Development of drop size distribution control technique

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Advanced technique to control spray characteristic was developed by using a vibratory mono-dispersed spray atomizer. The drop size distribution can be controlled independently to a mean drop size. The range of fluctuation in frequency decides the deviation of drop size distribution. By this technique, it is possible to change drop size distribution under constant drop size and also to change drop size under constant drop size distribution. In addition, stability of mean drop size for frequency changing is improved by the increase of diffusion air, which is supplied coaxially to the liquid jet.
Moreover, the generated spray has periodic change of its characteristics in the early period. However, it decays during flight process of spray. Moreover, it is possible to reduce periodicity of spray by fast sweeping.

1. Introduction

A general spray consists of a huge number of drops with various sizes. It is well known that the drop size distribution affects on phenomena related to spray. For example, ignition, combustion and flame propagation of fuel spray, quality of finished surface in painting, etc., depend on the drop size distribution. However, it is said that the drop size distribution is uncontrollable.

The purpose of this research is to develop the drop size distribution control technique. An electric vibratory atomizer is selected for this purpose. Drop size distribution is controlled by the sweep range of frequency impressed on a vibratory atomizer. It is possible to obtain a spray with the target drop size and deviation of drop size distribution by the optimal selection of impressing frequency and its sweep range.

In this paper, it is aimed to clarify the fundamental principle of this control technique and demonstrated how to control drop size distribution and mean drop size independently.

2. Experimental apparatus and methods

Electric vibratory atomizer is usually used for producing mono-dispersed spray. This atomizer is based on the periodically breakup phenomenon of liquid jet. Liquid jet break up has been researched in detail by many researchers. Rayleigh[1] found theoretically the optimal wavelength to produce mono-dispersed drops as

$$\lambda_{opt}=4.508D_j \quad (D_j\text{: Liquid jet diameter}). \qquad (1)$$

Furthermore, Schneider and Hendricks[2] found experimentally the range of λ which could generate mono-dispersed drops as

$$3.5D_j<\lambda<7D_j. \qquad (2)$$

The relation between initial drop size d_0 and liquid jet diameter is led from this result as

$$1.74<d_0/D_j<2.19\ . \qquad (3)$$

The size of mono-dispersed spray drops can be controlled in this range. Drop size of mono-dispersed spray can be calculated as

$$d_0=\left(\frac{6Q}{\pi f}\right)^{1/3}. \qquad (4)$$

Here, Q means the flow rate of sample liquid and f the impressed frequency. When the target drop size is out of this range, poly-dispersed spray is generated.

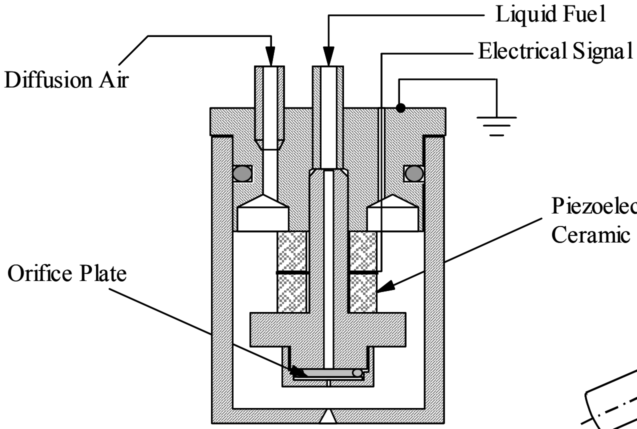


Fig.1 Experimental apparatus

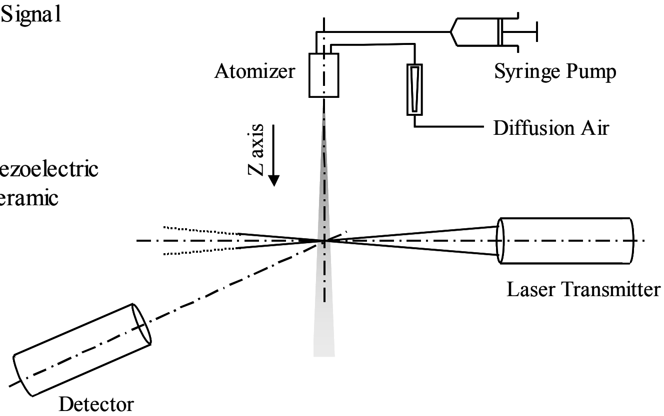


Fig.2 Experimental setup

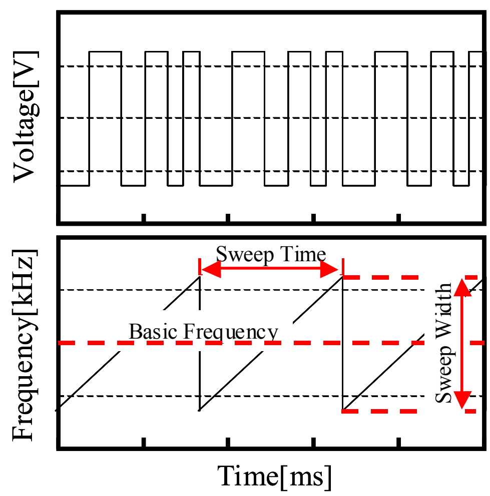


Fig.3 Schematic diagram of impressed signal

Table1 Experimental conditions

Parameters	Specification
Atomizer & Liquid	
Sample liquid	Tap water
Sample flow rate	1.5g/min
Airflow rate	0, 4.4, 8.6×$10^{-3}$$m^3$/min
Orifice size	66 μm
Distance from Injector tip	Z: 25, 50 mm
Impressed Signal	
Voltage	24Vp-p
Basic frequency	0.01Hz ~ 50kHz
Sweep width	0 ~ 60kHz
Sweep time	25 ~ 500ms/cycle

In this study, it is attempted to control the drop size and its distribution independently by making various breakup conditions periodically and superposing different drop size distributions.
Figure1 shows the test atomizer. The piezoelectric ceramic vibrator is attached to the atomizer body. A sample liquid is led from inlet to orifice hole set on a tip of atomizer and forms a fine liquid jet. It is actively vibrated in a set frequency by a pair of piezoelectric ceramics and disintegrated into drops. Produced drops are arrayed with narrow distances. Thus, the drops collide each other and are combined if these drops are not diffused. For this problem, the diffusion air is led to prevent from collision. Figure2 shows the experimental setup. Atomizer is set in a vertically and drops are measured along Z-axis by *Phase Doppler Particle Analyzer* (PDPA). A liquid is fed precisely by syringe pump controlled by stepping motor.

The schema of impressed signal is shown in Fig.3. Signal is square shape and its frequency is swept periodically. Frequency of impressed signal increases proportionally with time within each cycle. In this study, average frequency is defined as *basic frequency(BF)*, sweep range as *sweep width(SW)*, and the time to sweep one cycle as *sweep time(ST)*. Experimental conditions are shown in Table 1. Tap water was used as sample liquid.

3. Results and discussions

3.1 Effect of basic frequency on mean drop size and drop size distribution

Figure 4 shows variations of mean drop size (D_{10}) and relative standard deviation of drop size by impressing constant frequency, i.e., without frequency sweep. Drop size and its velocity are measured at 50mm under atomizer tip. According to the observation, a diameter of liquid jet at disintegration point is 67μm. It is thought from this result and Eqs.(3)and (4) that the mono-dispersed spray is generated between 15kHz to 30kHz and drop size is between 147 to 117μm. However, in this experiment, drop size distribution with narrow peak spray can generate between 10kHz to 25kHz. This region is defined as mono-dispersed spray region. When the frequency of impressed signal is out of this region, drop size distribution becomes broad and 2nd or 3rd peaks are appeared. Thus, out of mono-dispersed spray region is defined as poly-dispersed spray region.
The diffusion air has some influence on the liquid jet breakup and subsequent drop formation though the main purpose of diffusion air is to diffuse generated drops. In mono-dispersed spray region, relative standard deviation of drop size increases with the

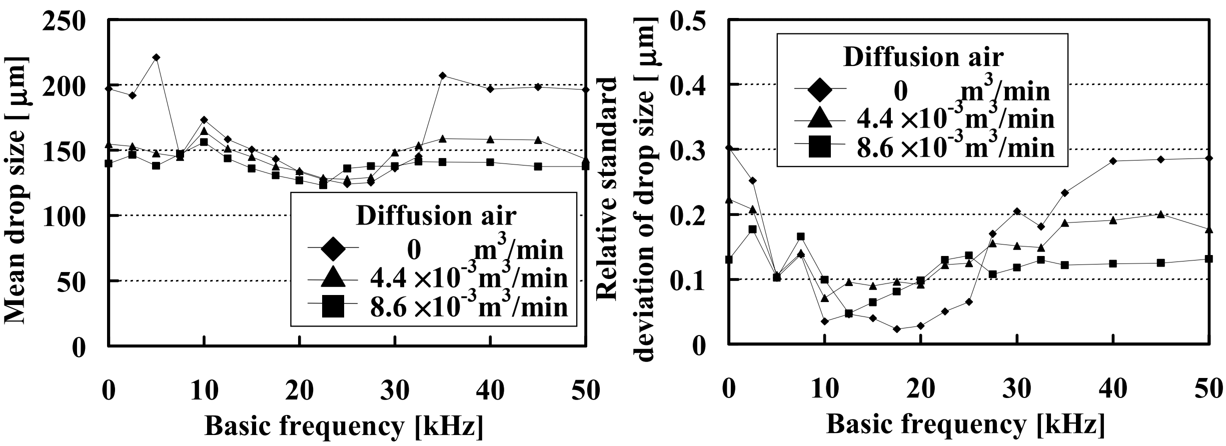


Fig.4 Effect of Basic Frequency

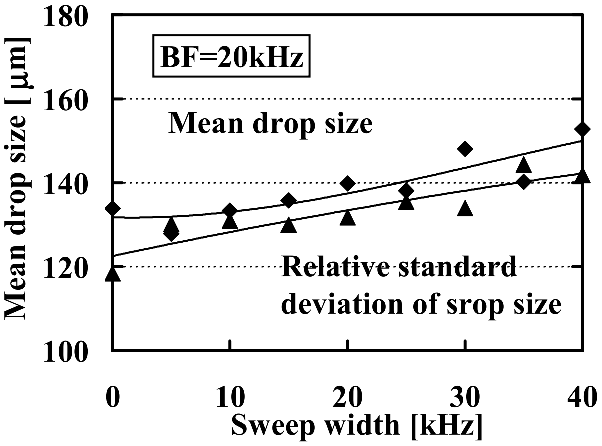


Fig.5 Effect of sweep width

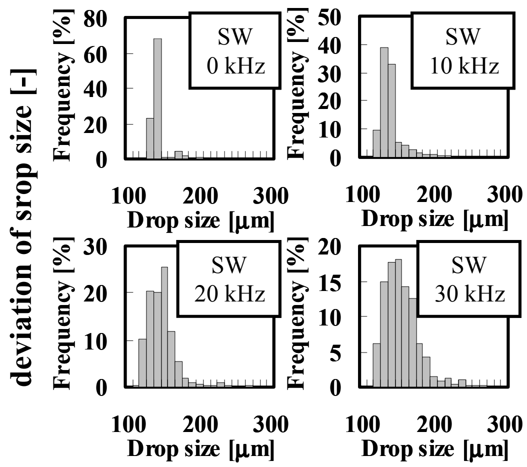


Fig.6 Typical drop size distribution of frequency sweeping cases

increase of diffusion air, because the turbulence by diffusion air becomes stronger and it is impossible to neglect the turbulence effect. However, it is possible to suppress the increase of mean drop size by the increase of diffusion air in poly-dispersed spray region though relative standard deviation also decreases in poly-dispersed spray region because breakup of liquid jet is assisted by the turbulence of diffusion air.

3.2 Effect of sweep width on drops in space

The effect of sweep width on both mean drop size and relative standard deviation are shown in Fig.5, and typical pattern of drop size distributions in Fig.6. The measurement point is the center of spray at 50mm under atomizer tip and the basic frequency is 20kHz. Here, sweep width 10kHz means that the frequency of impressed signal swept between 20KHz±5kHz, and SW=0kHz the case that only basic frequency is impressed.

With the increase of sweep width, drop size distribution with single peak becomes broad and mean drop size also increase with the increase of sweep width. Therefore, it is necessary to increase basic frequency with the increase of sweep width to control drop size distribution under constant mean drop size. In addition, it can be considered that it is possible to reduce the change of mean drop size by diffusion air as mentioned in 3.1.

Photographs of break up of liquid jets are shown in Fig.7. In this figure, top is the cases of being impressed signal with constant frequency and bottom the cases of frequency swept and those are taken by synchronizing with sweep signal. In order to observe break up of liquid jet, these photographs were taken without any diffusion air. It can be seen that the break up of liquid jet is same between constant frequency and corresponding frequency sweeping conditions.

This result suggests that quasi-steady liquid jet breakup is occurred periodically in this developed technique and the drop size distribution is predictable by the combination of drop size distributions corresponding to SW=0kHz conditions.

3.3 Periodicity of drop size

The principle of drop size distribution control method recommend here is the way that an electric signal impressed to a vibratory atomizer is controlled with time and different sized drops are produced. Therefore, the size of produced drops may changes with time. To make clear the effect of sweep time on the characteristics of drops in time and in space,

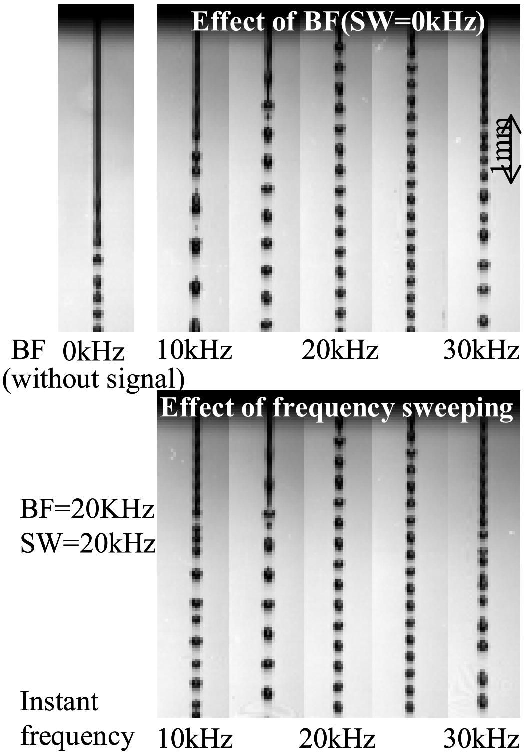


Fig.7 Break up of liquid jet

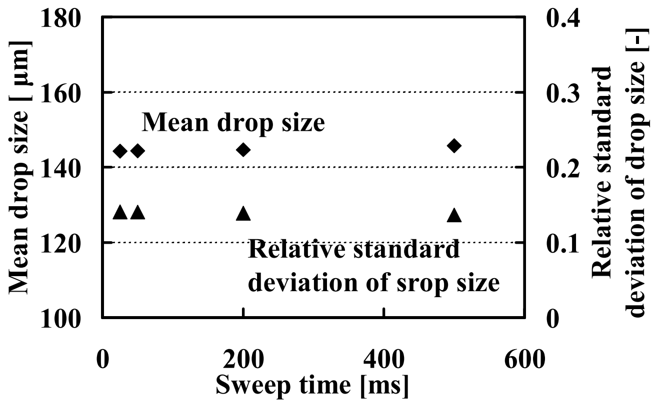


Fig.8 Effect of ST on drops

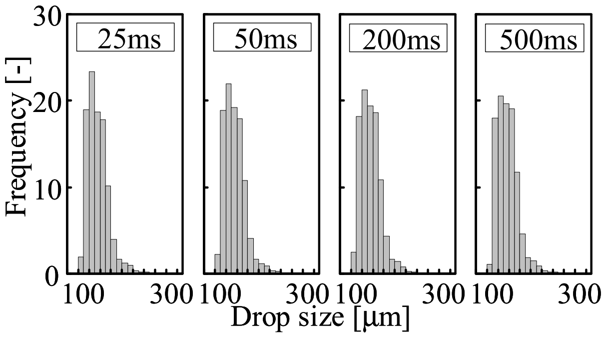


Fig.9 Typical drop size distribution of each sweep time

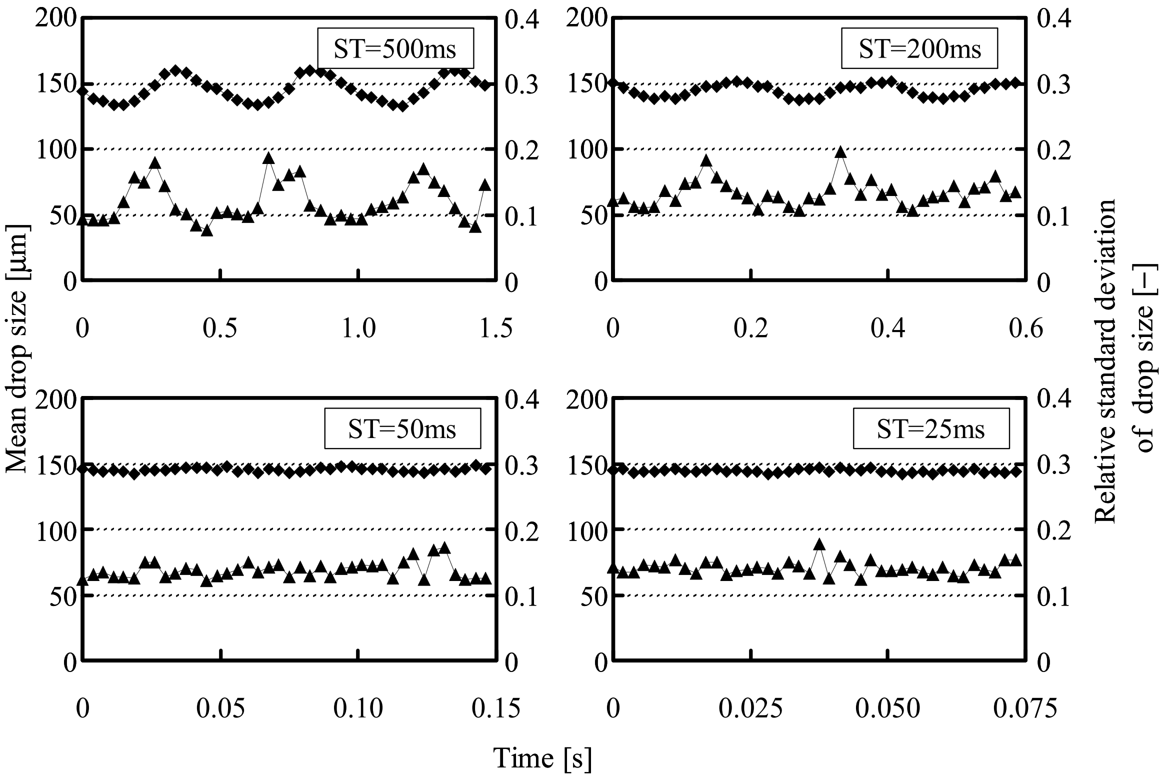


Fig.10 Effect of sweep time on periodicity of drop size

periodicity of both drop size distribution and mean drop size are measured and evaluated. In this section, all results are obtained under the condition of BF=20KHz and SW=20KHz and measured point is at 25mm under atomizer tip.

Time averaged mean drop size and relative standard deviation of drop size at ST= 25,50,200,500ms are shown in Fig.8. Typical patterns of drop size distribution are also shown in Fig.9. It is evident from those results that drop size distributions are very similar between these sweep time conditions and mean drop sizes agree precisely. These results mean that the macroscopic characteristics of drops are not affected by a sweep time in these experimental conditions. Ensemble mean drop size and its relative standard deviation are shown in Fig.10. Ensemble mean size stands for a mean size of drops windowed within a specific short time-period of each sweep cycle.

In the case of longer sweep time condition, a periodic change corresponding to the sweep time appears. On the other hand, in the case of short sweep time condition, such a periodic change cannot be observed in the figure. This fact suggests that it is possible to reduce periodicity of spray by shortening sweep time. Furthermore, the reduction of periodicity is occurred after liquid jet break up since the periodic un-uniform break up of liquid jet is observed (see Fig.7 bottom). It is thought that the mixing of drops is accelerated by the difference of drop size since drop velocity differs by drop size and so that smaller drops are delayed and mixed with following larger drops.

3.4 Demonstration of the developed control technique

Mean drop size and relative standard deviation of drop size at various basic frequencies and sweep widths are shown as contour map in Fig.11 and Fig.12, respectively. In these figures, sweep time is 50ms. Blank spaces are the regions where it is impossible to experiment because instant frequency becomes less than 0 in these areas.

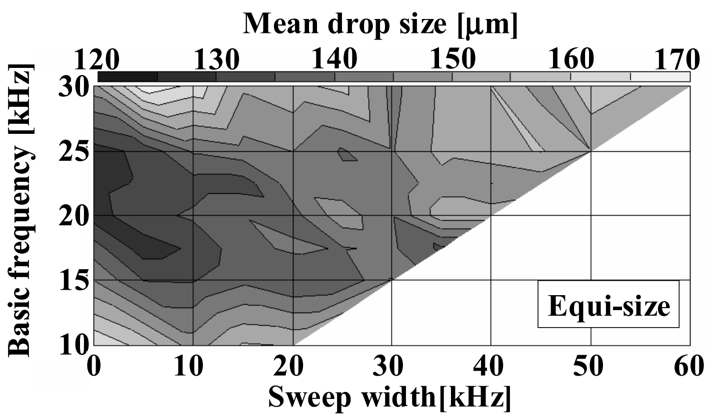


Fig.11 Contour map of mean drop size

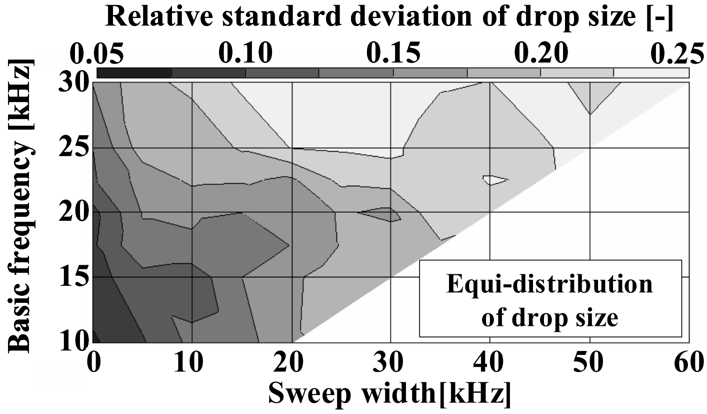
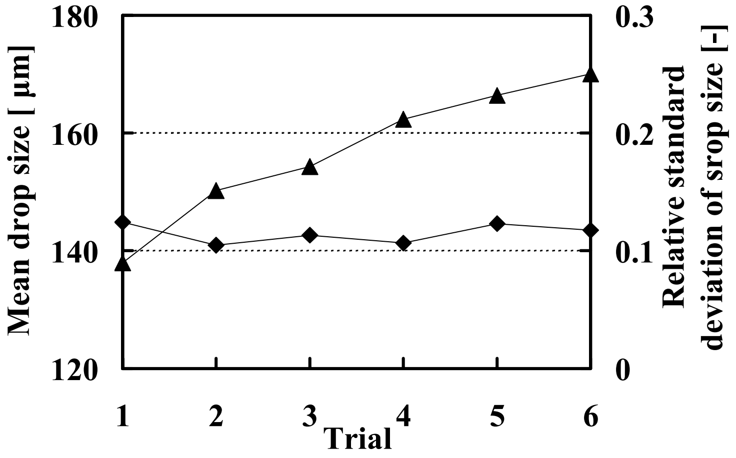


Fig.12Contour map of relative standard deviation of drop size



Trial	Basic frequency [kHz]	Sweep width [kHz]
1	15	0
2	17.5	20
3	22.5	20
4	22.5	30
5	25	30
6	30	30

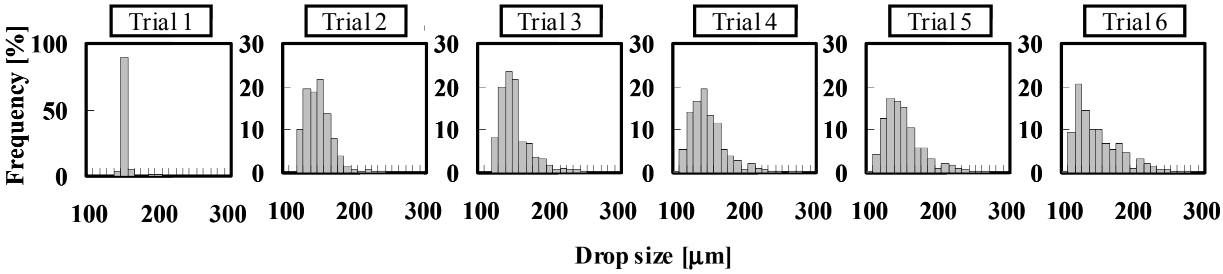
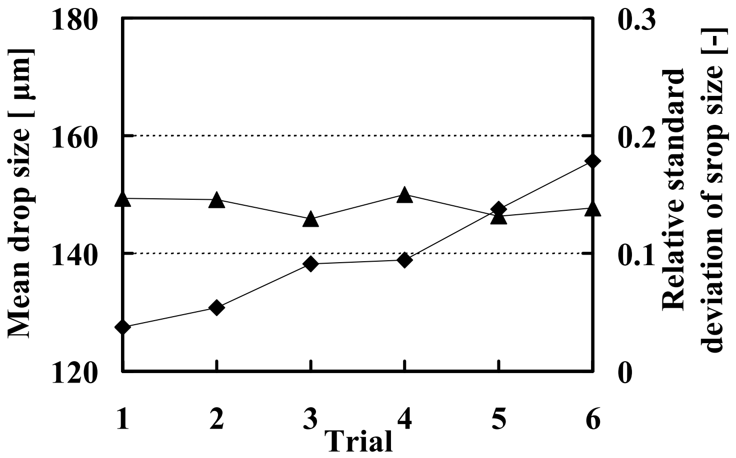


Fig.13 Result of drop size distribution control



Trial	Basic frequency [kHz]	Sweep width [kHz]
1	17.5	5
2	17.5	10
3	17.5	15
4	15	15
5	10	10
6	10	15

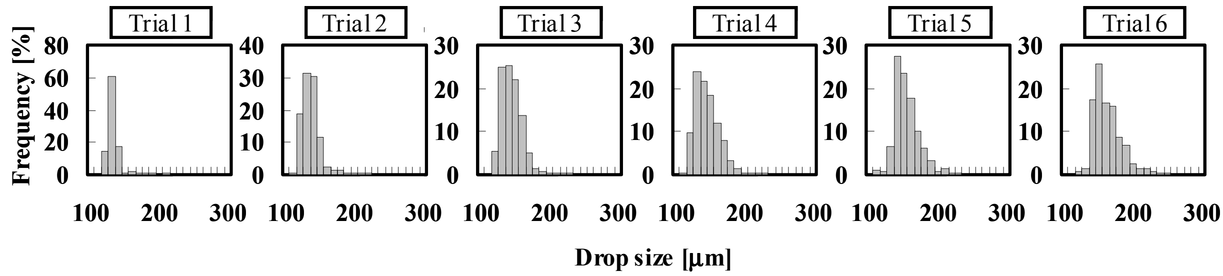


Fig.14 Result of drop size control

When basic frequency and sweep width are tuned on same equi-size of drops in Fig.11, it is possible to change drop size distribution under constant drop size. On the contrary, it is also possible to change drop size under constant drop size distribution by tuning basic frequency and sweep time under same equi-distribution of drop size in Fig.12.
Result of former control is shown in Fig.13 and the latter in Fig.14, respectively. In Fig.13,

relative standard deviation of drop size is changed from 0.09 to 0.25 under almost constant mean drop size. In addition, drop size distribution changes from mono-dispersed spray to poly dispersed-spray with single peak. On the other hand, mean drop size changes from 127μm to 156μm under the almost constant relative standard deviation of drop size in Fig.14.

4. Conclusions and future work

Advanced technique to control spray characteristic was developed by using a vibratory mono-disperse spray atomizer. The drop size distribution can control independently to a mean drop size. The results are summarized as follows;

- In this developed technique, quasi-steady liquid jet breakup is occurred and the drop size distribution is predictable by the combination of drop size distributions corresponding to SW=0kHz conditions.

- The diffusion air can reduce the change of mean drop size by the change of sweep width.

- Initially, the generated spray has periodic change of its characteristics. However, it decays during flight process of spray. It is possible to reduce periodicity of spray by shortening sweep time.

It is possible to generate the spray with various drop size distributions, for example multi-peak and drop size, by this technique. However, this technique is still experimental level at moment since the atomizer in this research has only a single hole and a low liquid flow rate. For the industrial use, one of the most important subjects is to increase a flow rate by other methods, e.g. multi-hole nozzle.

References

[1] Rayleigh,L., Proc.Lond. Math.Soc., 10, pp4-13, 1878
[2] Schneider,J.M. and Hendricks,C.D., Rev.Sci. Instrum.,35(10),pp1349-50,1964