Influence of Micro-Bubbles within Ejected Liquid on Behavior of Cavitating Flow inside Nozzle Hole and Liquid Jet Atomization

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Abstract

A basic study was performed to investigate the effects of micro-bubbles on the inside cavitating flow of a nozzle hole and atomization of liquid jet emerged from the hole type nozzle. Bubble generators, based on a cavitation method, were employed to produce micro-bubbles. The bubble generators within the atomizer were mounted upstream of the nozzle hole, so that the micro-bubbles were ejected from exit orifices of the bubble generators in the axial direction towards the entrance of the nozzle hole. The highly amount of micro-bubbles, which caused the bubble cavitation mode inside the nozzle hole, enhanced atomization of liquid jet.

Introduction

The atomization of liquid jets is strongly influenced by the cavitation produced inside a hole type nozzle, such as diesel nozzles. The effect of nozzle shapes, atmospheric pressure and injection pressure on liquid atomization with inside cavitating flow has been studied by several researchers [1-3]. Few researchers have investigated about influence of cavitation nuclei on atomization. Studies about hydraulics represented that the transition from the flow mode of sheet cavitation to that of bubble cavitaiton is occurred when bubble nuclei are supplied to the flow with sheet cavitation [4]. In other words, cavitating flow is significantly affected by the nuclei. Ordinary cavitating bubbles are produced within the liquid flow beside the wall of nozzle hole. However it is expected that almost nuclei will become cavitating bubbles and collapse if the nuclei will be homogeneously charged into a nozzle hole under the cavitating condition. As a result, it seems that atomization will be dramatically improved and, if possible, mono-dispersed fine spray will be obtained.

In general, relative low injection velocity results in poor atomization. For example, in diesel nozzles, lower injection pressure leads to lower needle lift and lower injection velocity. However low needle lift causes throttling effects in the seat area of diesel nozzles, i.e. cavitation bubbles are generated at the needle valve seat, so that the cavitation inside a nozzle hole is improved and atomization is enhanced [5]. Tamaki et al. [6] have studied about tandem configurated double orifices. The upstream orifice yields cavitation, and then bubbles produced are directly introduced into the downstream orifice. In these cases, it is exhibited that the generated bubbles, which are yielded at the upstream orifice, may behave as nuclei and may enhance atomization. Similar experiment about tandem configurated double orifices has been performed by Sharief et al. [7] by employing the ejecting liquid with dissolved gas. Thus bubbles are generated at the upstream orifice, so that flash boiling at the downstream orifice and atomization are improved.

Kato explained about nuclei which are bubbles of gas (mainly air) and those diameters are less than 100μm [4]. Thus it is reasonably expected that micro-bubbles may be essentially same as nuclei, so that micro-bubbles may markedly promote atomization. We suggested the method for improvement of atomization due to micro-bubbles, which are charged into nozzle hole under cavitating condition [8]. In this paper we will discuss the effects of micro-bubbles on cavitating flows inside hole type nozzles and atomization of liquid jets. Finally, we will reveal experimental results which will focus on population of micro-bubbles.

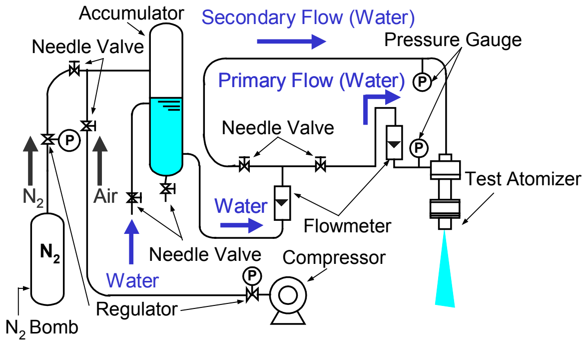

Fig. 1 Schematic diagram of experimental apparatus.

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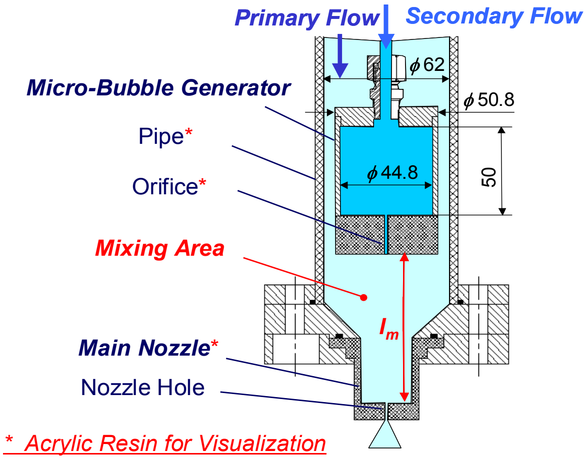
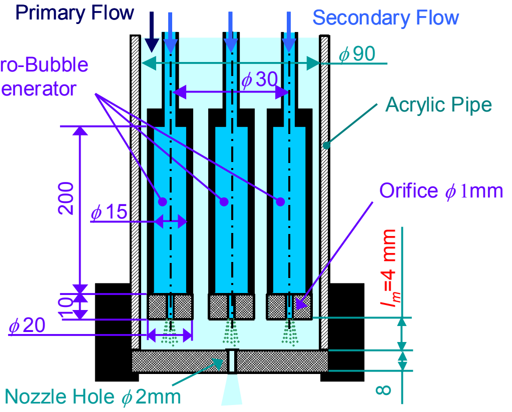


(a) Type A atomizer.



(b) Type B atomizer.

Fig. 2 Schematic diagram of test atomizers.

Experimental Setup and Procedure

Figure 1 shows the experimental setup for the present study. An accumulator containing water, which was employed as the test liquid, was pressurized by an air compressor up to 1.2MPa, and then by N_2 bomb to 2.8MPa. A pressure regulator was used to maintain the pressure in an accumulator.

The liquid from an accumulator was introduced steadily into flow meter to monitor total volumetric flow rate before being divided into two identical liquid lines for primary flow and secondary flow. The primary liquid was supplied directly into a main nozzle of our original test atomizers, which was shown in Fig. 2, through a flowmeter, a needle valve and Bourdon-type pressure gauge. The pressure gauge was used to monitor the upstream pressure of nozzle hole incorporated into a main nozzle, which was located just downstream of the micro-bubble generators. On the other hand, secondary liquid was introduced into a micro-bubble generator of a test atomizer through a needle valve and Bourdon-type pressure gauge. The pressure gauge was used to monitor the pressure just upstream of an orifice, which was incorporated into the exit of the micro-bubble generator.

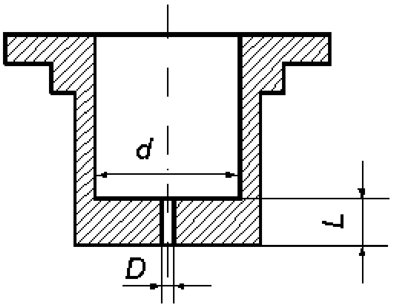


Fig. 3 Schematic diagram of the main nozzle incorporated into the type A atomizer.

Table 1 Specifications of the main nozzle incorporated into the type A atomizer.

Type of Nozzle	**Hole Nozzle**
Hole Diameter D	**2mm**
Hole Length L	**8mm**
Length to Diameter Ratio of Nozzle L/D	**4**
Inner Diameter of Pre-nozzle Region d	**25mm**
Opening Ratio d/D	**12.5**

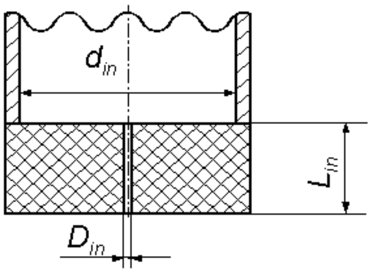


Fig. 4 Schematic diagram of the micro-bubble generator incorporated into the type A atomizer.

Table 2 Specifications of the micro-bubble generator incorporated into the type A atomizer.

Type of Nozzle	**Hole Nozzle**
Hole Diameter D_{in}	**1.5mm**
Hole Length L_{in}	**20mm**
Length to Diameter Ratio of Orifice L_{in}/D_{in}	**13.3**
Inner Diameter of Pre-Orifice Region d_{in}	**44.8mm**
Opening Ratio d_{in}/D_{in}	**29.9**

"Type A" or "Type B" atomizer, which are illustrated in Figs. 2(a) and (b), were used as test atomizers. The micro-bubble generators, which were based on a cavitation method, were mounted upstream of the nozzle hole of the main nozzle. A micro-bubble generator was mounted coaxially inside both type A and B atomizers. In addition to this central micro-bubble generator of the type B atomizer, four micro-bubble generators were axisymmetrically located around the central generator. Primary liquid flowed outside the micro-bubble generator, and secondary liquid flowed inside the micro-bubble generator.

Finally, the liquid was ejected downward into quiescent air from the exit of main nozzle under atmospheric conditions. The nozzle holes of both type A and B atomizer had a sharp-edged circular shape at the entrance as shown in Figs. 2(b) and 3. Specifications of main nozzle incorporated into type A atomizer are exhibited in Table 1. The diameter of both nozzle holes was 2mm and the length was 8mm, providing a length to diameter ratio of 4. The pre-nozzle regions of type A and B atomizer had diameter of 25mm and 90mm, respectively.

Each orifice of micro-bubble generator had a sharp-edged circular shape at the entrance, which was similar to main nozzles, as shown in Figs. 2(b) and 4. Specifications of the orifice of the micro-bubble generator incorporated into type A atomizer are shown in Table 2. The micro-bubble generator of type A atomizer (Fig. 4) had an orifice diameter of 1.5mm and a length of 20mm, providing a length to diameter ratio of 13.3 (Table 2). The liquid flowed a contraction from 44.8mm pre-orifice region to the orifice. On the other hand, the micro-bubble generator of type B (Fig. 2(b)) atomizer had an orifice diameter of 1mm and a length of 10mm, providing a length to diameter ratio of 10. The inner diameter of the pre-orifice region was 15mm.

When cavitation was caused inside the orifice of the micro-bubble generator in a specific condition, micro-bubbles emerged from the exit of the micro-bubble generator to the mixing area, which was defined as the area between micro-bubble generator and nozzle hole. Hence the secondary liquid with micro-bubbles was mixed with the primary liquid in the mixing area. The mixing length l_m was defined as an axial distance between the micro-bubble generator and the nozzle hole.

Results

Total flow rate of liquid Q_t, which is a sum of flow rate of primary and secondary liquid, is set in terms of flowmeter reading at 53.3cc/s when all experiment using type A atomizer are preformed. As a result, the flow rate of primary liquid is reduced if that of secondary liquid is increased. Pressure of the accumulator P_0 is maintained at 2.8MPa for testing about type A atomizer.

Figure 5 shows the effect of pressure difference between entrance and exit of orifice of micro-bubble generator ΔP, which is incorporated into the type A atomizer, on cavitating bubbles produced inside the orifice. Each photograph of bubble, which is illuminated by a Xenon strobe of 4μs duration, is captured by a still camera. The entrance and the exit of the orifice are located at 0mm and 20mm, respectively. Cavitating bubbles can not be observed at the pressure difference of the orifice of 0MPa and 0.28MPa. There exists an annular bubble of sheet cavitation inside the orifice in each photograph above 0.66MPa. The length of sheet cavitation bubble increases with increasing pressure difference of the orifice.

Figure 6 exhibits the effect of pressure difference between entrance and exit of the orifice of micro-bubble generator on micro-bubbles in the mixing area inside type A atomizer. Each front-lit photograph is captured by still camera illuminated by a Xenon strobe of 4μs duration. The orifice exit of micro-bubble generator is located at 0mm. It is noted that amount of micro-bubbles, which emerge to a mixing area, corresponds to bubble length of sheet cavitation observed within a micro-bubble generator as discussed below. Micro-bubbles are not apparent below 0.28MPa because of the non-cavitating condition at the orifice of the micro-bubble generator (Fig. 5). On the contrary, micro-bubbles are obtained above 0.66MPa, and number density and/or size of micro-bubbles increase with increasing the pressure difference of the micro-bubble

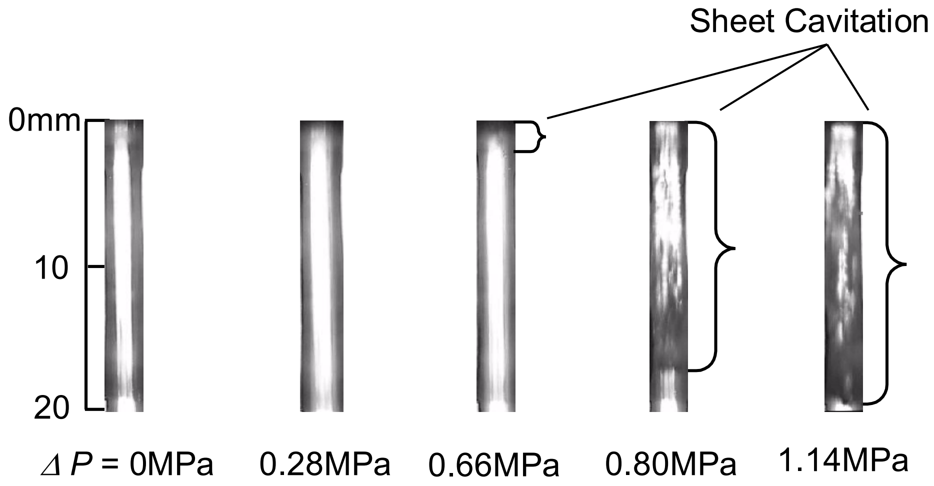


Fig. 5 Effect of pressure difference between entrance and exit orifice of the micro-bubble generator on cavitating flow inside the orifice. (Type A atomizer, P_0=2.8MPa, Q_t=53.3cc/s, l_m=55mm)

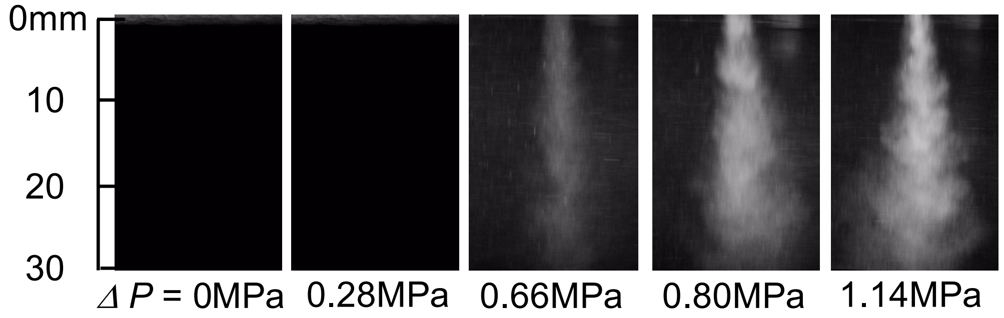


Fig. 6 Effect of pressure difference between entrance and exit orifice of the micro-bubble generator on micro-bubbles emerged to the mixing area. (Type A atomizer, P_0=2.8MPa, Q_t=53.3cc/s, l_m=160mm)

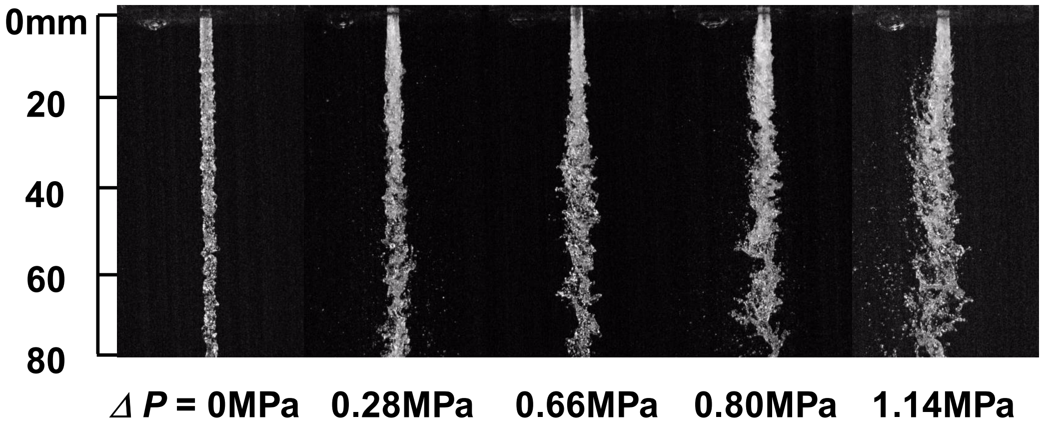


Fig. 7 Effect of pressure difference between entrance and exit orifice of the micro-bubble generator on liquid jets. (Type A atomizer, P_0=2.8MPa, Q_t=53.3cc/s, l_m=55mm)

generator.

Figure 7 shows front-lit photographs of liquid jets. Each front-lit photograph is captured by still camera illuminated by a Xenon strobe of 4μs duration. Nozzle exit is located at 0mm in each photograph. Irregular-shaped surfaces are observed on liquid columns, which are the continuous parts from the exit of nozzle hole, at the pressure difference of the orifice of 0MPa, 0.28MPa and 0.66MPa, corresponding to a “turbulent breakup” regime. In contrast, it is indicated that larger pressure difference of the orifice leads to more significant improvement of atomization due to micro-bubbles ejected into the mixing area above 0.80MPa.

Figure 8 shows the effect of the pressure difference of the orifice of the micro-bubble generator on cavitating bubbles inside the nozzle hole of type A atomizer. Each shadowgraph of liquid jet, which is illuminated by a Xenon strobe of 4μs duration, is captured by a still camera. A bubble of sheet cavitation is apparent near the entrance of nozzle hole at the pressure difference of the orifice of 0MPa. The cavitation sheet extended downstream up to the exit of the nozzle hole at 0.28MPa. On the contrary, small bubbles are observed near the entrance of nozzle hole at 0.80MPa, since the transition between the sheet cavitation and the bubble cavitation occurs due to micro-bubbles, which reach the nozzle hole. However, at 0.66MPa, the bubble cavitation can not be appeared but the sheet cavitation can be observed. A considerable reason for this is that the micro-bubbles ejected are absorbed by the liquid at the mixing area.

Figure 9 illustrates the effect of the mixing length on the spray angle θ. Spray angle gradually increases with increasing the pressure difference of the orifice of the generator up to 0.66MPa when type A atomizer has a mixing length of 160mm. Further increase in the pressure difference beyond 0.66MPa causes the spray angle to hardly increase. In this mixing length, it is considerable reason why micro-bubbles may not be able to reach the entrance of the nozzle hole due to absorption by liquid if micro-bubbles are yielded. When tests are performed by using the type A atomizer

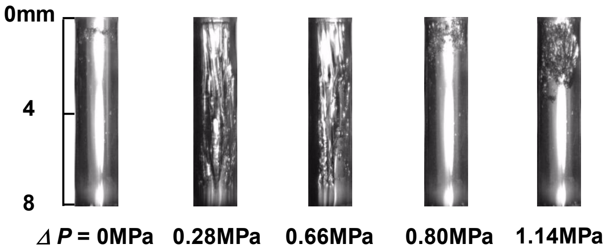


Fig. 8 Effect of pressure difference between entrance and exit orifice of the micro-bubble generator on cavitating flow inside the nozzle hole. (Type A atomizer, P_0=2.8MPa, Q_t=53.3cc/s, l_m=55mm)

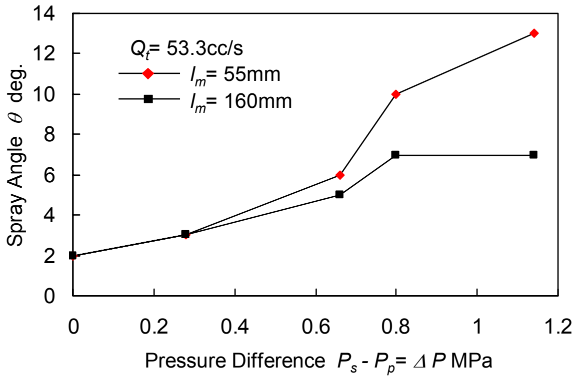
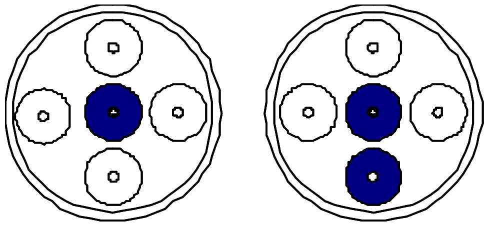


Fig. 9 Effect of the mixing length on the spray angle. (Type A atomizer, P_0=2.8MPa, Q_t=53.3cc/s)

which has a mixing length of 55mm, quantitatively similar trend is obtained up to 0.66MPa, i.e. the spray angle is gradually raised with increasing the pressure difference since the micro-bubbles can not be supplied to the nozzle hole (Fig. 6). Hence these values of the spray angles are similar to those obtained by using the atomizer which has the length of 160mm. However the spray angle is markedly increased above 0.80MPa. As a result, the spray angle of 55mm is larger than that of 160mm. The reason for this is that micro-bubbles, are emerged from the generator, may be introduced into the nozzle hole.

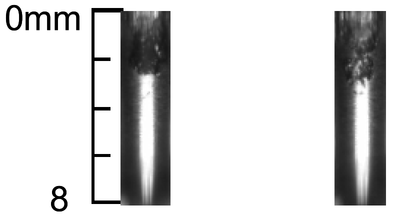
All of experiment using type B atomizer are preformed at the total flow rate of 41.6cc/s. Furthermore, the pressure of the accumulator is maintained at 1.2MPa only by air from the compressor. Figure 10 illustrates configurations of micro-bubble generator used. Blue circles indicate the micro-bubble generators used. Figure 10(a) exhibits the configuration 1B when only a central micro-bubble generator is used, and Fig. 10(b) shows the configuration 2C when a central micro-bubble generator and a peripheral micro-bubble generator are used. Figure 11 shows the effect of the configuration of micro-bubble generators used on cavitating bubbles inside the nozzle hole, and Fig. 12 demonstrates the effect of the configuration on the liquid jets. It is noted that characteristics of atomization by using two micro-bubble generators (configuration 2C) is compared with that by employing only one micro-bubble generator (configuration 1B). Liquid flow rate of every micro-bubble generator Q_{s1}, regardless of configuration, has same value so that number of micro-bubble generators used may correlate with population of micro-bubbles. It seems that the cavitating bubbles inside the nozzle hole and the spray atomization may not be affected by the configuration of micro-bubble generator as shown in Figs. 11 and 12.

Figure 13 exhibits the effect of configuration of micro-bubble generators on the spray angle. Spray angle remains low until the liquid flow rate of 8cc/s, and then significantly increases with increasing the liquid flow rate. The values of spray angle for the configuration 2C are similar to those for the configuration 1B below 16cc/s. However liquid jet for the configuration 2C becomes larger than that for the configuration 1B at 20.8cc/s. Furthermore, fluctuation of the spray angle can be slightly observed for the configuration 2C while significant fluctuation can be appeared for the configuration 1B. The micro-bubble generator in the periphery of the atomizer is located relatively far from the entrance of the nozzle hole, so that micro-bubbles from this generator must have longer residence time in the mixing area than that from the central generator. Thus the population of the micro-



(a) Configuration 1B (b) Configuration 2C

Fig. 10 Schematic diagram of configurations of the micro-bubble generators used incorporated into the type B atomizer.



Configuration: 1B 2C

Fig. 11 Effect of configuration of the micro-bubble generators used on cavitating flow inside the nozzle hole. (Type B atomizer, P_0=1.2MPa, Q_t=41.6cc/s, Q_{s1}=20.8cc/s, l_m=4mm) bubbles from the micro-bubble generator in the periphery of the atomizer may be reduced due to absorption by the liquid. As a result, few micro-bubbles may be able to supplied into the nozzle hole when the liquid flow rate is relatively low.

Conclusions

An experimental study was performed to investigate the effects of micro-bubbles on the inside cavitating flow of a nozzle hole and atomization of liquid jet emerged from the hole type atomizer. Conclusions drawn from this study are as follows.

1. The highly amount of micro-bubbles, which causes the bubble cavitation mode inside the nozzle hole, enhances atomization of liquid jet. Therefore spray angle increases with increasing amount of micro-bubbles.
2. The spray angle increases with decreasing mixing length, which is distance between the entrance of nozzle hole and the exit of micro-bubble generator.
3. If an additional micro-bubble generator is employed, the spray angle is increased.

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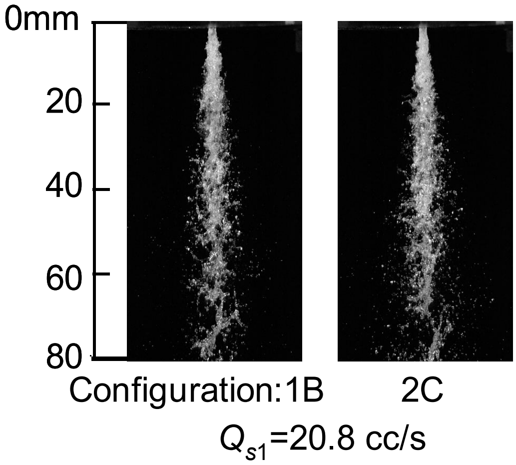

Fig. 12 Effect of configuration of the micro-bubble generators used on sprays. (Type B atomizer, P_0=1.2MPa, Q_t=41.6cc/s, l_m=4mm)

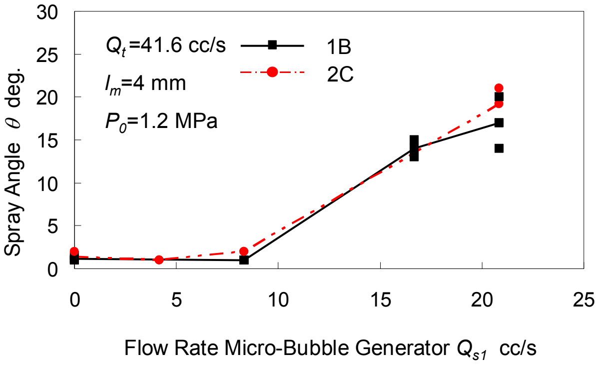

Fig. 13 Effect of configuration of the micro-bubble generators used on the spray angle. (Type B atomizer, P_0=1.2MPa, Q_t=41.6cc/s, l_m=4mm)