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<td>Author(s)</td>
<td>Sadatomi, Michio; Tanaka, Keiichi; Kawahara, Akimaro</td>
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Comparison of mist generators between twin-fluid water suction type and single-fluid swirl type

Michio Sadatomi, Keiichi Tanaka and Akimaro Kawahara

Abstract—Sadatomi and Kawahara invented a multi-fluids mixer which is categorized as a twin-fluid type but have a merit of water suction type. The mixer is usable to generate micro-bubbles, etc. besides mists, fine droplets. In the mists generation, pressurized air alone is supplied because water can be sucked automatically by a negative pressure arisen downstream from the orifice in the mixer. The objective of the present study is to compare the performance between the above twin-fluid type atomizer and a common single-fluid swirl type atomizer studied in the present experiments. The comparison results showed that the twin-fluid type was superior to the single-swirl type in the performance of CO$_2$ adsorption by the mists. The CO$_2$ adsorption rate by the twin-fluid type was about twice. Such results on the experiments and the comparisons are described in this paper.

Keywords—atomizer, twin- and single-fluid types, hydraulic performance, CO$_2$ adsorption

I. Introduction

Sadatomi and Kawahara invented a multi-fluids mixer shown in Fig. 1 [1] which is categorized as a twin-fluid type but have a merit of water suction type. The mixer is usable to generate mists [2–5], fine liquid droplets, as well as micro-bubbles [6, 7] when water is supplied and air is sucked. In the mists generation, pressurized air alone is supplied because water can be sucked automatically through a porous pipe by a negative pressure arisen downstream from an orifice in the mixer. Thus, the mixer is called as twin-fluid water suction type atomizer in the present paper. In our previous studies [2–5], better geometrical parameters was clarified, i.e., the diameter ratio of the orifice to the mixer pipe, the ratio of outlet length from the rear end of the porous pipe to the mixer pipe diameter, the geometry of the orifice, and the whole size.

The purpose of the present study is to compare the above twin-fluid type atomizer with a common single-swirl type one on the hydraulic and the CO$_2$ adsorption performances by the mists generated. At first, some findings in our previous study [4] have been introduced for the twin-fluid type mixer. Secondary, the present experimental results on the single-swirl type atomizer together with the comparison results between the twin-fluid type with the best size and the single-swirl type with the best performance have been introduced in the present paper.

II. Experiment

A. Test Atomizers

In our previous study [4], three twin-fluid type atomizers of L, M and S were tested in order to study size effects. As listed in TABLE I, the S type had 7 mm in the pipe diameter, 4.58 mm in the orifice diameter, and 20.5 mm in the outlet length, and fiber porous pipe of 25 mm in porosity and 1.5 mm in thickness. The M type and the L type were twice and three times larger than the S type besides the pore diameter and thickness of the porous pipe. In addition, the proportion of the mixer, such as the orifice to the pipe diameter ratio and the outlet length to the pipe diameter ratio, was determined so as to give best performance [2–5].

Fig. 2 shows the single-fluid swirl type atomizer tested. It is composed from a 7 mm I. D, pipe, a swirlor, an orifice and a cap. The pipe diameter is the same as that of the twin-fluid S type atomizer. The swirlor is the same as that used in a commercial atomizer (Maruhachi Co., Japan). As the orifice, eight types, each different in orifice diameter (0.5, 0.7, 0.9 and 1.1 mm) and thickness (1.0 and 3.0 mm), were tested to find the vest combination. For reference sake, the orifice originally used in the Maruhachi’s atomizer was 0.7 mm in diameter and 3 mm in thickness, but having a conical dip face to the swirlor.

TABLE I. SPECIFICATIONS OF TWIN–FLUID TYPE ATOMIZERS TESTED.

<table>
<thead>
<tr>
<th>Name</th>
<th>Pipe dia. D mm</th>
<th>Orifice dia. d mm</th>
<th>Orifice opening area ratio, (d/D)$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-type</td>
<td>21</td>
<td>13.8</td>
<td>0.429</td>
</tr>
<tr>
<td>M-type</td>
<td>14</td>
<td>9.16</td>
<td>0.429</td>
</tr>
<tr>
<td>S-type</td>
<td>7</td>
<td>4.58</td>
<td>0.429</td>
</tr>
</tbody>
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Figure 1. Twin-fluid atomizer patented by Sadatomi and Kawahara.

Figure 2. Single-fluid atomizer tested.
B. Hydraulic Performance Test

Fig. 3 shows the test apparatus for the single-fluid type atomizer. Water was supplied with a high pressure pump after controlling the volume flow rate, \( Q_L \), by monitoring the gauge pressure at the atomizer inlet, \( P_{L\text{in}} \). The pressure was measured with a calibrated sensor and a data acquisition system. A calibration curve between \( Q_L \) and \( P_{L\text{in}} \), obtained in our preliminary test, permitted us the accuracy of within 1% for the \( Q_L \) measurement. The hydraulic power required for the mist generation, \( L_L \), was obtained by substituting the data into

\[
L_L = (P_{L\text{in}} + \rho_L v_{L\text{in}}^2/2)Q_L.
\]

Here, \( v_{L\text{in}} \) is the mean water velocities at the atomizer inlet.

In the twin-fluid type [2-5], air was supplied from a gas compressor, and the volume flow rate, \( Q_G \), and the gauge pressure, \( P_{G\text{in}} \), at the atomizer inlet were measured with calibrated sensors and a data acquisition system. Water, on the other side, was sucked from a water tank whose water level was the same as the water inlet of the atomizer. The water flow rate, \( Q_L \), could be controlled with a valve before measuring flow rate. The pneumatic power required for the mist generation, \( L_G \), were obtained by substituting the above measured data into

\[
L_G = (P_{G\text{in}} + \rho_G v_G^2/2)Q_G.
\]

Here, \( \rho_G \) and \( v_G \) are the air density and the mean air velocity at the atomizer inlet.

Furthermore, mist droplet diameter was measured with an oil pond method. In the method, the droplets were captured momentarily by opening a shutter covering the inlet of a small oil pond, and the diameters of the droplets in the pond was measured with a digital microscope and an image processing system. Spray angle was measured with a picture and the radial distribution of mist flow rate below 0.50 m below from the atomizer exit. The distribution was determined by collecting the droplets with a lot of test tubes square arrayed.

C. \( \text{CO}_2 \) Adsorption Test

Fig. 4 shows the test room for \( \text{CO}_2 \) adsorption by the mist. The room was divided into the \( \text{CO}_2 \) room and the mist room by a perforated plate. The atomizer was placed at the center of the plate 1.8 m above from the bottom of the room, 1.2 m in width and depth and 2.0 m in height. \( \text{CO}_2 \) concentration in the mist room was detected by two sensors placed at the bottom. The procedure of the \( \text{CO}_2 \) adsorption test was as follows: Firstly, 1.5 l \( \text{CO}_2 \) at standard condition was filled in a balloon placed outside the \( \text{CO}_2 \) room. Secondly, three minutes after the mist spray in the mist room, the \( \text{CO}_2 \) in the balloon was released into the \( \text{CO}_2 \) room for two minutes for full diffusion while the mist was sprayed continuously in the mist room. Thirdly, after the stop of spray, \( \text{CO}_2 \) began to flow down through a lot of 50 mm I.D. holes in the perforated plate by removing a sheet covering the plate. At the same time, \( \text{CO}_2 \) concentrations at the bottom of the mist room were measured every 5 seconds for 10 minutes. To know the effects of the mist spray, a similar measurement with no mist spray was also conducted.

III. Experimental Results

A. Hydraulic Performance of Twin-fluid Type Atomizer [4]

Fig. 5 shows mist flow rate data, \( Q_L \), when the water suction valve was full opened, against the mean air velocity at the atomizer inlet, \( v_{G\text{in}} \). The data for L, M, S type atomizers are simultaneously plotted. \( Q_L \) increased with \( v_{G\text{in}} \) because a negative pressure downstream from the orifice was stronger with \( v_{G\text{in}} \). \( Q_L \) is highest in L type because the porous pipe area for sucking water becomes wider with the atomizer size.

Fig. 6 compares mist flow rate data, \( Q_L \), for the three sized atomizers against the power, \( L_L \). \( Q_L \) data when two S type atomizers were used are also shown. This figure teaches us that if \( Q_L \) demand is over 0.0125 l/s, multiple use of S type atomizer is better than the use of L type because \( L_L \) becomes low. Thus, S type is the best in the hydraulic performance.
orifice thickness, \( t \), are small. \( P_{L(\text{in})} \) increases non-linearly with \( v_{L(\text{in})} \) at a fixed \( d \) because it is the same as the pressure drop through the atomizer. In addition, the gradient of \( P_{L(\text{in})} \) to \( v_{L(\text{in})} \) is steeper with decreasing of the orifice diameter, \( d \).

Since \( t \) effects on the atomizer performance are small as described above, the data for \( t = 1.0 \) mm orifice case alone are used hereafter to compare data for the twin-fluid type.

Fig. 9 compares \( Q_L \) data between the single-fluid 1.0 mm thick orifice type at \( P_{L(\text{in})} = 100 \) kPa and 600 kPa and the twin-fluid S type. The abscissa is the power needed for the mist generation, \( L_L \) for the single-fluid type and \( L_L \) for the twin-fluid type. \( Q_L \) in the single-fluid type is roughly proportional to \( L_L \) while that in the twin-fluid type is roughly proportional to \( L_L \). The ratio of the mist generation rate to the power needed for the mist generation, \( Q_L/L_L \) or \( Q_L/L_L \), was about ten times higher in the single-fluid type than the twin-fluid type. Thus, for saving energy, the single-fluid type is superior to the twin-fluid type.

### C. Droplet Diameter and Atomization Angle

For the twin-fluid type atomizer, the Sauter mean droplet diameter of the mist, defined as \( d_{32} = \Sigma d_i^3/\Sigma d_i^2 \), was reported in our previous papers [4, 5]. Here, \( d_i \) is the diameter of each droplet. For the S type, most of the droplet diameter was 5 to 50 \( \mu \)m, and \( d_{32} \) was 82 \( \mu \)m at \( v_{G(\text{in})} = 78 \) m/s (\( Q_G = 180 \) l/min) and \( Q_L = 0.1 \) l/min [4]. In addition, \( d_{32} \) became smaller with increasing of \( v_{G(\text{in})} \), and with decreasing of \( Q_L \).

For the single-fluid type atomizer, droplets diameter data were obtained at \( P_{L(\text{in})} = 600 \) kPa in the present experiment for the four atomizers with 1 mm thick orifices. TABLE II lists the mean and the Sauter mean diameters of droplets captured at 0.3 m below the atomizer exit. The droplets becomes bigger with increasing of \( d \). The composition of the droplets is shown in Fig. 10. It depends on the orifice diameter, \( d \), i.e., the smaller droplets become dominant with decreasing of \( d \).

Fig. 11 compares the radial distributions of droplets at 0.5 m below the atomizer exit. The data for the twin-fluid S type,
Figure 10. Effects of orifice diameter on droplet diameter composition for single-fluid 1 mm thick orifice type atomizers.

Figure 11. Comparison of radial distribution of droplets captured at 0.5 m below atomizer exit.

Figure 12. Time variation in CO₂ concentration in air at the bottom of mist room – Effects of orifice diameter in single-fluid 1 mm thick type atomizers.

Figure 13. Time variation in CO₂ concentration in air at the bottom of mist room – Effects of mists generated by a single-fluid type atomizer (1 mm thick orifice with 0.7 mm orifice diameter) and a twin-fluid S type atomizer.

D. CO₂ Adsorption Performance

In Fig. 12, time variation in the CO₂ concentration in air at the bottom of the mist room are compared among five cases: four mist filled cases by the atomizers with different orifice diameters at \( t = 1.0 \) mm, and no mist spray case. Shortly after the release of CO₂ from the CO₂ room, the detection of CO₂ concentration at the bottom of the mist room was started. The CO₂ concentration in about 30 second from the start, showed the same value as that outside of the mist room, i.e., about 480 ppm, because CO₂ could not reach to the detectors. The concentration after 30 seconds rapidly increased with time, and took a maximum value at about 150 to 600 seconds. The arrival time to the detector depended on the existence of the mist, and the fastest case was the no mist spray case. In no mist spray case, the concentration after the peak decreased gradually because of some leakage of CO₂ to the outside.

The mass of CO₂ adsorbed by the mist is known from the concentration difference between the mist filled case and the no mist spray case. Thus, the atomizer with 0.7 mm orifice diameter is the best among the atomizers tested. Since it gave the highest percentage in a droplet diameter range from 20 µm to 80 µm (or 70 and 60 µm) in Fig. 10, the droplets in this diameter range must be effective to the CO₂ adsorption.

The mist whose droplet diameter is smaller than 20 µm is called “dry-mist” in Japan, and is reported to be effective to the mitigation of heat island phenomena in megalopolis [8]. This means that the droplets smaller than 20 µm cannot adsorb CO₂ because of evaporation. In addition, the droplets larger than say 80 µm seems ineffective to the CO₂ adsorption, because of too short adsorption time due to the faster falling velocity. Furthermore, the interfacial area concentration (= the sum of interfacial area divided by the volume occupied by droplets and air) is lower for the larger droplets than the smaller droplets at a fixed total liquid volume.

Fig. 13 compares the CO₂ adsorption performance between the mists filled with the single-fluid 0.7 mm orifice diameter type at \( P_{\text{lin}} = 600 \) kPa and the twin-fluid S type at \( v_{G_1} = 78 \) m/s and \( Q_L = 0.1 \) l/min. The CO₂ concentration difference from the no mist spray case is about twice larger in the twin-fluid type than the single-fluid type. This suggests that the droplets from 20 µm to 80 µm (or 70 and 60 µm) are twice more in the twin-fluid type case than the single-fluid type case.
By considering the CO₂ concentration difference between the value at 600 s and the value at 30 s for three cases, we can confirm that about 70 % of CO₂ in the mist room was adsorbed in the twin-fluid type case while about 35 % in the single-fluid type one. Thus, the twin-fluid atomizer is superior to the single-fluid atomizer in the CO₂ adsorption by the mist under the above operation conditions.

Figs. 14 (a) – (d) shows the pictures of mist room after the stop of spray by the single-fluid atomizer and the twin-fluid atomizer. Figs. 14 (a) and (d) are those shortly after the stop of spray while (b) and (d) 5 minutes later. In the single-fluid atomizer case, the inside of the room is lightly foggy because the larger droplets fell down within 5 minutes after the stop of spray. In the twin-fluid case, the other side, the inside of the room is densely foggy because almost of the droplets are smaller than 50 µm, and some of them suspended even after 5 minutes. This is why the CO₂ adsorbed is more in the mist by the twin-fluid atomizer.

iv. Conclusions

The performance of the twin-fluid water suction type atomizer invented by Sadatomi and Kawahara was compared with those of the single-fluid swirl type atomizer with the same inlet pipe diameter. For the twin-fluid type, the size effects on the hydraulic performance [4] and the air and water flowrates effects on the droplets size [5] are briefly introduced, and the best one, i.e., S type was selected. For the single-fluid type, the effects of orifice thickness and orifice diameter were clarified in the present study, and the best one, the atomizer of 1 mm thick orifice with 0.7 mm orifice diameter, was selected. From the comparison of the above two best atomizers, the followings were found:

1. The ratio of the mist generation rate to the power required, \( Q_1/L_p \) or \( Q_2/L_G \), was about ten times higher in the single-fluid type than the twin-fluid type.
2. The droplet size of the mist in the central part was similar between the two types, but that in the outer part was larger in the single-fluid type than the twin-fluid type.
3. The CO₂ adsorption performance by the mist was about twice higher in the twin-fluid type than the single-fluid type.

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References


About Authors:

Michio Sadatomi: Professor, Dept. of Advanced Mechanical Systems Graduate School of Science and Technology Kumamoto University, Japan.

Keiichi Tanaka: Master course student Dept. of Advanced Mechanical Systems Graduate School of Science and Technology Kumamoto University, Japan.

Akimaro Kawahara: Associate Professor Dept. of Advanced Mechanical Systems Graduate School of Science and Technology Kumamoto University, Japan.