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 is adjusted by the weight <8> and the spring <10> to demonstrate the effects of droplet evaporation and the Sauter mean diameter of the number of droplets when the first image was captured (the number of droplets in a certain time to the mean value from the population besides the number of captured droplets, respectively).

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 νr.

Figure 2 represents selected samples of the variations in the droplet number density N/N0 (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 tc from the first droplets image was captured.

\[ D_{32} = \frac{\sum N_i D_i^3}{\sum N_i D_i^2} \]

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].

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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 $T_S$ and $v_f$ under the same $v_f$ and $T_S$, 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 $T_S$ 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 $v_f$. The value of $D_{32}$ at $t_c = 200$ ms and $v_f = 5 \times 10^4$ 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 $T_S$ 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 $T_S$ and the silicone-oil viscosity $v_f$.

Figure 4 depicts the effects of the droplet area fraction $A_F$ on the Sauter mean diameter $D_{32}$ for various silicone-oil viscosity $v_f$. 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 $\nu_T$. While $D_{32}$ value is almost constant to be 10 $\mu$m independently of silicone-oil viscosity $\nu_T$ 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 $\nu_T$ increases can be seen due to an increase in $T_s$. It is thought that its phenomenon occurs as $\nu_T$ 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 of the smallest silicone-oil viscosity $\nu_T = 10^3$ mm$^2$/s. The only droplets smaller than 20 $\mu$m are captured at $T_s = 76$ ms. The most of the captured droplets consist of fine droplets with diameters smaller than 5 $\mu$m 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 $\mu$m at $T_s = 103$ ms and 50 $\mu$m 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 $\nu_T = 5 \times 10^4$ mm$^2$/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 $\nu_T$ 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 $\delta_L$ 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 $\delta_L$ with the shutter opening period $T_s$. The value of $\delta_L$ increases linearly as increasing $T_s$ and reaches the maximum value of $\delta_L \approx 3000$ at $T_s = 103$ ms. On the contrary, in the case of $T_s > 103$ ms, the value of $\delta_L$ 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 $\delta_L$ together with the results from other researchers are shown in Fig. 9. The value of $D_{32}$ is almost constant up to $\delta_L \approx 3000$, while the value of $D_{32}$ increases rapidly and $\delta_L$ 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 $\delta_L$ to become the maximum value $\delta_L$. 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 $\delta_L$ 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 $\delta_L$ for
each mean diameter of the droplets must be determined in advance.

In this experiment, the suitable local droplet number per unit area \( \delta_L \) should be under 3000 per unit \( \text{mm}^2 \) considering the efficiency and droplet coalescence in the immersion liquid method to measure droplet size.

Because the increase of immersion liquid viscosity \( \nu_T \) may affect on the droplet coalescence in the immersion liquid method, the variations in \( D_{32} \) with the silicone-oil viscosity \( \nu_T \) for different \( T_S \) is shown in Fig. 10. While little influence of \( \nu_T \) on \( D_{32} \) can be seen at \( T_S < 123 \text{ ms} \), \( D_{32} \) increases with \( \nu_T \) at \( T_S > 123 \text{ ms} \), especially for longer \( T_S \). The difference in \( D_{32} \) for different \( T_S \) becomes large as \( \nu_T \) increases. In the experimental range, the minimum \( D_{32} \) value occurs for \( \nu_T = 10^3 \text{ mm}^2/\text{s} \). Although the influence of the silicone-oil viscosity \( \nu_T \) on the droplet coalescence is not thought to be large at short shutter opening period, the increase of \( \nu_T \) is one of the factors of droplet coalescence in the range of longer \( T_S \). The suitable value of \( \nu_T \) is about \( 10^3 \text{ mm}^2/\text{s} \) 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 \( \delta_L \) should be under 3000 per unit \( \text{mm}^2 \) considering the efficiency and droplet coalescence in the immersion liquid method to measure droplets size in the range of 10 \( \mu \text{m} \). Therefore the suitable shutter opening period \( T_S \) is 103 ms in this study.

3. Although the influence of the silicone-oil viscosity \( \nu_T \) on the droplet coalescence is not thought to be large at short shutter opening period, the increase of \( \nu_T \) is one of the factors of droplet coalescence in the range of longer \( T_S \). In addition, \( \nu_T \) should be \( 10^3 \text{ mm}^2/\text{s} \) for the minimum influence in droplet coalescence.
References


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