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Droplet Size Measurement of Liquid Atomization by Immersion Liquid Method
(Droplet Coalescence and Evaporation on the Immersion-Liquid Surface)

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Abstract
Some problems were investigated with the immersion liquid method, which is a basic technique to measure droplet diameters and their distributions in mist flow, and which is also adopted to confirm adequacy of the data obtained by a Phase-Doppler Particle Analyzer. The effect of droplet evaporation on droplet-measurement accuracy was experimentally investigated. Then, the effect of droplet coalescence on its accuracy was investigated under the experimental conditions which the effect of droplet evaporation can be diminished. On the basis of experiments conducted using water mist and silicone oil as the immersion liquid, the authors conclude that when the shutter opening period is shorter than the time it takes local droplet number per unit area to become the maximum value, it becomes possible to obtain the correct droplet size, since the droplet coalescence on the oil surface can be diminished. Moreover, it was found that no influence of the immersion liquid viscosity on the Sauter mean diameter can be seen at a short shutter opening period in which the effect of droplet coalescence can be neglected.
Keywords: immersion liquid method, droplet coalescence and evaporation, sauter mean diameter, shutter opening period, silicone-oil viscosity

1 Introduction
The liquid atomization is very important process and can be found in many industrial fields such as spray painting and cooling, producing powder metal in material processing, pharmaceutical products, powder productions and capsule technology in the food industry, and so on. Therefore it is important to understand of the property of liquid spray droplets produced by the liquid atomization is essential. The droplet characteristics include the mean droplet size and distributions of the spray droplets, the temporal development process and spatial flow rate distributions. An improvement of the droplet size measurement is highly expected in not only mechanical fields but also in a wide variety of fields because it is vital for improving its efficiency and performance to analyze various types of industrial equipment based on the liquid atomization.

Immersion liquid method, impression method, direct photography method and solidifying method have been reported as the droplet size measurement. Droplet size measurements using laser beam are also reported in these years. Although the non-contact optical method provides much information on droplet size measurement in a short time, it requires occasional confirmations and collections to ascertain the measurement accuracy. The immersion liquid method is the classic calibration for the optical method [1].

In the immersion liquid method, liquid droplets are captured onto an immersion liquid surface within a glass plate or a shallow vessel, and a microscope is used to obtain magnified photographs of the droplets in the immersion liquid for measurement of droplet size. This method is often used for the case where fuel or the like is sprayed out into an open space, since the method is cost-efficient and easy to use, and is one of the most fundamental, mechanical techniques to measure droplet sizes and their distributions. For instance, the method is used to measure droplets generated by swirl atomizers or rotating jets, ultrasonic vibrations, imitated disturbance waves, dispersed droplets in gas-liquid two phase flow [2].

Hiroyasu [3] and Kurabayashi [4], however, have raise arguments with measurement accuracy caused by droplet coalescence, evaporation and disintegration on the immersion liquid surface. Therefore it has been studied that the conditions of the immersion liquid, the effects of droplet coalescence, evaporation and disintegration on its surface and a fine droplet escape during inserting a collector. In most of the previous studies regarding measurement accuracy, however, cylindrical collectors with a rotating shutter utilized by Tanazawa [5] are used. No sliding shutter in which the shutter moves linearly is used to investigate the measurement accuracy.

In this study, droplet size measurement using the immersion liquid method with the linear collector is performed and silicone oil is used as the immersion liquid. The effects of droplet evaporation on the droplet-size measurement accuracy are presented. Then, the effects of droplet coalescence are demonstrated. The purpose of this study is to obtain the most suitable value of shutter opening period and silicone-oil viscosity.

2 Experimental Apparatus and Procedure
Figure 1 shows a schematic diagram of the experimental apparatus. Spray droplets generated by an ultrasonic humidifier (National, FE-05KYC) <1> were jetted into still air through a 4 mm diameter nozzle <2>. Downward liquid droplets generated from the nozzle are then captured by the sampling collector <3> which consists of 39 mm outer diameter. An aperture with a diameter of 4 mm <4> was drilled in an outer casing

<5> of cylindrical droplet sampling collector which is mounted a shutter <6> and a sampling rod <7> inside. The shutter <6> is connected to a weight <8> with a wire. As the stopper <9> is removed from the outer casing <5>, the shutter <6> moves to the right under the force of a spring <10>. When the aperture in the outer casing <4> matches up with the shutter aperture <11>, spray droplets passing through the circular aperture are captured in the sampling tank <12> (4 mm × 8 mm area and 1.5 mm depth) coated with silicone oil. The shutter opening period Ts is adjusted by the weight <8> and the spring <10> to demonstrate the effects of droplet coalescence and changed from 8 to 453 ms. The kinematic viscosity of the immersion liquid varied from 10^3 to 5×10^4 mm^2/s. Water and the silicone-oil temperatures are maintained at a definite temperature 298±2 K. At the same time, room temperature and humidity are controlled to be 298±2 K and higher than 65 %, respectively, by an air conditioner and the ultrasonic humidifier. The distance between the nozzle edge of the ultrasonic humidifier and the silicone-oil surface was set to be 80 mm. The nozzle was adjusted to coincide with the central axis of the hole in the collector. The droplet velocity at the collector was measured to be u_m = 9.0 m/s by a high-speed video camera (nac, HSV-400).

The 410×410 μm images of the spray droplets captured on the silicone-oil surface were captured, through the microscope <13> and CCD camera <14> mounted on the central axis of the nozzle, into the image processing system (ADS, PIP-4000) and calculated the mean diameter of the spray droplets: the Sauter mean diameter which is defined by

$$D_{32} = \frac{\sum N_i D_i^3}{\sum N_i D_i^2} \tag{1}$$

where D_i and N_i are the reference diameter and the number of captured droplets, respectively.

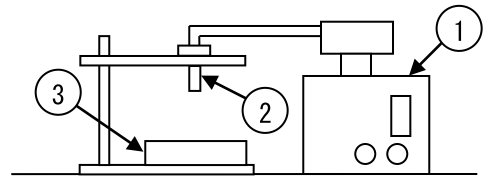
There are some uncertainties in calculating the mean value from the population besides the uncertainties of measurements. In this experiment, more than 2000 samplings under the same condition were captured in order to calculate the Sauter mean diameter by reference to the previous studies [5].

3 Experimental Results and Discussion

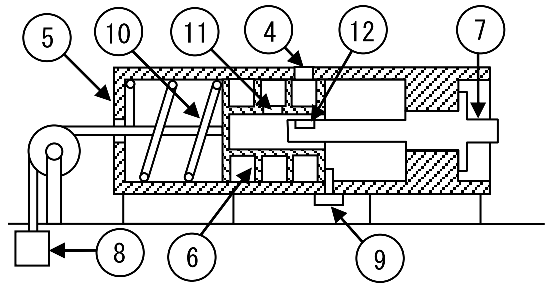
3.1 Effects of droplet evaporation on the droplet-size measurement accuracy

The liquid droplets may evaporate on the silicone-oil surface, since the collected droplets exit on the oil in our immersion liquid method. Therefore the effects of droplet evaporation on the droplet-size measurement accuracy were examined. In this section, an experiment was carried out in order to determine the suitable measurement conditions varying the shutter opening period Ts and the silicone-oil viscosity ν_T.

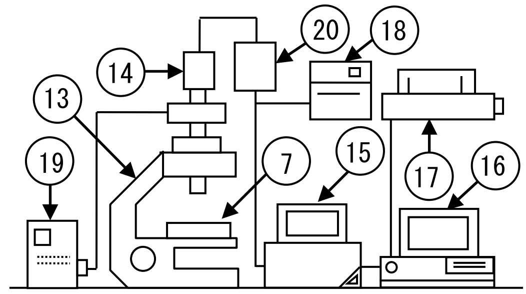
Figure 2 represents selected samples of the variations in the droplet number density N_i/N_0 (the ratio of the number of droplets in a certain time to the number of droplets when the first image was captured) with elapsed-time t_C from the first droplets image was captured.



(a) Sampling system



(b) Details of droplet sampling collector



(c) Droplet size measurement system

1 : Ultrasonic humidifier	11 : Shutter aperture
2 : Nozzle	12 : Sampling tank
3 : Droplet sampling collector	13 : Microscope
4 : Outer casing aperture	14 : CCD camera
5 : Outer casing	15 : Flexible image processor
6 : Shutter	16 : Desktop computer
7 : Sampling rod	17 : Printer
8 : Weight	18 : Graphic printer
9 : Stopper	19 : Light source
10 : Spring	20 : Video control unit

Fig. 1 Schematic diagram of experimental apparatus

Figure 2(a) shows the results in the case of the smallest of silicone-oil viscosity in this study. In the case of Ts = 76 ms, N_i/N_0 decreases up to 25 % at t_C = 30 s and the droplets disappears at t_C = 90 s. In other cases, the same trends can be seen in a qualitative manner. However at $Ts \geq 103$ ms the droplets exist up to $t_C \cong 90$ s. N_i/N_0 increases with ν_T in **Figs. 2**(b) and (c), although the same trends can be seen as that of **Fig. 2**(a). **Figure 2**(d) shows the results for the largest $\nu_T = 5\times10^4$ mm^2/s. The droplets exist on the oil surface up to t_C = 150 s at Ts = 200 ms. This is attributed to that the

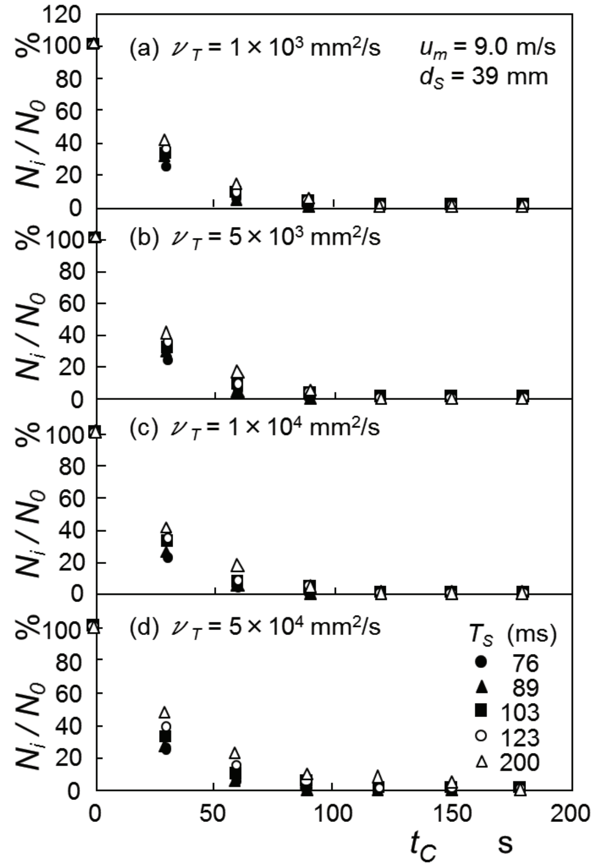


Fig. 2 Variations in droplet number density N_i/N_0 with elapsed-time t_C

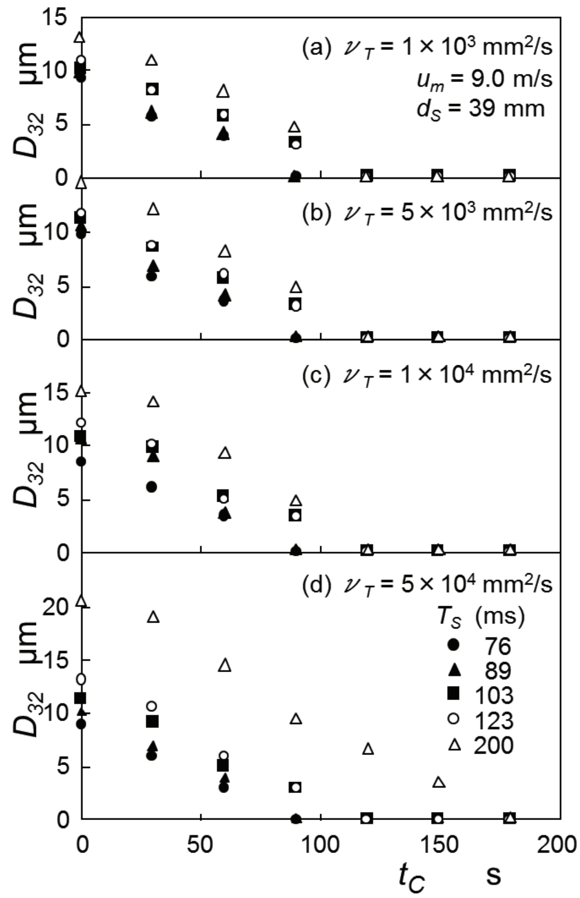


Fig. 3 Variations in Sauter mean diameter D_{32} with t_C

droplets take long time to evaporate because the droplets are large.

The droplet number density N_i/N_0 rapidly decreases as t_C increases. In addition, the value of N_i/N_0 increases with Ts and ν_T under the same ν_T and Ts, respectively.

Figure 3 shows selected samples of the variations in the Sauter mean diameter D_{32} with elapsed-time t_C, corresponding to the results in **Fig. 2**.

The Sauter mean diameter D_{32} at t_C =0 becomes large when Ts is set to be large value, and becomes small when t_C becomes large due to the evaporation on the silicone-oil surface for each ν_T. The value of D_{32} at t_C = 200 ms and ν_T = 5×10^4 mm^2/s gradually decreases compared to the other cases because of large droplets captured. This indicates that the smaller droplets are sensitive to evaporation than the larger ones and the evaporation is affected by the droplet size.

The both values of N_i/N_0 and D_{32} decrease as t_C increases, which implies the droplet evaporation on the silicone-oil surface. Therefore the effect of the droplet evaporation on the oil surface is one of vital factors. Then, t_C is selected not to exceed 3s in this study.

3.2 Effects of droplet coalescence on the droplet-size measurement accuracy

In general, the coalescence of liquid droplet decreases as the shutter opening period Ts decreases. However, in this method, one must capture as many liquid droplets as possible to maintain measurement accuracy and not lose measurement efficiency. So, it is important to grasp the most suitable value of local droplet number per unit area (the number of captured droplets per unit area which is calculated from the all sampling images) and the droplet area fraction (the ratio of area occupied by captured droplets to sampling image area). In this section, the effects of droplet coalescence on the silicone-oil surface were investigated by varying the shutter opening period Ts and the silicone-oil viscosity ν_T.

Figure 4 depicts the effects of the droplet area fraction A_F on the Sauter mean diameter D_{32} for various silicone-oil viscosity ν_T. While D_{32} is quasi constant 10 μm up to about A_F = 10 %, it increases rapidly at A_F > 10 %. Increasing A_F indicates the increasing number of captured droplets resulting from the long shutter opening period. In the case of A_F > 10 %, droplets are captured too many on the oil surface, so that the droplet coalescence occurs among droplets and increasing rate of A_F becomes suppressed, resulting in large D_{32} value. Tate reported that the droplet coalescence can be diminished if A_F is smaller than 5 % [6]. In this experimental study, D_{32} grows rapidly at A_F > 10 %. This difference between Tate's experiment and the results of this experiment can be caused by the difference of the keeping method of droplets. In Tate's experiment, droplets were inside the immersion liquid. On the other hand, the droplets exist on the oil surface in this experiment. The droplet coalescence occurs easily in Tate's experiment, since it is considered that the possibility of droplets float and move during submerging into the immersion liquid.

Figure 5 shows the influence of shutter opening period T_S on the droplet area fraction A_F. The similar trends can be seen in the results for different silicone-oil viscosity. In the case of $T_S \leq 103$ ms, A_F increases almost linearly with T_S, since the captured droplet number on the oil surface increases. However, the increasing rate of A_F diminishes as T_S increases at $T_S >$ 103 ms, which implies that droplet coalescence occurs among droplets on the oil surface.

Figure 6 explains the influence of T_S on D_{32} for various silicone-oil viscosity ν_T. While D_{32} value is almost constant to be 10 μm independently of silicone-oil viscosity ν_T for $T_S \leq 103$ ms, D_{32} increases quickly as T_S increases for $T_S > 103$ ms. This indicates that droplet coalescence on silicone-oil surface with the increasing number of captured droplets and T_S, which is supported by the results in **Figs. 4 and 5**. The precipitous increase of D_{32} as ν_T increases can be seen due to an increase in T_S. It is thought that its phenomenon occurs as ν_T increases, since droplets are kept for long time on the silicone-oil surface.

Droplet size distributions for T_S = 76 ms representing the case of a subtle influence of droplet coalescence, 103 ms representing the case of boundary and 453 ms representing the case of great influence of droplet coalescence are shown in **Fig. 7**. The numbers in the **Fig. 7** indicates the number of droplets for each size range of captured droplets. **Figure 7**(a) shows the case

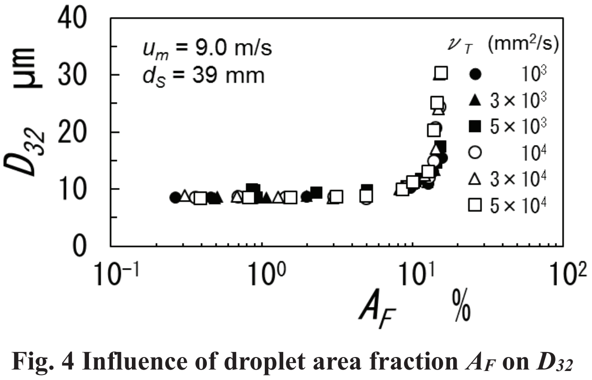


Fig. 4 Influence of droplet area fraction A_F on D_{32}

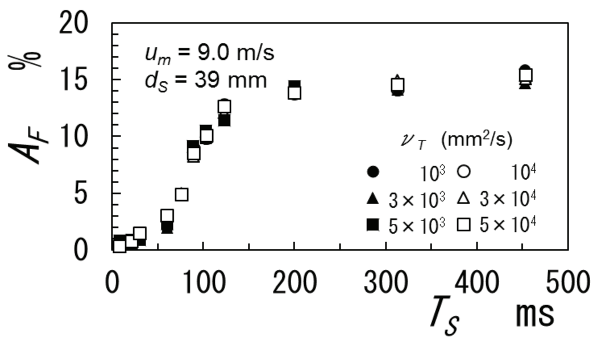


Fig. 5 Influence of shutter opening period T_S on A_F

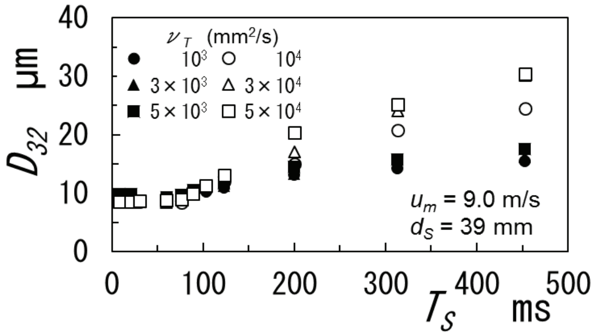


Fig. 6 Influence of T_S on D_{32}

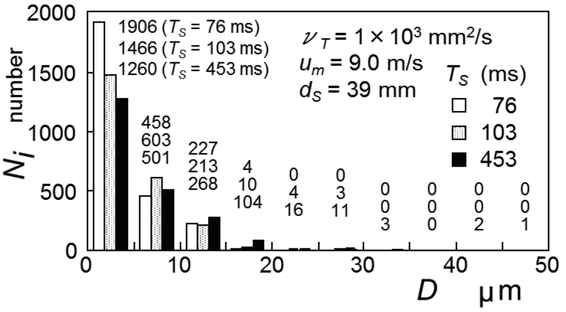
of the smallest silicone-oil viscosity $\nu_T = 10^3$ mm²/s. The only droplets smaller than 20 μm are captured at T_S = 76 ms. The most of the captured droplets consist of fine droplets with diameters smaller than 5 μm and the number of captured droplets decreases as the droplet size increases. The similar trends can be seen in the results for all the cases of T_S. However the maximum of the captured droplet size increases with T_S, for instance the maximum size is 30 μm at T_S = 103 ms and 50 μm at T_S = 453 ms. This indicates that the increase of T_S contributes to droplet coalescence. Although the similar trends can be seen in **Fig. 7**(b) for the large $\nu_T = 5\times10^4$ mm²/s, the number of large droplets increases compared to the results in **Fig. 7**(a), especially at large T_S. This result confirms the increasing number of captured droplets on the oil surface with T_S and the existence of droplet coalescence because droplets are kept for long time on its surface in the case of larger ν_T as mentioned in **Fig. 6**.

The droplet coalescence on the silicone-oil surface can be diminished if the shutter opening period T_S is short. However, it is important to determine the suitable value of the local droplet number per unit area δ_L in order to maintain the measurement accuracy and not lose measurement efficiency.

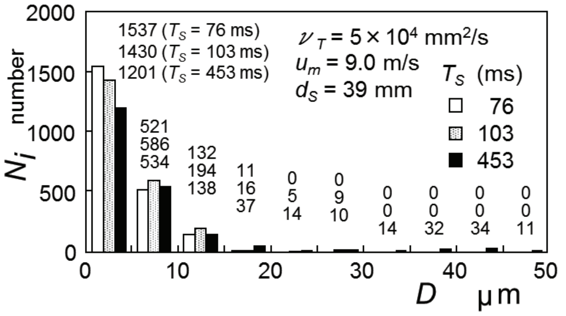
Figure 8 shows the variations in the local droplet number per unit area δ_L with the shutter opening period T_S. The value of δ_L increases linearly as increasing T_S and reaches the maximum value of $\delta_L \cong 3000$ at T_S = 103 ms. On the contrary, in the case of $T_S >$ 103 ms, the value of δ_L decreases as T_S increases. This suggests that the suitable shutter opening period T_S should be 103 ms for high measurement efficiency.

The variations in the Sauter mean diameter D_{32} with δ_L together with the results from other researchers are shown in **Fig. 9**. The value of D_{32} is almost constant up to $\delta_L \cong 3000$, while the value of D_{32} increases rapidly and δ_L decreases due to droplet coalescence at $\delta_L > 3000$. Therefore the droplet coalescence on the silicone-oil surface can be diminished, if the shutter opening period T_S is shorter than the time it takes for local droplet number per unit area δ_L to become the maximum value δ_L. The similar trends can be seen in the results of twin-fluid atomizer ($\delta_L > 30$) by Okada *et al.* [7] and the results of rotating nozzle atomizer ($\delta_L > 2$) by Kurabayashi [8]. As shown in **Fig. 9**, however, the maximum value of δ_L takes various values under the influence of the mean diameter of droplets generated from different atomizers. So, to maintain measurement accuracy and efficiency, the maximum value of δ_L for each mean diameter of the droplets must be determined in advance.

In this experiment, the suitable local droplet number per unit area δ_L should be under 3000 per unit mm^2 considering the efficiency and droplet coalescence in the immersion liquid method to measure droplet size



(a) $\nu_T = 1\times10^3$ mm^2/s



(b) $\nu_T = 5\times10^4$ mm^2/s

Fig. 7 Droplet size distributions

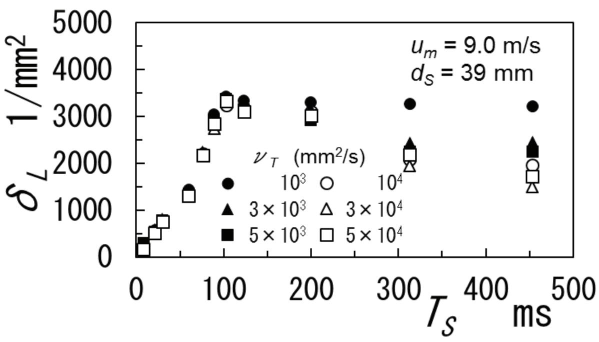


Fig. 8 Variations in the local droplet number per unit area δ_L with T_S

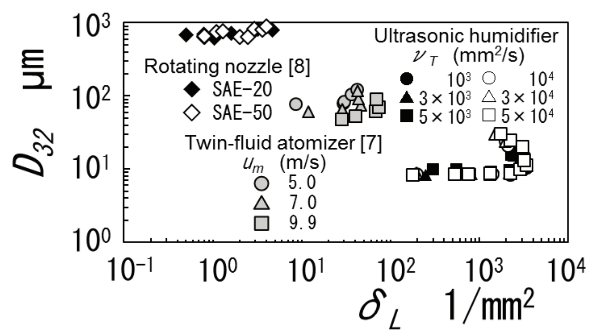


Fig. 9 Influence of δ_L on D_{32}

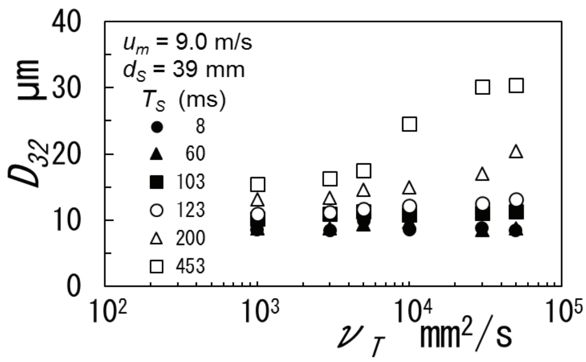


Fig. 10 Variations in D_{32} with silicone-oil viscosity ν_T

in the range of 10 μm. Therefore the suitable shutter opening period T_S is 103 ms in this study.

Because the increase of immersion liquid viscosity ν_T may affect on the droplet coalescence in the immersion liquid method, the variations in D_{32} with the silicone-oil viscosity ν_T for different T_S is shown in **Fig. 10**. While little influence of ν_T on D_{32} can be seen at T_S < 123 ms, D_{32} increases with ν_T at T_S > 123 ms, especially for longer T_S. The difference in D_{32} for different T_S becomes large as ν_T increases. In the experimental range, the minimum D_{32} value occurs for $\nu_T = 10^3$ mm^2/s. Although the influence of the silicone-oil viscosity ν_T on the droplet coalescence is not thought to be large at short shutter opening period, the increase of ν_T is one of the factors of droplet coalescence in the range of longer T_S. The suitable value of ν_T is 10^3 mm^2/s in the experimental range which is supported by Kurabayashi [8] reporting that the proper viscosity of immersion liquid ν_T is about 10^3 mm^2/s in the immersion liquid method.

4 Conclusions

The effects of droplet coalescence and evaporation on the accuracy of droplet size measurement in the immersion liquid method using silicone oil as immersion liquid and spray droplets generated by ultrasonic vibrations in the water were clarified by the experimental study. The main results of this experiment may be summarized as follows:

1. Shorter time between the sampling droplets and the inputting image is desirable since the evaporation of captured droplets on silicone-oil surface quickly occurs.
2. The suitable local droplet number per unit area δ_L should be under 3000 per unit mm^2 considering the efficiency and droplet coalescence in the immersion liquid method to measure droplets size in the range of 10μm. Therefore the suitable shutter opening period T_S is 103ms.
3. Although the influence of the silicone-oil viscosity ν_T on the droplet coalescence is not thought to be large at short shutter opening period, the increase of ν_T is one of the factors of droplet coalescence in the range of longer T_S. In addition, ν_T should be 10^3 mm^2/s for the minimum influence in droplet coalescence.

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