical pressure vessel of which the diameter is 190 mm and the length is 1100 mm was used. A diesel nozzle of a single-hole type was mounted in the top of the pressure vessel, and transparent windows were fitted diametrically opposite to the side of the pressure vessel.

Liquid was continuously injected by the injection system from the diesel nozzle into the pressure vessel. This system was designed for injection pressures from 0.1 MPa to 90 MPa. It consists of an injection pump and a pressure accumulator for reducing the pressure pulsation. The injection pressure is here represented by the absolute pressure in the injection nozzle.

The droplet size was measured using an optical technique that is based on the Fraunhofer diffraction. The technique, reported by Swithenbank⁽⁸⁾ and Felton⁽⁹⁾, has been developed for the on-line measurement of the droplet size distribution. The monochromatic and coherent light of He-Ne gas laser beam with a diameter of 6 mm illuminated the spray droplets. The diffracted light that has information on the droplet size distribution was gathered by a Fourier transform lens and detected by a

Fig.1 A schematic diagram of the experimental apparatus

multi-photodetector fixed on the focal plane of the Fourier transform lens. The focal distance of this lens was 300 mm. The detected signal was analyzed by a program developed by Malvern Instrument Ltd. This program can calculate the most suitable Roisin-Rammler volumetric distribution function. In this work, the Sauter mean diameter X_{32} was calculated and printed out as the final output of the data processing.

Figure 2 shows the optical arrangements for taking photographs of the diesel spray under the high ambient pressure. Two kinds of light sources were used. One of them is a micro flash as shown in Fig.2(a), and the other is flood lamps as shown in Fig.2(b). The camera was set at one side of the transparent windows fitted on the pressure vessel, and at the opposite side, the two kinds of light sources were set. Further, a black screen was set behind the spray to emphasize the contrast of the photographs of the diesel spray. The spray angle was given by many photographs of the spray taken by the system as shown in Fig.2(b).

In order to study the effect of the kinematic viscosity on the Sauter mean diameter and the spray angle, glycerine water solutions that were different in the kinematic viscosity were prepared. The physical properties of glycerine and water at the temperature of 20°C are shown in Table 1. Those liquids have almost the same values of density and surface tension but a marked difference in the kinematic viscosity. Therefore, the effect of the kinematic viscosity can be analyzed separating the effects of the density and the surface tension. As a matter of fact, the measurements of the droplet size

Table 1 Physical properties

	Density ρ kg/m ³	Surface Tension σ N/m	Viscosity μ Pa·s	Kinematic Viscosity ν m ² /s
Water	0.998×10^3	72.75×10^{-3}	1.002×10^{-3}	1.004×10^{-6}
Glycerin	1.264×10^3	63.4×10^{-3}	1495×10^{-3}	1183×10^{-6}

(T = 20°C)

Fig.2 The optical arrangement for taking photographs of the diesel spray

and the spray angle were carried out over a range of the kinematic viscosities from $1 \times 10^{-6} \text{ m}^2/\text{s}$ to $120 \times 10^{-6} \text{ m}^2/\text{s}$.

3. Spray angle

3.1 The effect of the kinematic viscosity on the spray angle

In order to study the liquid viscosity on the spray angle and to observe the atomizing process of the diesel spray at high ambient pressure, numerous photographs of the spray were taken. Figure 3 shows a series of the photographs illuminated by the micro flash. These photographs indicate the effect of the kinematic viscosity on the atomization process under the ambient pressure of 3 MPa.

In the case of the low viscosity liquid of $1.53 \times 10^{-6} \text{ m}^2/\text{s}$, that is low enough to be atomized with the injection pressure of 11 MPa, the spray is completely formed at the exit of the nozzle hole. However, when the liquid viscosity is $5.67 \times 10^{-6} \text{ m}^2/\text{s}$, the spray is not formed at the exit of the nozzle. We can see a smooth liquid column near the nozzle and a spray formed downstream of the jet. In other words, this is an atomizing process that makes progress from

the liquid column to the spray along the jet stream. With more increase of the liquid viscosity, that smooth liquid column grows longer and the spray is formed far downstream at the jet. At last, the spray is not formed in the case of the high viscosity of $14.7 \times 10^{-6} \text{ m}^2/\text{s}$. In this state, the atomization is very poor.

An atomizing process making progress from the liquid column to the spray along the jet stream was also observed in the case of a different diameter of the nozzle hole. But this atomizing phenomenon begins to appear at lower viscosity of the liquid with an increase in the diameter of the nozzle hole.

Figure 4 shows the photographs illuminated by the flood light under almost the same condition as in Fig.3. When Fig.4 is compared with Fig.3, the cone of the spray in Fig.4 is larger than that in Fig.3. It is considered that the method used the flood light is useful enough to photograph the small droplets around the spray as shown in Fig.4. Therefore, the spray angle was measured from the photographs shown in Fig.4, and the spray angle θ in this report is defined as shown in Fig.5.

The correlation between the spray

Fig.3 The effect of the kinematic viscosity on the atomization process (illuminated by the micro flash)

Fig.4 the effect of the kinematic viscosity on the atomization process (illuminated by the flood lamps)

angle θ and the liquid viscosity at various diameters of the nozzle hole is shown in Fig.6. The spray angles decrease with an increase of the liquid viscosity for any diameter of the nozzle hole. When the liquid viscosity is as low as $\nu=1.0 \times 10^{-6} \text{ m}^2/\text{s}$, the effect of the nozzle diameter on the spray angle is very small. But the effect of nozzle diameter grows larger with an increase of the liquid viscosity. The spray angle rapidly decreases in the case of the nozzle diameter 0.4 mm and the spray angle comes down to about 0.02 rad. This value is a lower limit value of the spray angle defined in this work and in substance, the spray angle is zero at this point. In the case of the small size of the nozzle hole, the spray angle gradually decreases and does not come down to the limit value of the spray angle till at a higher viscosity of the liquid than that in the case of the large hole diameter.

3.2 The effect of the injection pressure on the spray angle

The relative velocity between liquid jet and ambient air generally increases with an increase of the injection pressure. Therefore, it is likely that a high viscosity liquid can be atomized at a

high injection pressure condition. In this work, the effect of the injection pressure on the spray angle was studied.

Figure 7 shows photographs of the low viscosity liquid injected into the high ambient pressure at various injection pressures. A fine spray is completely formed from the nozzle at over the injection pressure of 9 MPa. However, when the injection pressure is $P_i = 3.5 \text{ MPa}$, the spray forming region is located away from the exit of the nozzle hole and a fine spray is not formed.

The effect of the injection pressure on the spray angle is shown in Fig.8 at the same condition as in the photographs of Fig.7. At relatively low injection pressure condition, the spray angle rapidly increases with an increase of the relative velocity of liquid jet and air. After that, the increase of spray angle is small.

Also when a liquid of high viscosity was injected, the effect of the injection pressure on the spray angle was studied. Figure 9 shows sprays of the glycerine water solution with a kinematic viscosity of $53.1 \times 10^{-6} \text{ m}^2/\text{s}$ injected into an ambient pressure of 3 MPa.

When the injection pressure is 80 MPa that is enough to atomize such a high

Fig.5 The spray angle

Fig.6 The effect of the kinematic viscosity and the nozzle diameter on the spray angle

Fig.7 The effect of the injection pressure on the atomization process at the low liquid viscosity

viscosity liquid, the spray is completely formed at the exit of the nozzle hole. With a decrease of the injection pressure, the injected liquid does not come to be well atomized. We can also find a smooth liquid column near the nozzle and that the liquid jet makes progress from liquid column to the spray along the jet stream. When the injection pressure become lower, the smooth liquid column grows longer. The spray can not be formed at an injection pressure of less than $P_i = 50$ MPa. There is also the state that the liquid jet makes progress from liquid column to the spray along the jet stream, the same as in Figs.3 and 4. It is considered that the state of the liquid jet is strongly influenced by the surrounding ambient air and the effect of the ambient air differs along the axial distance of the jet stream.

The correlation between the spray angle θ and the injection pressure is shown in Fig.10 using a parameter of kinematic viscosity. With an increasing injection pressure there is the maximum spray angle in any case of the glycerine water solution. The spray angle increases with an increase of the injection pressure. After that the spray

angle reaches the maximum value at some critical injection pressure. This critical value of the injection pressure decreases with an increase of the kinematic viscosity of the liquid.

When the injection pressure is sufficiently high, the spray angle decreases slightly with an increase of the injection pressure. The kinematic viscosity of the liquid has no effect on the spray angle over the injection pressure of $P_i = 80$ MPa.

It is considered that the defined spray angle includes surrounding small droplets around spray sheath as shown in Figs.3 and 4. Therefore, with an increase of the injection pressure, inflow of the air from the surrounding to the jet increases and the small droplets around the spray sheath can not be dispersed into the surrounding widely. On the other hand, the turbulence of the inner flow in the nozzle at high injection pressure condition is higher than that at low injection pressure condition. At high injection pressure condition, there might be some kind of a separated and contracted flow in the nozzle. So, the spray angle decreases as shown in Fig.10.

4. The mean droplet size

4.1 The Sauter mean diameter

In a routine work developed by Malvern Instrument Ltd. for the ST-1800 particle analyzer used in this study, the following Rosin-Rammler volumetric distribution function was used.

$$\frac{1}{v} \frac{dv}{dX} = \frac{\beta}{X_p} \left(\frac{X}{X_p} \right)^{\beta-1} \exp \left[- \left(\frac{X}{X_p} \right)^{\beta} \right] \quad \dots (1)$$

where: v = volume of droplets
 X = diameter of droplet
 X_p = characteristic diameter where it can be seen that a weight fraction $1/e (=0.368)$ is larger than X_p and 62.3% of the droplets are less than X_p
 β = measure of the spread of the size distribution.

Fig.8 The effect of the injection pressure on the spray angle at the low liquid viscosity

Fig.9 The effect of the injection pressure on the atomization process at the high liquid viscosity

The physical meaning of the Sauter mean diameter X_{32} is more directly connected with an evaporating phenomenon of the spray than X_p , which was introduced as a characteristic diameter in the Rosin-Rammler equation (1). Therefore, in this work, the Sauter mean diameter X_{32} was calculated as the final output of the droplet size analyzer.

The relation between the Sauter mean diameter and the Rosin-Rammler equation is

$$X_{32} = \frac{X_p}{\Gamma\left(1 - \frac{1}{\beta}\right)} \quad (2)$$

where: Γ : gamma function of β .

The equation (2) was accurate only when the droplets were distributed from an infinitely small size to an infinitely large size. But in a spray, there were lower and upper limits to the droplet diameter. So the Sauter mean diameter of the spray had to be obtained as follows (10).

$$X_{32} = \frac{\int_{X_A}^{X_B} X^3 dn}{\int_{X_A}^{X_B} X^2 dn} \quad (3)$$

where: X_A = lower limit of diameter

X_B = upper limit of diameter

n = number of droplets.

Figure 11 shows the measuring

Fig.10 The effect of the injection pressure and the kinematic viscosity on the spray angle

Fig.11 The position measuring the Sauter mean diameter

position of the droplet size. The laser beam with the diameter of 6 mm intersected the center axis of the spray at right angles and a distance of 70 mm from the nozzle. In this work, all of the Sauter mean diameters were calculated from the measured result at this position.

4.2 The effect of the liquid viscosity on the Sauter mean diameter

It is commonly believed that the high viscosity of the injection liquid causes an increase of the Sauter mean diameter. But there are few measuring results of this effect. In this work, the effect of the liquid viscosity on the Sauter mean diameter was measured under an ambient pressure of 3 MPa using several kinds of glycerine water solutions that have marked difference in the kinematic viscosity.

Figure 12 shows the effect of the liquid viscosity on the Sauter mean diameter at an injection pressure of 11 MPa. The Sauter mean diameter increases with an increase of the liquid viscosity at relatively low viscosity of the liquid. When the kinematic viscosity increases from some critical value that could produce fine droplets, a rapid increase of the Sauter mean diameter occurs. In this report this critical point is called the upper limit of the

Fig.12 The effect of the kinematic viscosity and the nozzle diameter on the Sauter mean diameter ($P_i = 11$ MPa)

Fig.13 The effect of the kinematic viscosity and the nozzle diameter on the Sauter mean diameter ($P_i = 50$ MPa)

viscosity. This upper limit of the viscosity increases with a decrease of the diameter of the nozzle hole. It is commonly known that the liquid injected into the high pressure air is disintegrated into fine droplets of the spray by the force from the surrounding ambient air. But, when the liquid viscosity is high, the atomization of the diesel spray is strongly controlled by the kinematic viscosity and the Sauter mean diameter rapidly increases.

Since the liquid which has higher viscosity than $\nu = 10 \times 10^{-6} \text{ m}^2/\text{s}$ can not be atomized at an injection pressure of $P_i = 11 \text{ MPa}$, the injection pressure is raised to $P_i = 50$ or 80 MPa to study the effect of the injection pressure over a wide range of the liquid viscosities. The increase of the Sauter mean diameter with an increase of the injection pressure is also observed at an injection pressure of $P_i = 50$ and 80 MPa as shown in Figs.13 and 14. These figures show that the effect of the diameter of the nozzle hole is smaller at the high injection pressure condition than at the low injection pressure condition. The Sauter mean diameter is not significantly independent of the nozzle diameter at the injection pressure of $P_i = 80 \text{ MPa}$ as shown in Fig.14.

Fig.14 The effect of the kinematic viscosity and the nozzle diameter on the Sauter mean diameter ($P_i = 80 \text{ MPa}$)

Fig.15 The effect of the kinematic viscosity and the injection pressure on the Sauter mean diameter ($D = 0.3 \text{ mm}$)

It is considered that the diameter of the nozzle hole has direct effect upon the first atomization process that is called the distortion or disintegration of the liquid column. But in the final atomization process in which the droplets of the spray are formed, the droplet size is independent of the diameter of the nozzle hole.

Figure 15 shows a rearranged result of the nozzle diameter of 0.3 mm in Figs.12, 13 and 14. It is clear that the Sauter mean diameter increases with an increase of the liquid viscosity. There is also the upper limit of the viscosity to produce fine droplets of the spray in any injection pressure condition. This upper limit of the viscosity increases with an increase of the injection pressure.

4.3 The effect of the injection pressure on the Sauter mean diameter

In the case of the low viscosity liquid, the effect of the injection pressure on the spray angle is previously shown in Fig.8. The Sauter mean diameter was also measured in the same injection condition of Fig.8. The result is shown in Fig.16. The Sauter mean diameter rapidly decreases with an increase of the injection pressure, at relatively low

Fig 16 The effect of the injection pressure on the Sauter mean diameter at relatively low kinematic viscosity

Fig.17 The effect of the injection pressure and the kinematic viscosity on the Sauter mean diameter

injection pressure condition. In this state, the spray angle rapidly increases as shown in Fig.8. When the injection pressure is higher than $P_i = 8$ MPa that is enough to atomize such a low viscosity liquid, the Sauter mean diameter is about $45\mu\text{m}$. It slowly decreases as the spray angle increases slowly with an increase of the injection pressure.

Figure 17 shows the effect of the injection pressure on the Sauter mean diameter with the parameter of the kinematic viscosity of the liquid under an ambient pressure of $P_a = 3$ MPa. As the relative velocity between an injected jet and an ambient air decreases with a decrease of the injection pressure, the injected liquid does not generally come to be well atomized as a fine spray. The Sauter mean diameter increases gradually with a decrease of the injection pressure from $P_i = 80$ MPa. However, when the injection pressure decreases to some critical value that can produce fine droplets, the Sauter mean diameter increases rapidly. This critical value is called the lower limit of the injection pressure in this report. Both the Sauter mean diameter and the lower limit of the injection pressure increase with an increase of the liquid viscosity.

Even if the injection pressure is higher than 80 MPa, the effect of the liquid viscosity on the Sauter mean diameter still remains. This result of the Sauter mean diameter disagrees with the result that the viscosity has no effect on the spray angle at the high injection condition as shown in Fig.10. This is because the liquid viscosity has direct effect upon the final atomization process in which the droplets are formed, and so this final process directly affects the Sauter mean diameter. But, as the spray angle is not related with the final atomization process, it is not influenced by the liquid viscosity at the high injection pressure condition such as over 80 MPa.

5. Conclusions

In order to study the effect of the liquid viscosity, the injection pressure and the diameter of the nozzle hole on the Sauter mean diameter and the spray angle, several kinds of glycerine water solutions were injected into the high ambient air over a wide range of the injection pressures (3 to 90 MPa). The Sauter mean diameter was measured by the laser diffraction technique. Summarizing the results, the following conclusions are reached.

(1) The Sauter mean diameter measured at

a distance of 70 mm from the nozzle increases with an increase of the liquid viscosity, and there is the upper limit of the viscosity to produce a fine spray. This upper limit decreases with an increase of the nozzle diameter. But at the high injection pressure, the nozzle diameter has no effect on the Sauter mean diameter.

(2) With an increase of the liquid viscosity, the injected liquid does not come to be well atomized. We can find the liquid jet making progress from the liquid column to the spray along the jet stream. In this state, the Sauter mean diameter increases and the spray angle decreases rapidly.

(3) The Sauter mean diameter increases with a decrease of the injection pressure at the high ambient pressure. With an increase of the injection pressure, the spray angle reaches the maximum value and there after it slightly decreases.

(4) At the high injection pressure, the effect of the liquid viscosity on the Sauter mean diameter still remains, but the viscosity has no effect on the spray angle.

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