A Laser Diagnostic Technique for Sauter Mean Diameter of Fuel Oil Sprays

Hiroyuki Hiroyasu and Masataka Arai
Department of Mechanical Engineering
Hiroshima University*

Tsugio Kishi
Mitsubishi Heavy Industries, Ltd.**

Abstract

A laser diffraction system was used to obtain the history of the Sauter mean diameter of an evaporating fuel spray.

The errors due to the characteristic properties of the laser diffraction method were examined by using many kinds of sprays. Then, the application procedure was established by using a micro-computer system. The sectional Sauter mean diameter was introduced to examine the overall evaporation rate of a spray in hot air. The Sauter mean diameter of gasoline, kerosene and heavy oil sprays were measured. The Sauter mean diameter of an evaporating spray increased once and decreased at the end of the evaporation.

1. Introduction

Evaporation rate of spray and time-resolved Sauter mean diameter of evaporating spray are the controlling factors which determine a combustion rate of a spray and the characteristics of its flame. To predict the spray combustion phenomena, we wanted to find the evaporation rate of an individual droplet in a burning spray. But due to the difficulties of measuring a droplet size in a burning spray and a statistical analysis of a droplet size distribution of an overall spray, we cannot obtain an evaporation rate of a fuel spray in a burning state or in a hot stream. Therefore the knowledge of the spray evaporation was first supplied by the measurement of the volumetric evaporation rate of a spray in a hot stream1)-3). Since a lack of knowledge of a droplet size distribution cannot be derived from a volumetric evaporation rate, it can not predict a spray combustion phenomena.

In recent years, the new laser diagnostic technique which is called the laser diffraction techniques was developed4)-7). The purposes of this report are to present one of the application technique of a laser diffraction system (ST-1800 particle analyzer) to an evaporating fuel oil spray, and to present the method of measuring a sectional Sauter mean diameter which presents an average Sauter mean diameter at any sectional area of a spray. Next, a time-resolved Sauter mean diameter of an evaporating spray was studied in fuel oil sprays.

2. Application of a laser diffraction system to a fuel oil spray

2.1 Laser diffraction system

An optical technique which is based on the Fraunhofer diffraction makes the on-line measurement of particle size distribution possible. When a spherical particle is illuminated by a parallel beam of monochromatic coherent light, a diffraction pattern is formed, super-imposed on the geometrical image, this pattern being large compared with the image. The first diffraction angle on which 84% of the diffraction light is gathered, is expressed as follows:

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* Shitami, Saijo, Higashi-Hiroshima, Hiroshima, 724
  TEL. 0824 (22) 7111

** Akunoura, Nagasaki, 850
  TEL. 0958 (61) 2111

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\[ \theta = \tan^{-1} \left( \frac{1.22 \lambda}{X} \right) \]  

(1)

where: \( \theta \) = diffraction angle of the first peak  
\( \lambda \) = wave length of monochromatic and coherent light  
\( X \) = diameter of a particle

If a lens is placed in the light path after the particle and screen placed at the focal plane, then undiffracted light is focussed to a point on the axis and diffracted light forms a pattern or rings around the central spot. Movement of the particle does not cause movement of the diffraction pattern, since light diffracted at angle \( \theta \) will give the same radial displacement in the focal plane irrespective of the particles' position in the illumination beam. The 'far field' diffraction pattern thus produced is known as a Fraunhofer diffraction pattern.

If, instead of a single particle, we have a collection of particles of different sizes, then the diffraction light from these particles is the sum of the contribution from individual particles. If a detector is used which is divided into a set of circular rings, then each of these rings will define a characteristic particle size. In the practical approach, the Rosin-Rammler distribution is first assumed as a particle size distribution and the pattern of the diffracted light from assumed particles is calculated. Next, the comparison of the assumed diffracted pattern and measured diffracted pattern is made. The most fitting Rosin-Rammler equation is defined by the least square estimating method by reiterating the above procedure.

The measuring system used in this work is shown in Fig. 1. The monochromatic and coherent light of which the wave length was 0.6328 \( \mu \)m and power was 2mW, was radiated by the He-Ne laser. The laser beam was expanded by the beam expander to a parallel laser beam of which the diameter was about 6 mm and illuminated spray particles. The focussing length of a fourier transform lens was 300 mm. The diffract light was detected by the multi-element photo detector. The detected signal was analyzed by the signal processor 1 (DEC, PDP-8/A) according to the program developed by Malvern Instrument Ltd. The signal processor 2 (HP, System 45S) was used to obtain a Sauter mean diameter and further knowledge of a spray size distribution mentioned later. The theory and detail processes of the laser diffraction method have already been reported by the pioneers in this field.

2. 2 Fitting error of a distribution curve

It was considered that there were two different error sources in a measuring system used in this work. One was a fitting error of a Rosin-Rammler distribution equation, and the other was an error due to multi-diffraction by particles which were spatially dispersed in the laser path.

In the routine work developed by Malvern Instruments Ltd. for ST-1800 particle analyzer, the following Rosin-Rammler volumetric distribution function was used:

\[ \frac{1}{\nu} \frac{d\nu}{dX} = \beta \left( \frac{X}{X_p} \right)^{\beta-1} \exp \left\{ -\left( \frac{X}{X_p} \right)^\beta \right\} \]  

(2)

where:  
\( \nu \) = volume of particles  
\( X \) = diameter of particle  
\( X_p \) = 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 particles are less than \( X_p \)  
\( \beta \) = measure of the spread of the size distribution

The fitting error of the Rosin-Rammler function to a spray distribution was tested first. To avoid a multi-diffraction by the particles, the particles which were disposed two-dimensionally on a glass plate were used. The used particles were glass beads which were relatively mono-disperse particles and paint particles which were sprayed a far distance from a glass plate and have almost the same size distribution.
as a fuel oil spray. Figure 2 shows the comparison between the Rosin-Rammler distribution curves obtained by ST-1800 particle analyzer and the distribution curves obtained by the micro-photographs of particles. The fitting error is larger for the glass beads than for the paint particles. It was considered that the distribution of the glass beads was more monodisperse than the distribution of the paint particles and the analyzing program of ST-1800 was developed favorably for poly-disperse particles.

The physical meaning of the Sauter mean diameter \( \bar{X}_{32} \) is more directly connected with an evaporating phenomena of a spray than \( X_p \) which was introduced as a characteristic diameter in the Rosin-Rammler equation. Therefore, in this work the Sauter mean diameter \( \bar{X}_{32} \) was printed out as the final output of the particle analyzer. The relation between \( \bar{X}_{32} \) and \( X_p \) was obtained by the definition of the Sauter mean diameter and the Rosin-Rammler equation:

\[
\bar{X}_{32} = \frac{X_p}{\Gamma(\beta-1)/\beta} \tag{3}
\]

where: \( \Gamma = \) gamma function of \( \beta \)

Equation (3) was only accurate if the particles were distributed from an infinitely small size to an infinitely large size. But in a spray, there were lower and upper limits of the droplet diameter. Then the Sauter mean diameter of a spray had to be obtained as follows:

\[
\bar{X}_{32} = \frac{\int X_b X^3 dN}{\int X_b X^2 dN} \frac{\int X_a X^3 dN}{\int X_a X^2 dN} \tag{4}
\]

where: \( X_a = \) lower limit of diameter
\( X_b = \) upper limit of diameter
\( n = \) number of droplets or particles

If the size distribution of \( X \) was expressed as the Rosin-Rammler equation, there was some difference in the Sauter mean diameters obtained by the equations (3) and (4). For example, \( X_p = 40 \mu m \) and \( \beta = 1.5 \) in the Rosin-Rammler equation and the lower and the upper limits of diameter were 5.7 \( \mu m \) and 562.9 \( \mu m \) according to the arrangement of the multi-detector shown in Fig. 1. The Sauter mean diameter obtained from equation (3) was 14.9 \( \mu m \) but 24.5 \( \mu m \) was obtained by equation (4). It was considered that the difference was due less to the weight of the smaller size particles than \( X_a \). Therefore in this work, the Sauter mean diameter obtained by equation (4) was used in the further analyses.

Table 1 shows the \( X_p, \beta \) and two kinds of \( \bar{X}_{32} \) of the glass beads and paint particles which were used in Fig. 1.

### 2. 3 Error due to a multi-diffraction

The error due to multi-diffraction was intrinsically unavoidable as long as a spray was being dispersed spatially. The experimental apparatus used for the investigation of a multi-diffraction is shown in Fig. 3. The main apparatus consisted of a throat (2) which controlled a flow rate of glass beads, stratified nets (3) for making uniform flow of glass beads and one pair of shutter (4) to control a width of the glass beads flow which was illuminated by a laser beam.

|             | Glass beads | Paint particles |
|-------------|-------------|----------------|
| \( X_{32} \) by micro-photograph | 99.1 \( \mu m \) | 39.8 \( \mu m \) |
| \( X_p \) | 102 \( \mu m \) | 56 \( \mu m \) |
| \( \beta \) | 8.6 | 2.1 |
| \( X_{32} \) by the equation (3) | 94.4 \( \mu m \) | 33.1 \( \mu m \) |
| \( X_{32} \) by the equation (4) | 94.7 \( \mu m \) | 36.3 \( \mu m \) |
Figure 4 shows the effect of the flow rate of glass beads on the measured Sauter mean diameter. $X_{\text{Sauter}}^{d_2}$ shows a Sauter mean diameter obtained by the equation (4). At the low flow rate, the Sauter mean diameter was consisted with the results which were obtained by measuring the glass beads on the glass plate. Therefore at the low flow rate, the effect of the multi-diffraction could be neglected. It was clear that by increasing the flow rate, the multi-diffraction effect increased and the Sauter mean diameter decreased. If the multi-diffraction occurred the diffraction angle always increased and it meant that there were some more small particles in the laser path. Other experimental results are shown in Fig. 5. In this figure, $M_g = \text{const.}$ means that the mass flow rate per unit area is constant. And $S_g = \text{const.}$ means that the total mass flow rate measured in the condition of the slit width $t = 30\, \text{mm}$ is $5.53\, \text{mg/} (\text{s}\cdot\text{mm}^2)$ and the flow rate per unit area increases being in inverse ratio to the width of the slit. In other words, the total number of particles illuminated by the laser beam is constant. Decreasing the width of the slit, the Sauter mean diameter of $M_g=\text{const.}$ increased and at $t = 0$ it would consist with the results obtained on the glass plate. But the results of $S_g = \text{const.}$ showed almost the same value at any width of the slit. It was considered that if $S_g$ was constant, the effect of the multi-diffraction was the same and it was independent of the width of the slit.

The many kinds of air blast atomizers and pressure-type nozzles were used to make the other kind of spray to calibrate the laser diffraction method. Finally we concluded that the Sauter mean diameter which was obtained by this analyzer (ST-1800) with the slit for a fuel oil spray was about $30\%$ smaller than that obtained by the direct photograph method. Therefore, we used the signal processor (2) in Fig. 1 to correct the final data.

3. Sectional Sauter mean diameter of a spray

3.1 Measuring apparatus for fuel oil spray

The error due to the multi-diffraction should not be neglected to use this system to measure a fuel oil spray. The Sauter mean diameter of a fuel oil spray could only be calculated from
local Sauter mean diameters which could be measured by the laser diffraction method mentioned above. **Figure 6** shows the experimental apparatus used for the study of spray evaporation. This apparatus consisted of a wind tunnel, an air blast atomizer, a slit and the laser diffraction system. The atomizing condition was determined by flow rate of atomizing air $W_a$, flow rate of atomized liquid $W_l$ and air orifice diameter $D_a$.

### 3.2 Calculation of a sectional Sauter mean diameter

A local Sauter mean diameter and a droplet density were not constant in a spray. Then to know a sectional Sauter mean diameter which presented the overall Sauter mean diameter of droplets that existed in any sectional area of a spray, it was necessary to measure the distributions of the Sauter mean diameter and the droplet density in this sectional area of a spray. The droplet density of a spray at any location was calculated by the following equations:

$$\rho = \frac{S}{U}$$  \hspace{1cm} (5)

$$S = \frac{Q}{A}$$  \hspace{1cm} (6)

where: $\rho$ = droplet density, g/(m$^3$ air)  
$S$ = dispersion, g/(s-m$^2$)  
$U$ = velocity of droplet, m/s  
$A$ = sampling area, m$^2$  
$Q$ = sampled mass of droplet, g/s

A droplet in a spray had its own velocity which was different from another droplet. Since in a spray atomized by an air blast atomizer, the droplet velocity was almost the same as the atomizing air velocity. The gas velocity measured by a hot wire method was used as the droplet velocity in this study. The dispersion $S$ was calculated by a sampling area and sampled mass of droplets which were captured by an isokinetic sampling probe.

One of the results of the measured dispersions is shown in **Fig. 7**. The dispersion on the spray axis took the highest value and it decreased by increasing the axial distance from the atomizer. **Figures 8 and 9** show the dimensionless expression of the velocity and the dispersion at $L_h$ = 80 mm, 160 mm and 300 mm.
respectively. The solid lines were the calculated results obtained by the following Gortler's equations:

\[ \frac{U}{U_m} = \frac{1}{1 + 0.414 \left( \frac{R}{R_m} \sqrt{\frac{U_m}{U_m} - 1} \right)^2} \]  \hspace{1cm} (7)

\[ \frac{S}{S_m} = \frac{1}{1 + 0.414 \left( \frac{R}{R_m} \sqrt{\frac{S_m}{S_m} - 1} \right)^2} \]  \hspace{1cm} (8)

where: \( R \) = radial distance from a spray axis
Subscript \( m \) = spray axis
Subscript \( 1 \) = any position except a spray axis
\( R_{u,\frac{1}{2}}, R_{s,\frac{1}{2}}, R_{p,\frac{1}{2}} \) = radial distance where \( u \) or \( S \) or \( p \) took the half value of the maximum

The estimated distributions of the velocity and the dispersion fit well to the experimental results. Therefore, for the simplification and rapidity of the experimental procedure, equations (7) and (8) could be used instead of the full experiments. If these equations were adopted, the measuring positions of the velocity and the dispersion were reduced to two points, that is, the positions on the spray axis and one of the other points. Usually, the position where \( U \) or \( S \) took the half value of the \( U_m \) or \( S_m \) was used as the position 1 respectively. The droplet density was calculated using equations (7) and (8) or the experimental distributions of the velocity and the dispersion. The droplet density obtained from Figs. 8 and 9 are shown in Fig. 10. The estimated results expressed as the solid line also fit well to the calculating results based on the measured \( U \) and \( S \). Therefore, equations (7) and (8) were used in the following analysis.

The sectional Sauter mean diameter \( \bar{X}_{32} \) could be calculated by considering the droplet density, as follows.

\[ \bar{X}_{32} = \frac{\sum \sum X_i^3 \rho(R_i) \Delta n(X_i, R_i)}{\sum \sum X_i^2 \rho(R_i) \Delta n(X_i, R_i)} \]  \hspace{1cm} (9)

The outline of the calculating procedure is shown in Fig. 11. This procedure was programmed in the signal processor 2 in Fig. 1 as the routine work.

4. Sauter mean diameter of evaporating spray
4.1 Water spray

Sauter mean diameter of evaporating spray in a hot air stream was studied by the laser diffraction measuring system mentioned above. The effect of the ambient temperature \( T_a \) on the sectional Sauter mean diameter along the spray axis is shown in Fig. 12. The sectional Sauter mean diameter increased by increasing the axial distance from the atomizer. The effect of the ambient temperature on \( \bar{X}_{32} \) increased by increasing the ambient temperature. It was considered that the evaporation rate of every droplet increased by increasing the ambient temperature. According to the theoretical analysis studied by the authors, it was considered as follows: When the air temperature was high, the relatively small droplets in the spray evaporated quickly before the relatively large droplets in the spray being heated up to the beginning of the evaporation. There-
Velocity of droplets $U(R)$

Dispersion $S(R)$

Görtler eq.

Density of droplets $\rho(R)$

Weight of droplets $W(R)$

Rosin-Rammler distribution $X_p(R)$, $\beta(R)$

Weight Fraction $F(X_p,R)$

Fig. 11 The flow chart for calculating the sectional Sauter mean diameter

Fig. 12 Sectional Sauter mean diameter of water spray ($W_l = 2.5$ g/s)

Therefore the increment of the sectional Sauter mean diameter at $T_a = 250^\circ$C was larger than at $T_a = 20^\circ$C. Figure 13 shows another result. In this case, the flow rate of atomized water was lower than in Fig. 12. When the ambient temperature was $250^\circ$C, the sectional Sauter mean diameter increased from 26 $\mu$m up to 46 $\mu$m and it was suddenly impossible to measure because of almost all of the spray droplets evaporated completely.

4. 2 Fuel oil spray

The sectional Sauter mean diameters of an evaporating spray of fuel oils were very important to know for the spray combustion phenomena of these fuels. So in this study, gasoline, kerosene and heavy oil were chosen as the high, medium and low volatile fuel, respectively. Figure 14 shows the results of gasoline and kerosene spray at room temperature. The initial Sauter mean diameter of these sprays were almost the same. The sectional Sauter mean diameter of the kerosene spray was not changed along the spray axis, but that of the gasoline spray increased rapidly. Figure 15 shows the results of the heavy oil. In this case, the fuel temperature $T_f$ was $90^\circ$C because at room temperature the viscosity of heavy oil was too high to be atomized.

Figure 16 shows the effect of the ambient air temperature on the sectional Sauter mean diameter of the kerosene spray. When the temperature increased from the room temperature to $50^\circ$C, the tendency of the increment of $X_{32}$ along the spray axis increased, but this effect

Water

$W_a = 2.20$ g/s

$W_l = 0.60$ g/s

$D_a = 4.10$ mm

$T_a = 250^\circ$C

$150^\circ$C

$20^\circ$C

Fig. 13 Sectional Sauter mean diameter of water spray ($W_l = 0.6$ g/s)

Gasoline

$W_a = 2.06$ g/s

$W_l = 2.00$ g/s

$D_a = 3.90$ mm

$T_a = 15^\circ$C

Kerosene

$W_a = 2.20$ g/s

$W_l = 2.00$ g/s

$D_a = 4.10$ mm

$T_a = 15^\circ$C

Fig. 14 Sectional Sauter mean diameter of a gasoline spray and a kerosene spray
was not clear at temperatures higher than 50°C. In the condition of $T_a = 150°C$, the sectional Sauter mean diameter increased once but after some axial position it decreased.

5. Conclusions

The laser diffraction method developed by Malvern Instruments Ltd. was modified to measure the sectional Sauter mean diameters of sprays. The modified points and the experimental results are as follows:

1. The multi-diffraction effect of this system could not be avoided. Therefore, the some correction factors and the slit were used to measure the Sauter mean diameter of a fuel spray.

2. To know the sectional Sauter mean diameter of the spray, the theoretical analysis and the routine program for this analysis were made.

3. The distribution of the Sauter mean diameter of the fuel sprays was measured. The experimental results showed that the Sauter mean diameter in the evaporating spray increased and then decreased along the spray axis.

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