Mean Drop Diameter of a Diesel Spray in a Vaporizing Process*

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The Sauter mean diameter and size distribution of a diesel spray in a vaporizing process were studied to obtain detailed information of the diameter change of the spray in an elevated-temperature and-pressure environment. In this study, direct photographs of the diffracted light from particles or spray drops were taken using a pulsed laser and analyzed directly. The mean particle size could be measured even if the diffracted light from particles passed through a high-ambient-temperature and-pressure environment. The liquids used for studying a vaporizing diesel spray were diesel fuel and n-heptane. The Sauter mean diameter increased to a maximum, then decreased with a further increase of the ambient temperature. The change of the Sauter mean diameter was different for different fuel evaporation rates. The increase of the Sauter mean diameter of n-heptane spray occurred at a lower ambient temperature condition than did that for the diesel spray.

Key Words: Internal Combustion Engine, Diesel Engine, Fuel Injection, Atomization, Diesel Spray, Vaporization, Sauter Mean Diameter, Laser Diffraction, Fraunhofer Diffraction

1. Introduction

Much research on characteristics of a diesel spray, such as break-up length(1), size distribution(2),(3), mixing(4) and vaporizing behavior(5) in a combustion chamber, has been carried out to investigate the relationship between spray and combustion characteristics in a diesel engine. Combustible mixture formation or evaporated fuel density in diesel sprays has become a key subject of these research works, because it has a closer relationship with combustion characteristics than with spray characteristics themselves(6)-(8). A spray injected into a combustion chamber of a diesel engine is unsteady while vaporizing in an elevated-temperature-and-pressure environment. Drops in a diesel spray are vaporized in such a short period after injection that the drop size distribution changes immediatly. Since the evaporation rate of a diesel spray can be derived from the change in size distribution of the spray, development of a new technique which can be utilized for measuring size distributions in vaporizing diesel sprays has become an important subject for studies of diesel combustion.

Recently, optical techniques coupled with lasers have been utilized for drop size measurement. As a result, change in the drop size of vaporizing sprays and the vaporization rate of the spray have been measured for sprays injected under atmospheric conditions(9)-(11). For continuous sprays, change in the size distribution and the vaporization rate of burning sprays or sprays injected into hot environments have been measured by laser diffraction techniques. Many efforts to measure the drop size distribution of a vaporizing diesel spray have been reported, and some new laser technique have been proposed. However, because of the difficulty in measuring transient sprays

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at elevated temperatures and pressures, there are few experimental results which can satisfy the technical requirements, such as the time resolution of a vaporizing diesel spray.

However, with the application of lasers, drop size distribution can be derived by analysis of the Fraunhofer diffraction light from a spray. To utilize this technique for transient diesel sprays, photodetector arrays which can detect diffracted light instantaneously and high-speed sample/hold circuits have been used(12),(13). The other method for detection of Fraunhofer diffracted light has come from applications of holographic techniques using pulsed lasers(14),(15). However, these two new methods are now at the development stage, and they cannot provide sufficient data for study of diesel combustion.

In this study, a new technigue for direct analysis of Fraunhofer light was developed and used to evaluate the Sauter mean diameter of a vaporizing diesel spray. A strong diffracted light image scattered from a diesel spray was produced by a pulsed ruby laser and recorded on a film directly. For the first step of this work, an image analysis technique to derive the Sauter mean diameter was established. A diesel spray was injected into an elevated temperature and pressure environment. Then, errors due to this measuring system and thermal and light noises of the environment were analyzed. In the last step of this work, the Sauter mean diameter of a diesel spray under a vaporizing process was measured, and the transient characteristics of a vaporizing transient spray were discussed.

2. Experimental Apparatus and Technique to Derive a Drop Size

2.1 Pressure vessel

The experimental apparatus for observing a vaporizing diesel spray injected into an elevated-temperature and-pressure environment is shown in Fig. 1. A high-temperature and-pressure vessel was used to simulate the environmental condition of a diesel combustion chamber. This vessel had a cylindrical shape, and its inner diameter was 150 mm. It had two quartz glass windows of 100-mm diameter for optical observation, and they were positioned 150 mm apart to prevent drops from attaching to the windows. The vessel was filled with pressurized nitrogen gas and heated by an electric heater mounted inside the vessel.

A diesel nozzle of a single-hole type was attached to the cylindrical wall of the vessel, and its opening pressure was adjusted to 22 MPa. Liquid fuel was supplied from a single injection pump system. It consisted of a motor, a diesel fuel injection pump and a rack control system for one-shot injection. The start of injection and the injection rate were detected by a needle lift detector and monitored by an oscilloscope. The onset timing of injection pressure rise was detected by a pressure transducer, which was used to control the flash timing of a ruby laser.

2.2 Drop size measurement

Drop size distribution was directly analyzed from a Fraunhofer diffraction image recorded on a film(16),(17). Figure 1 also shows a recording system for diffracted light. This system consisted of a pulsed ruby laser, a retarder to control the flash timing of the laser, an optical path in the vessel, a 1 000-mm-focal-length collecting lens and a recording film of 4×5-inch area. To obtain an instantaneous Fraunhofer diffraction image of a vaporizing diesel spray, a pulsed laser with a flash duration of 40 to 70 nanoseconds and a wavelength of 694 nm was coherently focused to a beam of 6-mm diameter. The diffracted light image from a spray in the vessel was collected and focused onto a film. A gray scale, used for linear transformation of the exposed density of a film to a diffracted light intensity, was superexposed on a film.

Diffracted light intensity was analyzed by an image analysis system with a vidicon camera. The optical system for this analysis is shown in Fig. 2. A

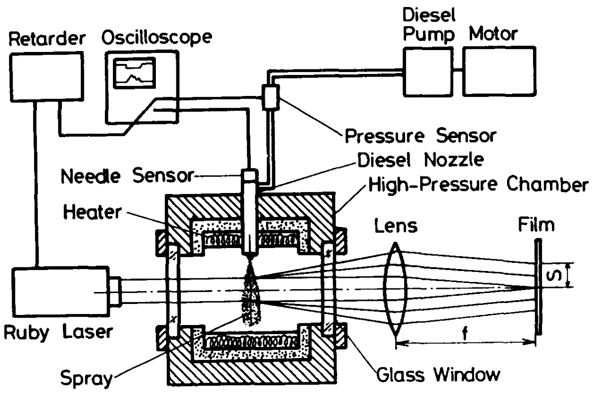


Fig. 1 Experimental apparatus

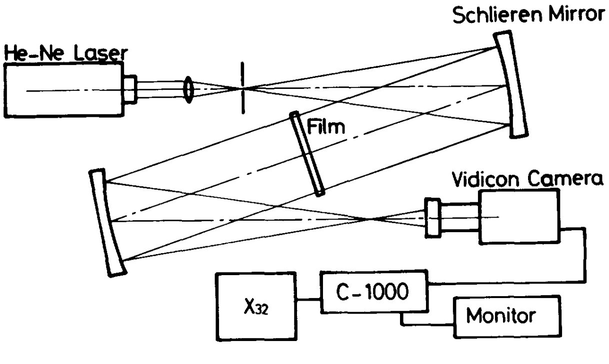


Fig. 2 Optical arrangement for measuring exposed film density

film was illuminated by a coherent and plain intensity light from a He-Ne laser. Light intensity corresponding to the exposed film density of the diffraction image was accepted by a vidicon camera. Figure 3 shows the flow chart of the procedure used to obtain the Sauter mean diameter of a spray. The procedure was started from linearization of exposed density data by the standard density given by the gray scale. The relative intensity of the diffracted light was computed by normalizing the original data. Relative light energy distribution along the S-direction shown in Fig. 1 was obtained. It was divided into 15 groups according to the S-direction for comparison with computed relative light energies derived from an assumed volumetric size distribution of a spray. The least-squares estimating method was used to find the best energy distribution determining the volumetric distribution function of a spray. The Sauter mean diameter and other spray characteristics were derived from the Rosin-Rammler distribution function obtained by this procedure.

2. 3 Accuracy of measuring method

Two groups of polystyrene particles and a paint spray were dispersed on glass plates and were used as test samples for this measuring technique. The Sauter mean diameters and size distributions of these three samples were determined by direct measurement of particle diameters from microphotographs of the samples. The Sauter mean diameter of the relatively large polystyrene particle group was 111.5 μm, and that for the smaller group was 56.0 μm. The Sauter mean diameter of the paint spray was 15.6 μm. The diffracted light energy distributions obtained by this optical system were compared with the energy distributions theoretically derived from size distributions measured photographically. Both energy distributions are comparativly shown in Figs. 4(a), 4(b) and 4(c). From the theory of Fraunhofer diffraction, it is known that a sample which has a smaller mean diameter produces an energy distribution with a peak

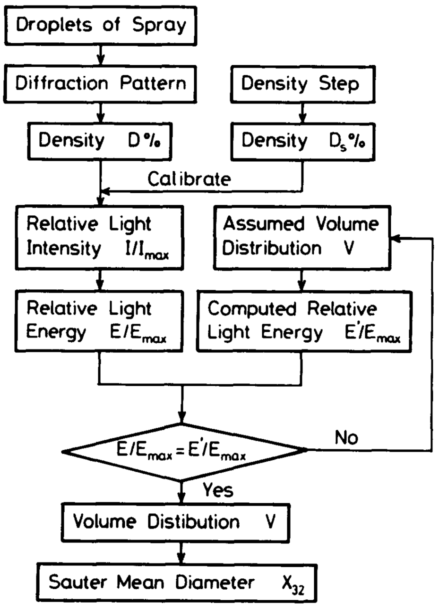
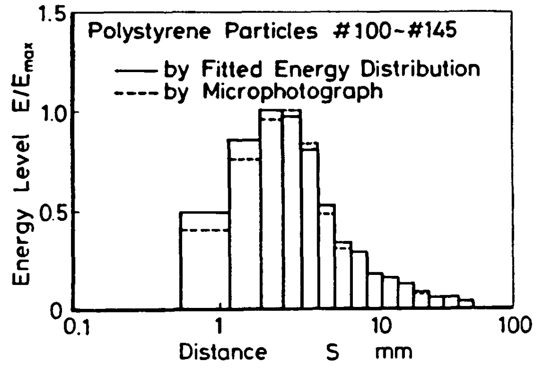
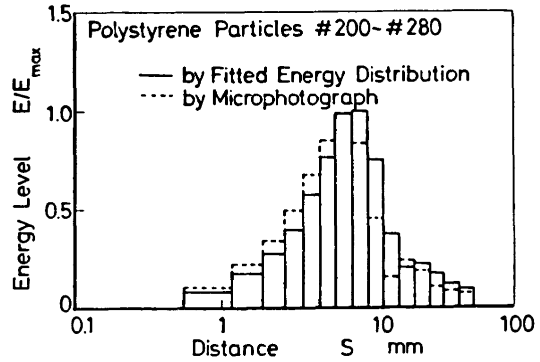


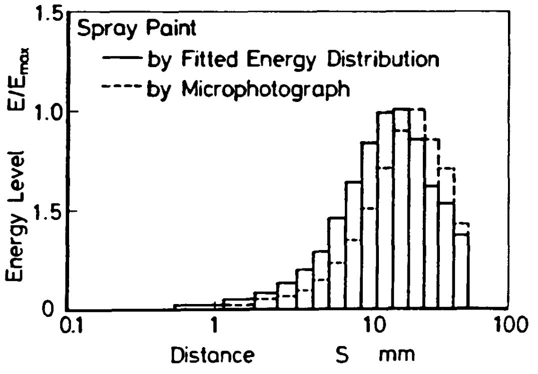
Fig. 3 Flow chart of the data process for obtaining the Sauter mean diameter



(a) Polystyrene particles (#100-#145)



(b) Polystyrene particles (#200-#280)



(c) Spray paint

Fig. 4 Energy distribution of Fraunhofer light
(a) Polystryene particles (# 100-# 145)
(b) Polystyrene particles (# 200-# 280)

further away from the optical center (S-direction on a film). Discrepancies of the peak positions and the distributions themselves in each figure were minimal, and this fact also showed the appropriateness of this measuring method. Figure 5 shows good agreement between three Sauter mean diameters obtained by different methods. The first one was measured photographically, the second was obtained by this method, and the last was measured by a conventional size analyzer (Malvern Ltd. ST-1800) which was based on the same Fraunhofer diffraction theory.

2.4 Error caused by an elevated-temperature and-pressure environment

The Fraunhofer diffraction system was not the only optical measurement system affected by optical disturbances and light noise emitted from the environment. Therefore, errors caused by these factors had to be estimated to obtain optical information with sufficient accuracy. Especially, the vessel in which temperature and pressure were elevated emitted a lot of thermal and optical noise distorting the optical path and disturbing the diffracted light. For example, when a steel plate that had a single small hole of 210-μm diameter was placed in the high-temperature and-pressure vessel, an optical center spot appeared on the film and moved irregularly. The diffraction image was distorted by a density fluctuation in the vessel. Therefore, in the next step of this work, the effects of optical disturbance caused by elevated temperature and pressure were investigated.

The effects of a high-temperature and-pressure environment on a laser beam and diffracted light were investigated in the following two cases.

(a) A laser beam was directed through a high-temperature and-pressure vessel and diffracted by particles.

(b) Laser light was diffracted by particles before being directed through a high-temperature and-pressure vessel.

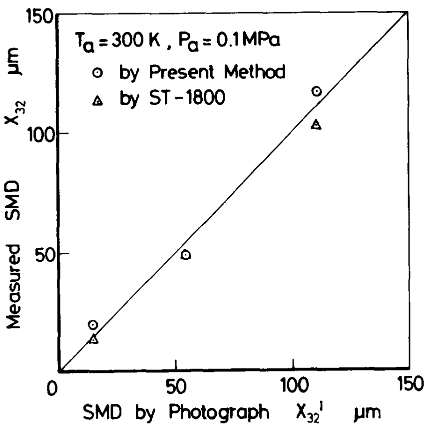


Fig. 5 Comparison of the Sauter mean diameter

An optical arrangement from estimating error caused by optical disturbance in case (b) was set up as shown in Fig. 6. The comparison of Fraunhofer images in both cases indicated that the distortion of the Fraunhofer diffracted light image produced in case (b) was more serious than that in case (a). It is considered that the diffracted light was dispersed throughout a wide angle and suffered from optical disturbance more seriously than a single beam. The Sauter mean diameters obtained from diffracted light passed through an atmospheric environment and that passed through a high-temperature and-pressure environment were compared and are shown in Fig. 7. There was no significant difference between these two cases. This means that the distortions of diffraction pattern from individual drops in a spray still existed, but in the summarized diffraction pattern from the spray, these distortions were canceled by each other.

3. Measuring Location in a Spray

Regarding a transient spray such as a diesel spray, the characteristics change with elapsed time

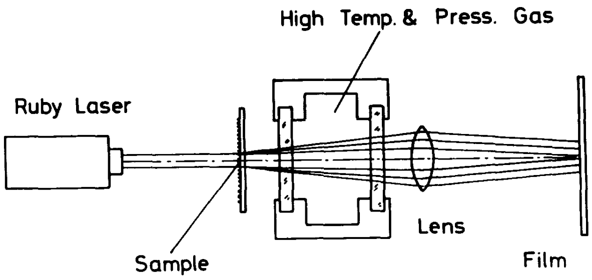


Fig. 6 Arrangement for evaluating the effect of optical disturbance

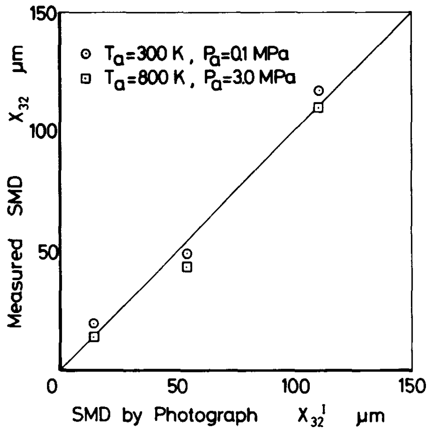


Fig. 7 Effect of optical disturbance caused by an elevated temperature and pressure on the Sauter mean diameter of particles

and location in the spray. To allow a discussion of the characteristics of moving sprays, the time and location for measurement were selected carefully. In this report, time t was the time interval between injection start and a flash of the laser, and length L_h indicated the axial distance between the nozzle and the measuring location. They were selected to determine a particular measuring condition. Figure 8 shows a demonstration photograph of a spray illuminated by the pulsed laser. The spray was injected at the ambient gas temperature of 300 K. The laser intersected the spray center axis 60 mm downstream of the nozzle. A portion of the spray illuminated by the laser formed the measuring volume for drop size distribution.

The spray was considered to be distributed concentrically around the spray axis, and the size distribution for drops near the spray axis might differ from that for drops in the peripheral region of the spray. This difference was investigated at the location 60 mm downstream from the nozzle. Figure 9 shows the measured energy distributions scattered by three groups of drops at different radial positions shown by R in the figure. The flash timing of this measurement was fixed at 3.5 milliseconds after the start of injection. The coordinate S is the radial distance from the center of the Fraunhofer diffraction image recorded on the film. The Fraunhofer diffraction light scattered from a group of small particles is concentrated in a larger radial location than the location of the scattered light from larger drops. Thus the radial energy distribution of the Fraunhofer light can reveal the drop size distribution. There were no significant differences between the energy distributions measured at $R=0$ mm or $R=1.5$ mm. Since the laser beam diameter was 6 mm, the sampling volumes of these two conditions partially overlapped. However, the energy distribution measured at $R=4.5$ mm shows a different pattern from the two former cases. It had two energy peaks corresponding to smaller and larger sizes of drops. This means the drops in the periphery

Fig. 8 Spray illuminated by a flash of the pulsed ruby laser

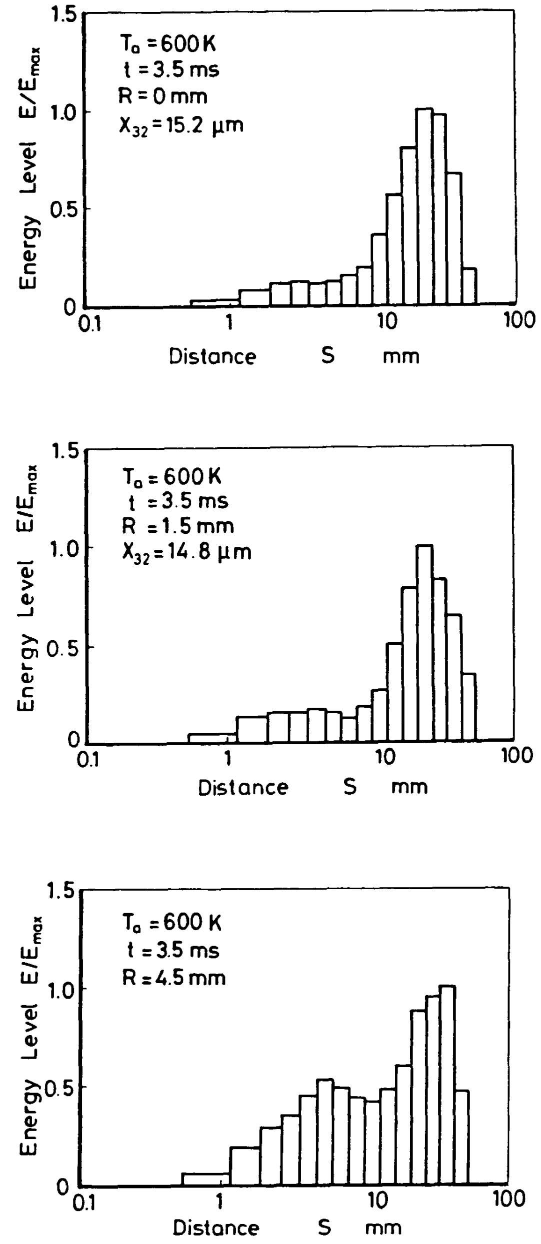


Fig. 9 Energy distributions of the image taken from different radial positions of a spray

of the spray had somewhat different size distributions. The drop number density around the spray axis was far higher than that in the periphery of the spray. Considering the number density and similarity of the energy distributions between $R=0$ and 1.5 mm, the standard sampling position used for the study of spray evaporation was fixed on the axis of the spray.

4. The Sauter Mean Diameter of a Nonvaporizing Spray

The spray tip penetration of a diesel spray is greatly affected by the presure of the surroundings into which the spray is injected. Since tip penetration decreases with an increase in the pressure, the Sauter mean diameters measured at fixed positions and fixed timing included the characteristics dependent upon local positions in sprays. In order to extract the net effect of the ambient pressure on the Sauter mean diameter, the timing of the laser was fixed such that the spray tip just reached 100 mm, with the measuring location fixed at 60 mm from the nozzle. This measurement location is illustrated in Fig. 10. Flash timings of the ruby laser differed depending on the penetration of sprays injected into different ambient pressures. However, the measurement locations were in the same portions of the sprays.

The Sauter mean diameters of nonvaporizing sprays are summarized in Fig. 11. The measured results using the instrument supplied by Malvern Ltd. (ST-1800) are also plotted in the figure. The Sauter mean diameter increased with an increase in the surrounding pressure and density. This increase in the Sauter mean diameter and its cause have been reported by the authors in previous papers(18),(19).

5. Sauter Mean Diameter of a Vaporizing Spray

5.1 Effect of ambient temperature

In order to extract the temperature effect on an evaporating spray, the ambient pressure should be changed to maintain a constant ambient gas density even with the effect of the temperature. This procedure is needed to remove the pressure effect on the diameter change shown in Fig. 11. In this study, a temperature of 800 K and a pressure of 3.0 MPa were chosen as the standard condition. When the temperature was changed from the above conditions, the pressure was also changed to keep the ambient gas density of 12.5 kg/m^3, corresponding to the gas density at the standard condition.

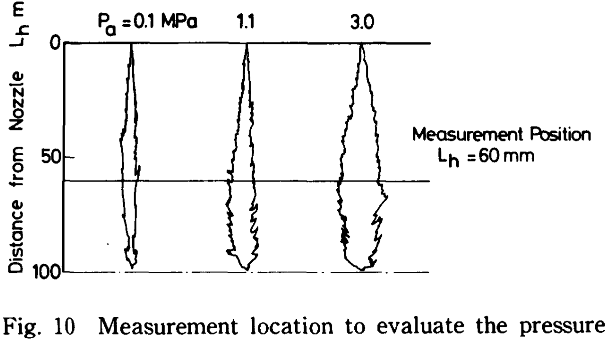


Fig. 10 Measurement location to evaluate the pressure effect on the Sauter mean diameter

Figure 12 shows an example of a vaporizing diesel spray in elevated-temperature-and-pressure sur-

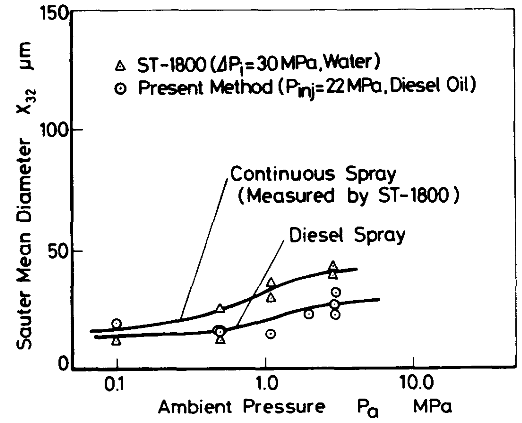


Fig. 11 Effect of the pressure on the Sauter mean diameter

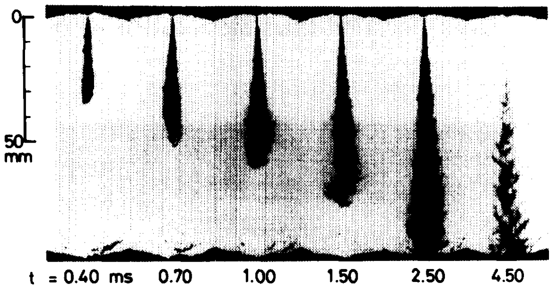


Fig. 12 Photographs of diesel sprays at different elapsed times from an injection

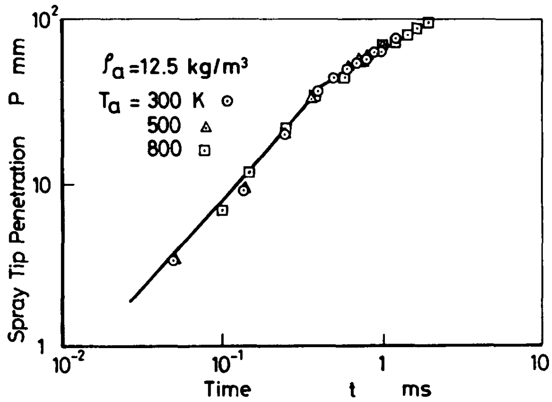


Fig. 13 Tip penetrations of sprays injected at different temperature environments

roundings. The temperature was 500 K, and the density of the ambient gas was adjusted to 12.5 kg/m^3. The tip penetrations measured from photographs of sprays at different ambient temperatures are summarized in Fig. 13. Since the ambient densities of different temperature conditions were adjusted to 12.5 kg/m^3, the tip penetrations were in agreement with each other. The Sauter mean diameters measured from different sprays but at a fixed timing and in the same measurement location gave accurate enough results to enable a comparison of the temperature effect on the diameter change. Figure 14 shows the relative position between the measurement location and a spray at various flash timings. Since the measurement location was fixed at 60 mm away from the nozzle, the Sauter mean diameters at different portions of a spray could be measured by changing the flash timing. For example, a flash timing of 1.0 millisecond gave the Sauter mean diameter of the leading edge of a spray. Laser flash timings of 2.5 and 4.5 milliseconds gave the Sauter mean diameter of the main body and tail of the spray, respectively.

Figure 15 shows the Sauter mean diameters of the sprays at different flash timings. The Sauter mean diameters were almost constant when the ambient temperature was under 500 K. When the temperature increased beyond 500 K, the Sauter mean diameter increased and reached a maximum at about 700 K. It then decreased with a further increase of the temperature.

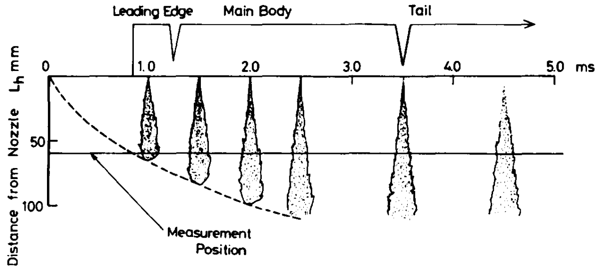


Fig. 14 Measurement position and spray

This diameter change is explained as follows. The drops which have relatively small diameters vaporize and vanish in the early stage of the spray vaporization process. However, relatively large drops in the spray remain through the early stage, keeping their diameter unchanged, because they need a long heat-up time to start vaporizing. After this time has elapsed, the larger drops may also vaporize. Furthermore, the vaporizing rate of drops increases with an increase of the ambient pressure. With the combined effects of the above phenomena, the Sauter mean diameter measured at a temperature of under less than 700 K was increased by the vaporization of the smaller drops in the spray, and the diameter measured at a temperature above 700 K was decreased by the vaporization of the larger drops in the spray. Even if the flash timing was greatly changed, the same tendency was observed. However, it was observed more clearly in the leading edge of the spray. When the flash timing was 1.0 millisecond, at which the spray tip reached about 70 mm, the measured result was considered to be the Sauter mean diameter in the spray tip. However, the result obtained from the measurement at 4.5 milliseconds was the Sauter mean diameter in the spray tail. Regarding the nature of the spray penetration, the spray tip was always exposed in fresh air of high temperature, and it was considered that the effect of the temperature on the evaporation process appeared strongly in the tip.

5. 2 Axial distribution of the Sauter mean diameter

In order to clarify the internal structure of a vaporizing diesel spray, the Sauter mean diameter

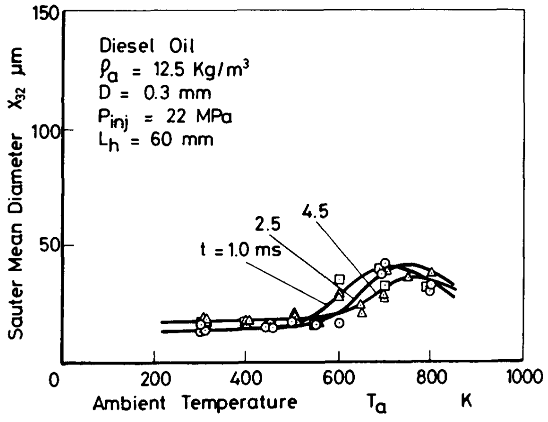


Fig. 15 Effect of ambient temperature on the Sauter mean diameter

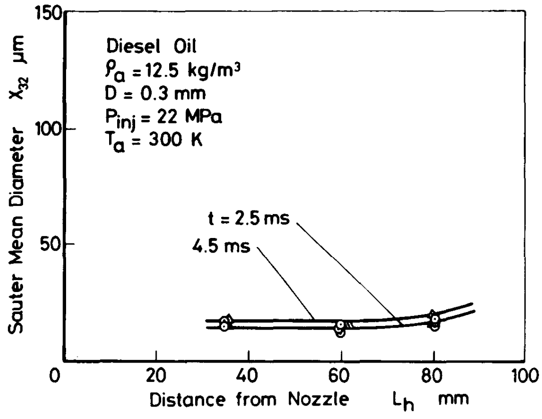


Fig. 16 Axial distribution of the Sauter mean diameter at 300 K

was measured at three axial locations. Figure 16 shows the Sauter mean diameter of a diesel spray vaporizing in the vessel of 300 K and 12.5 kg/m^3. The flash timings were 2.5 milliseconds and 4.5 milliseconds after the start of injection. Since the temperature of 300 K was far below the boiling temperature of the diesel fuel, the Sauter mean diameter did not change as time elapsed after injection. For the same reason, the tendency of the diameter to increase along the spray axis was no be clearly observed. The Sauter mean diameter of the spray appeared to be about 16 μm at any location in the spray.

The Sauter mean diameter of the vaporizing spray in a surrouding enviroment at 600 K is shown in Fig. 17. The Sauter mean diameter increased along the spray axis. It reached a maximum, subsequently decreasing at the measurement location of 80 mm. This diameter change was also considered to be due to the high rate of vaporization of the smaller drops in the spray.

When the ambient temperature increased to 800 K, the Sauter mean diameter showed a tendency to decrease along the spray axis as shown in Fig. 18. Due to the high temperature of the surroundings, vaporization of the smaller drops was almost finished before the first measuring location at 35 mm. Thus, the decreasing tendency of the Sauter mean diameter in this figure was mainly caused by the slow vaporization process of the larger drops in the spray.

Figure 19 shows the summary of the previous three figures. The sampling timing was 4.5 milliseconds after injection. The increasing and decreasing tendencies of the Sauter mean diameter were only observed at the intermediate temperature indicated at 600 K. It was presumed that the maximum location of the Sauter mean diameter moved toward the nozzle, and this maximum value increased with an increase of the temperature.

5.3 Effect of fuel property

Figure 20 shows the measured results of the Sauter mean diameters of an n-heptane spray under various temperature conditions. The Sauter mean diameter increased and reached the maximum as mentioned before. The results at 1.3 milliseconds are the Sauter mean diameters near the spray tips. The diameter change in this location appeared more distinctly than did the change at 2.1 milliseconds. It was also explained by a strong mixing effect with fresh surroundings, as mentioned before. The effect of the fuel property on the vaporization process was studied by comparing the Sauter mean diameters of diesel fuel and n-heptane sprays. Figure 21 shows the Sauter mean diameter of the sprays of both fuels. The temperatures at which the Sauter mean diameter reached maximum were different for the two fuels. The maximum Sauter mean diameter of the n-heptane appeared at a lower temperature than did that of the diesel fuel. Moreover, its maximum value was lower

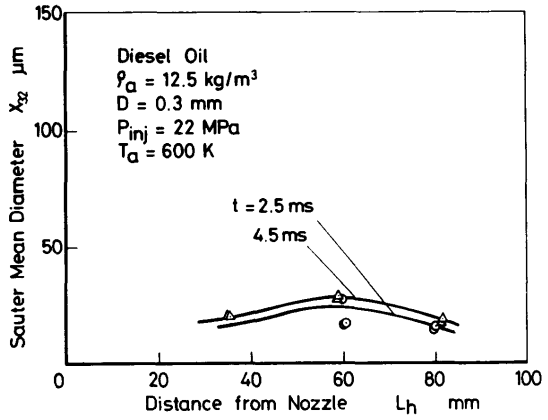


Fig. 17 Axial distribution of the Sauter mean diameter at 600 K

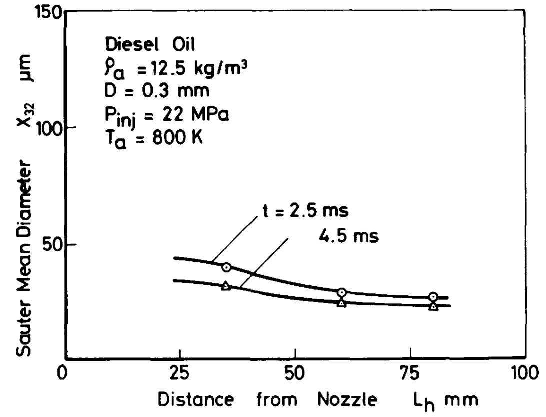


Fig. 18 Axial distribution of the Sauter mean diameter at 800 K

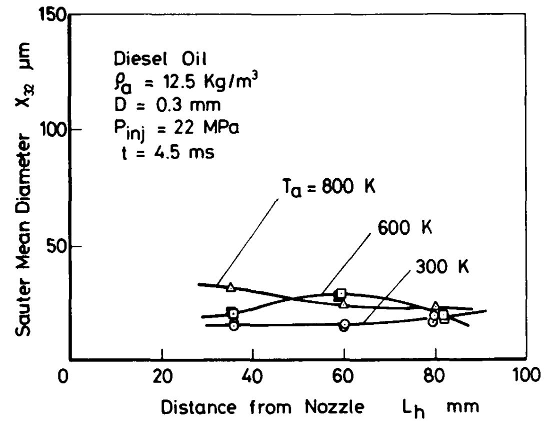


Fig. 19 Axial distribution of the Sauter mean diameter after the end of injection

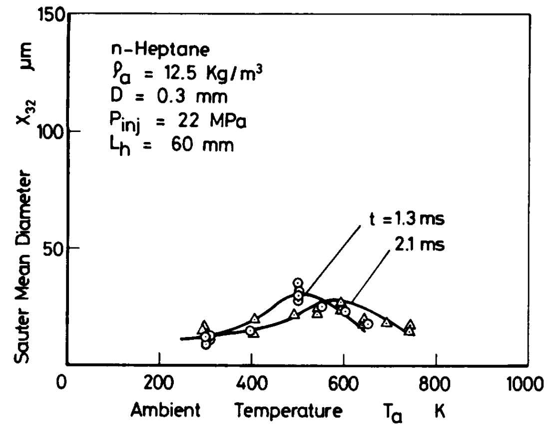


Fig. 20 The Sauter mean diameter of a vaporizing n-heptane spray

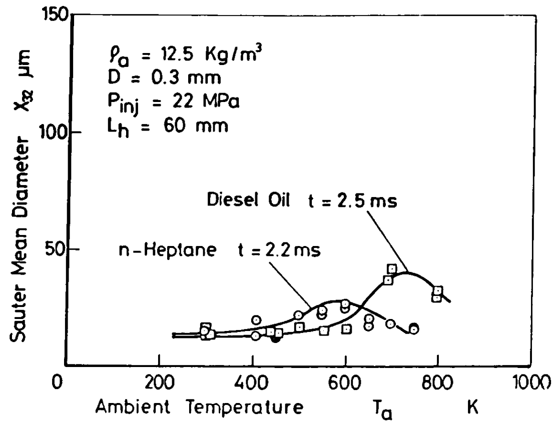


Fig. 21 Effect of fuel property on the Sauter mean diameters of vaporizing sprays

than that of the diesel fuel.

6. Conclusions

The Sauter mean diameter of a vaporizing diesel spray could be measured by the Fraunhofer diffraction method under the condition of elevated temperature and pressure. The measured results revealed the following.

(1) A new measurement system of the Sauter mean diameter for a transient spray was established. Even if a spray vaporized in a high-temperature and-pressure vessel, the Fraunhofer diffraction image was obtained and could be analyzed directly to obtain the Sauter mean diameter.

(2) The Sauter mean diameter of a diesel spray increased with an increase of the pressure of the surroundings.

(3) The effect of the temperature on the Sauter mean diameter appeared strongly at the portion of the spray tip.

(4) The Sauter mean diameter of a vaporizing spray changed with elapsed time. It increased and reached a maximum in the middle stage of the vaporization, then decreased in the final stages.

(5) The location in which the maximum diameter appeared shifted from the spray tip to the nozzle with an increase of the temperature and an increase of the elapsed time.

(6) The change of the Sauter mean diameter with vaporization more clearly occurred for diesel fuel than for n-heptane, which has a lower boiling temperature than diesel fuel.

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