Design Procedure and Performance Evaluation of a Flat-Jet Twin-Fluid Atomizer by Siphoning Liquid

J. F. Yao, K. Tanaka, A. Kawahara, and M. Sadatomi

***Abstract*—A design procedure and performance evaluation of a flat-jet atomizer is described. The objective is to achieve a flat spray with minimum drop size and high performance for stipulated flow conditions. In the design process, the flat spray was formed by using in-line orifices and a rectangular outlet. The high spray performance was achieved by adopting the same working principle of a full-cone atomizer patented by Sadatomi & Kawahara (2012), which only needs pneumatic power, and the liquid can be sucked by siphoning force due to the negative pressure caused by the orifice. In the evaluation process of the new design, the influence of the outlet with different lengths and the orifice with different shapes on spray characteristics were studied, and the optimum dimension and geometry of the outlet and orifice were determined. Next, at different flow conditions, the flat-jet atomizer was experimentally tested and the suitable flow condition was proposed. Finally, practical applications of the new design (e.g. CO_2 absorption) were recommended.**

***Index Terms*—Twin-fluid, flat-spray, siphon, outlet, orifice.**

I. Introduction

The superior performance of twin-fluid atomizers has motivated intensive studies during the past decades because of their wide applications to combustion, agriculture and industrial engineering [1], [2]. The function of atomizers is to transform bulk liquid into sprays and other physical dispersions of small liquid particles in a gaseous atmosphere. Especially, the atomization of twin-fluid atomizers is often accomplished by discharging a relatively slow-moving liquid into a high-velocity airstream [3]. Based on this theory, various kinds of twin-fluid atomizers with different spray patterns are developed depending on their respective applied purposes.

There are three basic spray patterns: full cone, hollow cone and flat fan (Fig. 1). Each of these has specific characteristics and applications. The full cone nozzle can produce large, evenly distributed drops and high flow rates, and it maintains its spray pattern over a range of pressures and flow rates. It is a low-drift nozzle and one typical application is soil incorporated herbicides. The hollow cone nozzle shows a spray pattern with more of the liquid concentrated at the outer edge of the pattern and less in the center. Any nozzle producing a cone pattern, including the whirl-chamber type, will not provide uniform distribution for broadcast applications when directed straight down at the sprayed surface. However, since hollow cone nozzles excel themselves by easily atomization of fine drops which move enough to compensate for the non-uniformity of the pattern, they are often used for atomization of fuels, spray-drying and in scrubbing towers for dust and gas [4]. The flat fan nozzle is effective in a line of spray. The impact of this spray is high when compared to full or hollow cone spray patterns, but not as high a solid stream nozzle. The droplet sizes produced by this type of nozzle are larger than cone nozzles, although very fine droplets can be produced by some air atomizing flat fan nozzles [5]. They are commonly used in series mounted on spray bars over conveyor systems due to their flat shape. In this way flat fan nozzles are used for pesticide spraying, coating, washing and lubricating applications for a huge number of industries and manufacturing processes.

There are two common methods to form a flat spray: elliptical orifice and deflection. For the elliptical orifice method, the liquid enters the nozzle in line with the axis length and is fed to a pressure chamber, from where it is ejected through an elliptical orifice. Flow pattern and spray angle are determined respectively from the orifice geometric and the orifice edge profile; in the deflection type nozzle, the liquid is fed under pressure to a round outlet orifice, and then deflected by a smooth curved surface so as to assume a flat-jet shape. This sophisticated design is of advantage since it offers a stronger jet impact using the same feed pressure. Experimental and numerical researches on the flat fan sprays can be found in [6].

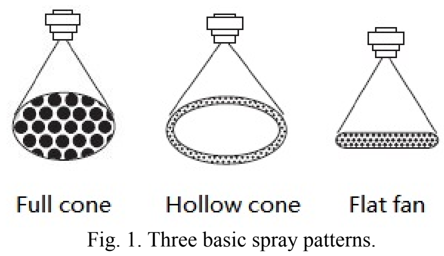

Fig. 1. Three basic spray patterns.

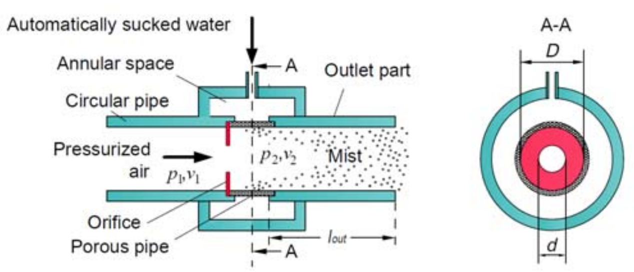

Fig. 2. Schematic diagram of the twin-fluid atomizer with full cone spray by siphoning liquid invented by Sadatomi & Kawahara [1].

Since 2008, our research team is working on the development and evaluation of a special large-flow-rate

Manuscript received April 2, 2014; revised July 14, 2014. This work was supported in part by Graduate School of Science and Technology of Kumamoto University, Budget number: 1619500408.

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DOI: 10.7763/IJET.2015.V7.831

twin-fluid atomizer (full cone spray type) with a low pneumatic power consumption by siphoning liquid based on the invention of Sadatomi & Kawahara [1] (Fig. 2). The working process is as follows: compressed air is fed through the inlet (with velocity v_1, pressure p_1), then water is sucked automatically into the air-flow through the porous pipe by the vacuum pressure (p_2) arising just behind the orifice. With the increased high velocity (v_2), air and water interact each other in the internal mixing chamber, and mist is formed and sprayed throughout the outlet. All the parts of our atomizer are easy to manufacture because of its simple structure, e.g. the inlet and outlet are straight cylindrical pipes, the orifice and porous pipe are cut off and assembled easily [7].

From our previous study on three sizes of atomizers (named LO, MO, SO), it has been clarified that, very small droplets (about 80% of their diameters are less than 20 μm) could be generated with lower air pressure in high efficiency [8] due to the utilization of a fiber porous pipe and an orifice; spray angle could be expanded by using a propeller under the nozzle, in order to improve the performance of harmful gas absorption [9]. In addition, the influence of the component geometries on the spray performance was studied, which gives a guiding significance for the follow-up designing and research of twin-fluid atomizers [10], [11].

Though the superiority of the previous atomizers was confirmed, there are still a few points we should consider:

1) The smaller size of atomizer with full cone spray has a higher liquid atomization efficiency than the larger ones, and multi-use of small sized atomizer was recommended [10]. However, several cone spray atomizers grouped in a cluster have a poor coverage performance since each one has a spray coverage in a round area.
2) The previous atomizers have been successfully applied to air cooling [8], CO_2 absorption [9], etc. We want to extend the application range of our atomizer (e.g. spray painting, spray washing), which is limited by the cone spray pattern.

The use of an improper performance spray nozzle results in over or under application. The over application is wasteful and costly; the under application results in a reduction in performance or the need for re-application. In order to make full use of the advantages of our atomizer, and extend its application fields, a new flat-jet atomizer is proposed in the present study. The new one has a cuboid-shaped outlet to form a flat-jet spray, which is quite different from the traditional ones (i.e. elliptical orifice and deflection). In the present paper, after the description of the procedure of designing, experimental results on the optimization of geometrical factors and flow conditions is described. Finally, the application of the new flat-jet atomizer is recommended.

II. Design Considerations

A. Evaluation Criterion for Designing

Based on the study of various types of atomizers, Lefebvre (1989) [3] described that, an ideal atomizer should possess all the following characteristics:

3) Ability to provide good atomization over a wide range of liquid flow rates;
4) Rapid response to changes in liquid flow rate;
5) Freedom from flow instabilities;
6) Low power requirements;
7) Capability for scaling, to provide design flexibility;
8) Low cost, light weight, ease of maintenance, and ease of removal for servicing;
9) Low susceptibility to damage during manufacturing and installation.

In addition to the above features, the present new atomizer should have the following feature:

10) Flat jet with uniform spray distribution within the scope of the spray;
11) Low designing cost (e.g. interchangeability of parts), try to utilize the previous experimental facility as much as possible.

B. Designing Scheme

The new flat-jet atomizer is based on the previous atomizer (Fig. 2), and is composed of five parts (Fig. 3):

1) Inlet; the same interface with that of the previous middle sized atomizer, having the taper pipe of 1 inch.
2) Orifice; three types with different geometrics (i.e. 4-Cir.,4-Rec., 1-Rec. in Fig. 4) but the same opening area ratio (0.429) with the previous atomizer in order to study the influence of orifice geometry on spray performance, since different orifices may generate different drop sizes and different pressure loss [12].

The definition of the opening area ratio, β, is:

$$\beta = \frac{A_o}{A} \tag{1}$$

A_o is the opening area of the orifice, and A is the cross sectional area of the outlet.

3) Porous plate; 5 mm width × 32 mm length with numerous holes of 25 μm in diameter (same as that of the porous pipe in the previous atomizer).
4) Water suction part; the interface to connect to liquid source, having the same female screws as the previous atomizer.

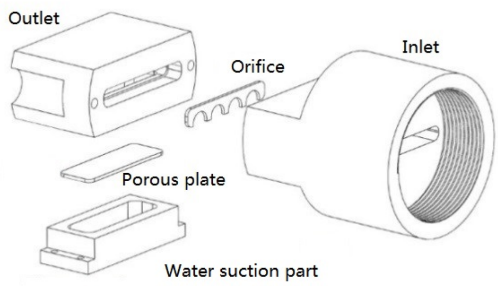
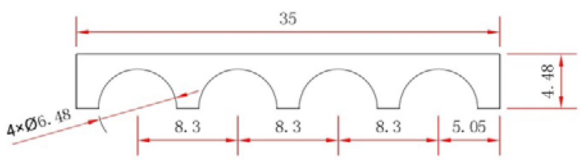
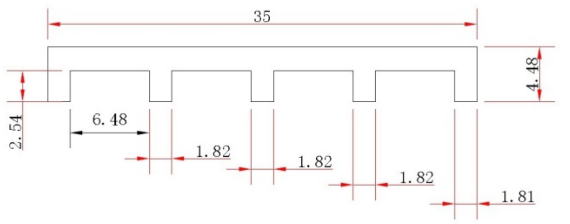


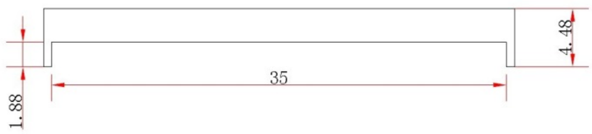
Fig. 3. Designing scheme of the new flat-jet atomizer.



(a) 4-Cir.



(b) 4-Rec.



(c) 1-Rec.

Fig. 4. Orifices in different geometries but the same area ratio.

TABLE I: MAIN DIMENSIONS

Name	Chamber [mm]	Orifice d_O [mm]	Orifice ^{o} [mm^2]	Chamber [mm^2]	Area ratio (=A_o/A)
SO	7 i.d.	4.58	16.5	38.5	0.429
FO	4.48×35	6.48	65.9	153.9	0.429

5) Outlet; a flat cuboids with the inner dimension of 35 mm wide and 7 mm high, four times in area of the small sized atomizer (Table I). Since the outlet length affects water suction force and drop size as studied by Yao *et al*. [10] and Kushari [13], four types of outlets in different lengths (20.5 mm, 24 mm, 27.5 mm, 31 mm) were tested, in which 20.5 mm is the optimum length in the previous small sized atomizer [9].

III. EXPERIMENTS AND METHODS

The overall experimental apparatus for the hydraulic performance test is revealed in Fig. 5. Two bold lines are connected to the atomizer nozzle, one line for compressed air supply from an air compressor, and the other for water suction from a water tank. The level of water surface in the tank is the same as that of the water suction port of the atomizer to eliminate the influence of level difference. Two more fine lines are connected to pressure sensors. The output signals from the flow rate and pressure sensors were acquired by a personal computer via an A/D converter. In order to collect and obtain the radial distribution of the droplets, 88 test tubes each 13 mm apart in center to center distance are arranged in line in four radial directions at 800 mm downward from the atomizer.

The atomization mechanism of the present atomizer is quite similar to an airblast atomizer applied to engine combustion as described by Lefebvre [14], who experimentally proved that, the atomization effect at a low liquid injection, becomes almost solely dependent on the gas/liquid mass flow rate ratio (GLR) and the momentum of the atomizing air. More specifically, Lefebvre stated that, gas/liquid mass flow rate ratio (GLR) played a key role in the mean droplet size in all cases. So the influence of various flow rates of air and liquid on the droplet size was studied as a key point in this paper. A general equation to evaluate the atomization quality (i.e. the droplet size) is generally described as:

$$d_{ab} = \left[\frac{\sum_i n_i d_i^{\,a}}{\sum_i n_i d_i^{\,b}} \right]^{\frac{1}{a-b}} \tag{2}$$

In (2), i denotes the number of a droplet size range, n_i is the number of the droplets in the size range i, and d_i is the diameter of the size range i. Thus, for example, d_{10} is the arithmetic mean diameter of all the drops in the spray. d_{32}, the Sauter mean diameter, is the ratio of total volume to total surface area of the entire spray, which is often of use in the applications to efficiency studies and mass transfer. In addition, Lefebvre [14] suggest that d_{32} is the best measure of the fineness of sprays. So d_{10} and d_{32} are used to evaluate the spray characteristic in the present study.

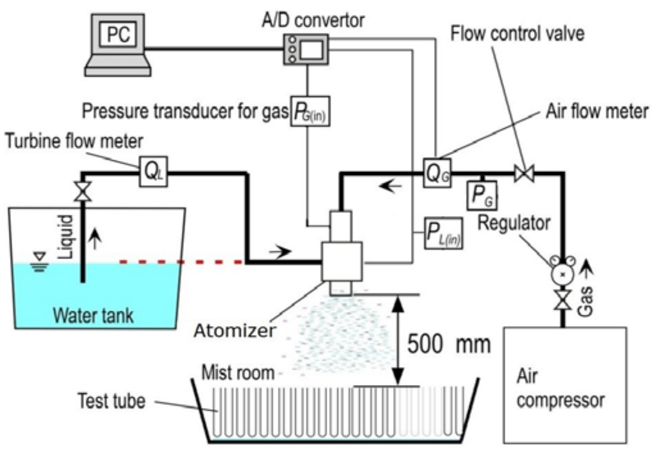


Fig. 5. Experimental setup.

In the experiment, the operation process is as follows: firstly, by using the 4-Cir. orifice, four outlets with different lengths were tested and optimized; then, three types of orifices in different shapes with the optimum outlet were tested and optimized; finally, spray characteristics of the optimized flat-jet atomizer were studied at some specified flow conditions, in order to clarify the suitable flow conditions for practical applications.

IV. RESULTS AND DISCUSSION

Two purposes in this section are: to clarify the spray performance of the new design, and to optimize some parts of the atomizer, since the optimization of an atomizer design is quite necessary in order to obtain the best spray performance in applications.

A. Outlet in Different Lengths

The liquid volume flow rate (Q_L) of the atomizer with different outlet length (l_{out}) is plotted against the gas volume flow rate (Q_G, under standard conditions) in Fig. 6. The data for the respective length have the similar trends, namely, the water flow rate increases with the increasing of the gas volume flow rate. This is attributed to the stronger negative pressure caused by the larger gas volume flow rate. Though the difference among the four outlets is small, the outlet length of 27.5 mm has a little larger water flow rate than others. Similar influence of the outlet length on the liquid flow rate was reported by Watanawanyoo *et al*. [15] for several types of twin-fluid atomizers.

Moreover, for the influence of outlet length on drop size, Kufferath *et al*. [16] stated that, longer internal mixing chamber prompts the internal droplet disintegration due to the extension of the mixing time, but leads to more pressure loss; on the other hand, shorter chamber causes the prominent oscillation in the spray, indicating unstable atomization. For our atomizers, the outlet is actually the mixing internal chamber, and a higher water suction performance broadens the range of GLR for different applications; as mentioned before, the droplet size atomized by our atomizer is dominantly influenced by GLR and air velocity, so the influence of the outlet length on the droplet size was not studied in the present experiment. Eventually we selected the outlet length of 27.5 mm as an optimum one for the following test due to its largest water suction performance.

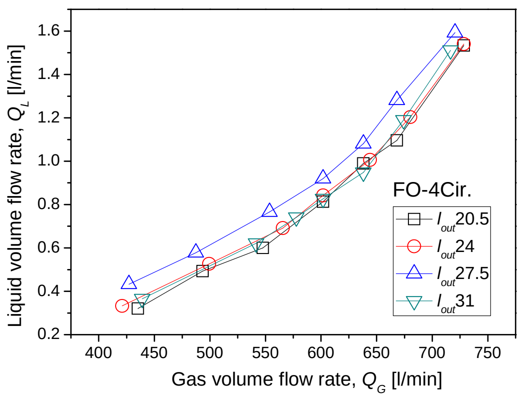


Fig. 6. Influence of outlet length on water suction performance.

B. Orifices in Different Geometries

Fig. 7 compares of liquid volume flow rates (Q_L) for different orifice geometries. Q_L increases gradually as the gas volume flow rate (Q_G) increases for each orifice type. The 4-Cir. orifice with 4 semi-holes shows stronger negative pressure than 4-Rec. orifice in all gas flow rate region, which is attributed to the less pressure loss produced by the circular shape than the rectangular shape [12]. On the other side, the narrow passage inside the atomizer, i.e. 1-Rec. orifice, inevitably brings about an uneven gas-flow distribution. As a result, the gas-flow in the internal mixing chamber with 1-Rec. orifice is much more concentrated in the center of the flow cross section than that of 4-Rec., which greatly weakens the total of the water suction force in the entire area of the porous plate. Therefore, the liquid flow rate induced by 1-Rec. orifice is lower than that by 4-Rec. orifice.

From an economical point of view, liquid atomization efficiency is the higher the better, which can be calculated by (3) and (4) [17]:

$$L_G = (p_1 + \frac{\rho_{G1}}{2} v_{G1}{}^2) Q_G \quad (3)$$

$$\eta_M = (\rho_L Q_L v_{G1}{}^2 / 2) / L_G \quad (4)$$

In (3), L_G is the pneumatic power consumed by the atomizer, p_1 is the gauge pressure of gas with a density of ρ_{G1} and a mean velocity at v_{G1} at the inlet of the atomizer, Q_G is the gas volume flow rate under the standard conditions. In (4), v_{G1} is the velocity of the liquid droplet, but is taken to the same as that of air at the exit of the outlet.

The atomization efficiencies for the atomizers with different orifices are presented in Fig. 8. 1-Rec. orifice has a similar atomization efficiency with that of 4-Cir. orifice at lower Q_G, nevertheless, it has a similar efficiency with that of 4-Rec. orifice at a higher Q_G, just because uneven distribution of gas flow increases with the increase of Q_G, resulting a decrease of Q_L. Anyway, the atomizer with 4-Cir. orifice has the highest efficiency among the three types.

As for the influence of orifice geometry on the drop size, we have studied for the previous circular atomizers and concluded that the orifices in fractal geometries generate various velocity scales including more mixing and causing the flow to form a series of jets, then more disturbances in the mixing chamber and more mixing between air and water, resulting in a finer droplet spray. From this point, the present atomizer with 4-Cir. orifice and 4-Rec. orifice are expected to generate a finer spray than that with 1-Rec.

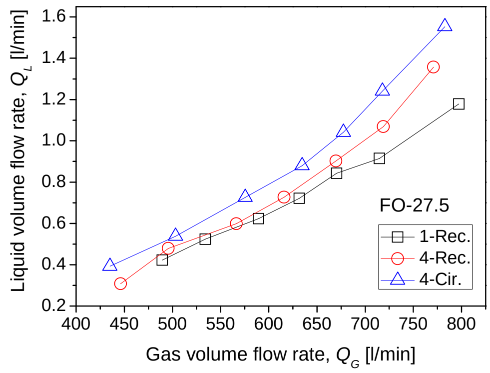


Fig. 7. Influence of orifice shape on water suction performance.

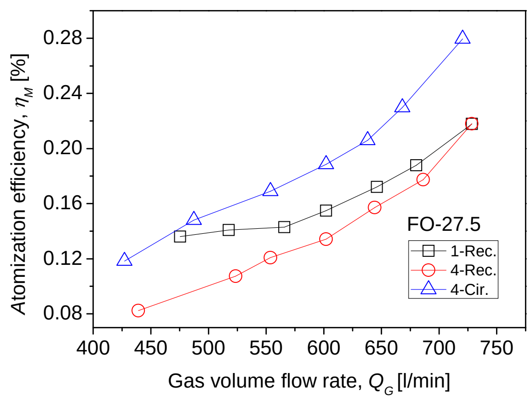


Fig. 8. Comparison of liquid atomization efficiencies (η_M) among three types of orifices.

As a summary of the experimental results for the three types of orifices, 4-Cir. orifice was selected as the optimum one for the following study because of its high atomization efficiency and fine spray characteristics.

C. Comparison between Two Types of Atomizers

As mentioned before, the small sized atomizer (SO-4.58-20.5, the orifice diameter 4.58 mm, the outlet length 20.5 mm) used in our previous study showed a high spray performance and applied successfully to some practical applications [8], [9]. So, the present flat-jet atomizer (FO-4Cir.-27.5) is compared with SO-4.58-20.5, which can be regarded as an evaluation criterion.

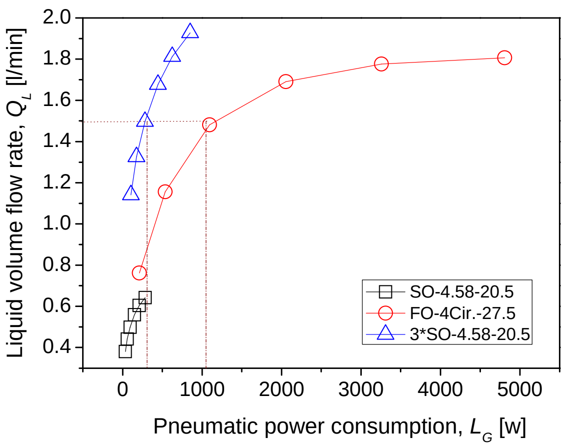


Fig. 9. Comparison of liquid volume flow rates (Q_L) between two types of atomizers against pneumatic power consumptions (L_G).

Fig. 9 compares the liquid volume flow rates (Q_L) between two types of atomizers against pneumatic power consumptions (L_G). The gradients of two curves decrease with the increase of pneumatic power, that means more energy supplied, more power loss. The flat-jet atomizer (FO-4Cir.-27.5) gives much larger Q_L than the small sized atomizer (SO-4.58-20.5) by consuming more power (L_G), just because the flat-jet atomizer has a larger inlet cross sectional area, four times of that the small sized one. The triple use of SO-4.58-20.5, which is plotted as triangular symbols, is compared with FO-4-Cir.-27.5, because FO-4-Cir.-27.5 can generate mist as triple flow rate of SO-4.58-20.5. The comparison shows that, FO-4-Cir.-27.5 consumes about 4 times energy of SO-4.58-20.5 (see the third data point as an example). For practical applications, if the jet flow pattern is not specially specified, the multi-use of SO-4.58-20.5 is recommended [11]. If the jet flow pattern of flat-spray is required, the use of FO-4Cir.-27.5 is recommended in $Q_L < 1.5$ l/min, since it consumes too much energy in $Q_L > 1.5$ l/min.

D. Spray Characteristics in Different Flow Conditions

Table II compares the droplet sizes in different flow conditions for FO-4Cir.-27.5 atomizer. Since the gas velocity at the inlet of the atomizer (v_{Gin}) and gas/liquid mass flow rate ratio (GLR) are the two predominant factors influencing the drop size, the flow conditions are set two different liquid volume flow rates for two different mean gas velocities. At a fixed gas velocity of v_{Gin} = 101 m/s or 72 m/s, the arithmetic mean diameter (d_{10}) and the Sauter mean diameter (d_{32})of droplets decreased with increasing of GLR. When the GLR is similar but gas velocities are different, d_{10} and d_{32} decrease with the increasing of gas velocities. Moreover, the influence of gas velocity (v_{Gin}) on droplet size is much more than that of gas/liquid mass flow rate ratio (GLR), though v_{Gin} and GLR are regarded to be two predominant factors influencing the droplet size (see pictures in Fig. 10).

Elshanawany and Lefebvre [18] reported that: for the twin-fluid atomizers, except for the influence of gas velocity and gas/liquid mass flow rate ratio, the droplet size is also influenced by the atomizer size, and it increased according to about 0.43 power of the atomizer size, since the drop size for the twin-fluid atomizers depends on the thickness of the pre-filming liquid sheet or the diameter of the ligament. For our atomizer, both FO-4Cir.-27.5 and SO-4.58-20.5, they all employed the same fiber porous material with small holes of 25 μm in diameter. So, all of our atomizers have the similar droplet sizes if the gas velocity and gas/liquid flow rate ratio are the same.

In Fig. 11, one typical photo of spraying by flat-jet atomizer was taken at v_{Gin} = 101 m/s, Q_L = 1.5 l/min, and the spray angles for long and short sides from the outlet of FO-4Cir.-27.5 were roughly measured. Since the high penetration and turbulence in the mist flow, the spray area in the target surface (placed 800 mm downstream from the atomizer outlet) is as a shape nearly between elliptical and rectangular.

TABLE II: DROPLET SIZES IN DIFFERENT FLOW CONDITIONS

v_{Gin} [m/s]	Q_L [l/min]	GLR [-]	d_{10} [m]	d_{32} [m]
101	1.5	1.3	37	64
	0.75	2.5	26	50
72	1.1	1.4	68	112
	0.55	2.8	56	106

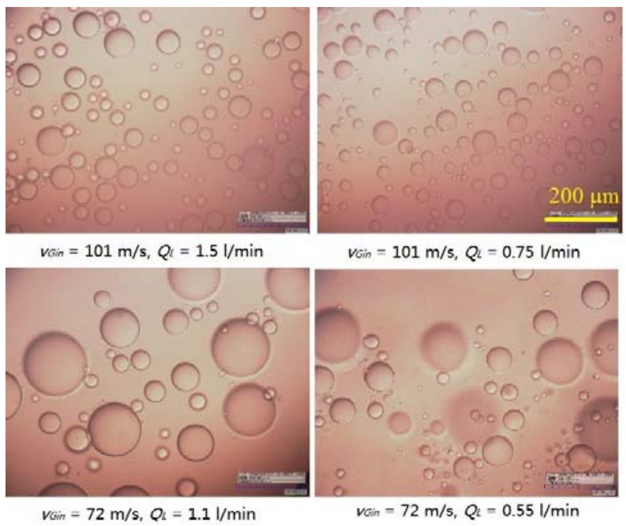
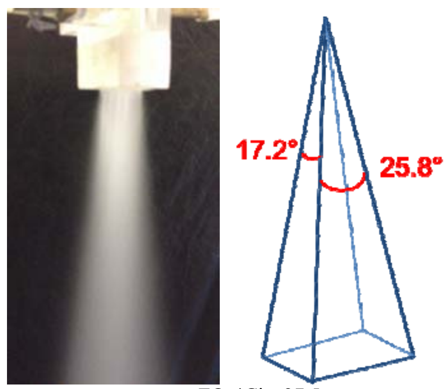


Fig. 10. Droplets captured by microscope camera in different flow conditions.



FO-4Cir.-27.5.

Fig. 11. Spray image and spray angle at v_{Gin} = 101 m/s, Q_L = 1.5 l/min.

Furthermore, the influence of flow conditions and outlet length on the spray angle is also reported by some researchers though distinct difference was not found in our experiments. Shafaee [19] *et al*. stated that, increasing the length of mixing chamber causes a little decrease in spray cone angle; in addition, Juslin *et al*. [20] proved that, increasing the pressure leads to a decline in the spray angle.

E. Practical Applications

As for the practical applications of the new flat-jet atomizer, some recommendations are as follows:

CO_2 absorption in a large-closed farm (i.e. pig farm, chicken farm), due to the convenience of multi-use by flat-spray. The overlap area of sprays by flat-jet atomizers in a row is much less than that of the full cone atomizers. The CO_2 absorption performance by mist was clarified by Yao *et al*. [11] for SO-4.58-20.5.

As a matter of fact, the flat-jet spray itself should be valid for any circumstance where needs a flat spray or a flat spray contributes to a more effective working condition.

V. Conclusions

The design procedure and performance evaluation of a new flat-jet twin-fluid atomizer was presented in this paper. The results of the experimental study are summarized as follows:

1) A flat-spray could be formed by employing a rectangular outlet, and four different lengths of outlets (20.5 mm, 24 mm, 27.5 mm and 31 mm) were tested, and the optimum outlet length was confirmed to be 27.5 mm.
2) High spray performance with low power consumption was achieved, since pneumatic power alone was necessary. The liquid could be sucked by a negative pressure arisen downstream from an orifice. The influence of different shapes of orifices (4-Cir., 4-Rec. and 1-Rec.) on spray characteristics was studied and the optimum one was determined to be 4-Cir. orifice.
3) The influence of jet flow conditions on spray characteristics was studied, mean gas velocity and gas/liquid flow rate ratio are the two main factors influencing the droplet size. The suitable flow conditions (v_{Gin} = 101 m/s and Q_L = 0.75 l/min to 1.5 l/min) were recommended because of the fine spray and relative low power consumption at this flow condition.
4) The new twin-fluid atomizer with a flat spray can be applicable to CO_2 absorption in large-closed farms, just because the conveniences of multi-use due to its advantage of flat spray. Furthermore, it is applicable to any circumstance where needs a flat spray or a flat spray contributes to a more effective working condition.

Future study will focus on the multi-use of flat-jet atomizer, and comparison of spray characteristics between multi-use of the flat-jet atomizer and full-cone atomizer. Expansion of the application fields of all the atomizers in our research team is also being considered.

Acknowledgment

The authors would like to express their sincerely appreciation to Graduate School of Science and Technology of Kumamoto University for the Research Funding Support (Budget Number: 1619500408); Many Thanks to Mr. S. Tsuji, the undergraduate course student at Kumamoto University, for his experimental cooperation. Appreciation is also for Chinese Government for the full scholarship to Mr. Jiafeng Yao.

References

[1] M. Sadatomi and A. Kawahara, "Fluids mixer and fluids mixing method," Japanese Patent, no. 5103625, 2012.

[2] N. Sozbir and S. C. Yao, "Experimental investigation of water mist cooling for glass tempering," *Atomization and Sprays*, vol. 14, pp. 191-210, 2004.

[3] A. H. Lefebvre, *Atomization and Sprays*, Hemisphere Publishing, United States, 1989.

[4] S. Nonnenmacher and M. Piesche, "Design of hollow cone pressure swirl nozzles to atomize newtonian fluids," *Chemical Engineering Science*, vol. 55, pp. 4339-4348, 2000.

[5] J. C. Thompson and J. P. Rothstein, "The atomization of viscoelastic fluids in flat-fan and hollow-cone spray nozzles," *Journal of Non-Newtonian Fluid Mechanics*, vol. 147, pp. 11-22, 2007.

[6] M. Altimira, A. Rivas, G. S. Larraona, R. Anton, and J. C. Ramos, "Characterization of fan spray atomizers through numerical simulation," *International Journal of Heat and Fluid Flow*, vol. 30, pp. 339-355, 2009.

[7] M. Sadatomi, A. Kawahara, H. Matsuura, and S. Shikatani, "Micro-bubble generation rate and bubble dissolution rate into water by a simple multi-fluid mixer with orifice and porous tube," *Experimental Thermal and Fluid Science*, vol. 41, pp. 23-30, 2012.

[8] M. Sadatomi, A. Kawahara, K. Fukamachi, F. Matsuyama, and N. Tanaka, "Development of a new large-flow-rate and efficient mist generator, and its application to air cooling in greenhouses," *Multiphase Science and Technology*, vol. 22, pp. 79-93, 2010.

[9] J. F. Yao, A. Kawahara, M. Sadatomi, E. Sakurai, and S. Furusawa, "Expansion of mist jet generated by a special twin-fluid atomizer for co_2 capture," *WIT Transactions on Engineering Sciences*, vol. 80, pp. 495-506, 2013.

[10] J. F. Yao, K. Tanaka, A. Kawahara, and M. Sadatomi, "Performance evaluation of an air assisted atomizer with liquid siphon," *Journal of Applied Sciences*, vol. 13, pp. 4985-4993, 2013.

[11] J. F. Yao, K. Tanaka, A. Kawahara, and M. Sadatomi, "Geometrical effects on spray performance of a special twin-fluid atomizer without water power and its co_2 absorption capacity," *Japanese Journal of Multiphase Flow*, vol. 27, pp. 2014.

[12] A. A. E. A. Aly, A. Chong, F. Nicolleau, and S. Beck, "Experimental study of the pressure drop after fractal-shaped orifices in turbulent pipe flows," *Experimental Thermal and Fluid Science*, vol. 34, pp. 104-111, 2010.

[13] A. Kushari, "Effect of injector geometry on the performance of an internally mixed liquid atomizer," *Fuel Processing Technology*, vol. 91, pp. 1650-1654, 2010.

[14] A. H. Lefebvre, "Some recent developments in twin-fluid atomization," *Particle & Particle Systems Characterization*, vol. 13, pp. 205-216, 1996.

[15] P. Watanawanyoo, H. Mochida, T. Furukawa, M. Nakamura, and H. Hirahara, "Experimental study on the spray characteristics of an air assisted atomizer with internal mixing chamber," *European Journal of Scientific Research*, vol. 84, pp. 507-521, 2012.

[16] A. Kufferath, B. Wende, and W. Leuckel, "Influence of liquid flow conditions on spray characteristics of internal-mixing twin-fluid atomizers," *International Journal of Heat and Fluid Flow*, vol. 20, pp. 513-519, 1999.

[17] M. Sadatomi, F. Matsuyama, A. Kawahara, and T. Fukamachi, Development of a large-flow-rate mist generator-prediction of hydraulic performance, Proceeding of the ASME Fluids Engineering Division Summer Meeting, *ASME*, California USA, 2007, pp. 507-514.

[18] M. S. Elshanawany and A. H. Lefebvre, "Airblast atomization - effect of linear scale on mean drop size", *Journal of Energy*, vol. 4, pp. 184-189, 1980.

[19] M. Shafaee, S. A. Banitabaei, V. Esfahanian, and M. Ashjaee, "An investigation on effect of geometrical parameters on spray cone angle and droplet size distribution of a two-fluid atomizer," *Journal of Mechanical Science and Technology*, vol. 25, pp. 3047-3052, 2012.

[20] L. Juslin, O. Antikainen, P. Merkku, and J. Yliruusi, "Droplet size measurement: I. Effect of three independent variables on droplet size distribution and spray angle from a pneumatic nozzle," *International Journal of Pharmaceutics*, vol. 123, pp. 247-256, 1995.

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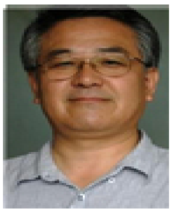

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