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Performance Evaluation of an Air Assisted Atomizer with Liquid Siphon

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Abstract: Experimental studies were conducted for a special air assisted atomizer patented by Sadatomi and Kawahara (2012); in which atomization is attained by supplying the pressurized air alone into a mixing chamber inside the nozzle, and water can be sucked automatically with siphon principle. Since the energy for atomization is only supplied by an air compressor, consumption of energy to produce a fine spray is lower than usual twin-fluid-type atomizers. In our previous study, experimental and analytical results for the atomizer of small size with outlet of 7 mm i.d. were reported. In the present paper, in order to test the scaling capability of the atomizer, similar experiments have been conducted for that of medium size with outlet of 14 mm i.d. In the experiments, atomizers with a series of outlets in different lengths were tested since some spraying effects (vacuum pressure, diameter of droplet, etc.) are considered to be influenced by the lengths of outlet. In addition, six types of PET (Polyethylene Terephthalate) propellers with different blades and outer diameters were tested to expand the spray dispersion. After the optimization of the middle sized atomizer, comparisons of atomization performance were made between the two sized atomizers, and the superiority of the small sized atomizer was confirmed.

Key words: Atomizer, liquid siphon, outlet length, propeller

INTRODUCTION

Atomization is normally fulfilled by discharging a liquid at high velocity into a relatively slow moving air stream. Typical examples include the various forms of pressure atomizers and also rotary atomizers that eject the liquid at high velocity from the periphery of a rotating cup or disc. An alternative method is to eject a high-velocity air-stream to a relatively slow moving liquid. The latter approach is generally called twin-fluid, air assisted, or air blast atomization (Lefebvre, 1989a).

The air assisted atomizer is one of the typical twin-fluid atomizers (other types are air blasting, effervescent nozzles, etc.), where the compressed air is supplied for atomizing the liquid, while the liquid is supplied by one of the three ways, pressure feed, gravity feed, and siphon principle. Actually, the air assisted atomizer provides the finest degree of atomization under a given flow capacity and supplied pressure (Liu, 1999).

Lal *et al.* (2010) described that an air assisted atomizer provided droplets with Sauter mean diameter in the range of 15 - 85 μm, atomized by both pressurized air and water flow. The experimental data suggested that such injectors can be potentially used in the suppression of fire with high mist generation rate and small droplet size. However, from the perspective of energy saving, this generator consumes higher power than that of (Watanawanyoo *et al.*, 2012), where the pressurized air expands within the internal mixing chamber, thereby helping the liquid be sucked by a vacuum pressure due to the ejector effect. This atomizer possessed the sufficient performance and spray characteristics required for the micro gas turbine systems. Nevertheless, the atomizer has the primary nozzle and secondary nozzle, which lead to a relative complex structure from the perspective of manufacturing.

An air assisted atomizer with an orifice in the flowing air tube was patented by Sadatomi and Kawahara (2012) in Fig. 1. In the atomizer, the pressurized air is supplied into the air tube, then the water is sucked automatically into the air flow through a porous pipe by vacuum pressure arising just downstream the orifice. With the increased high velocity, air and water interacts each other in the internal mixing chamber, and mist is formed and discharged through the outlet.

The atomizer has the following merits:

- it is the lower power consumption since the energy is supplied only by an air compressor or blower, quite lower than those for other atomizers, this characteristic has been confirmed by Sadatomi *et al.* (2010)

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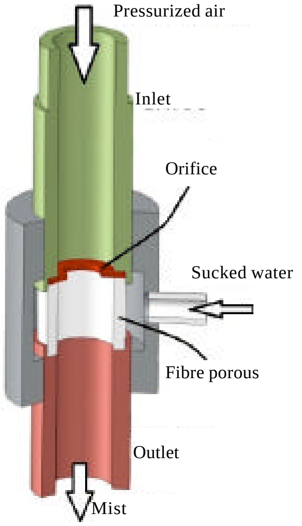

Fig. 1: Schematic of the air assisted atomizer patented by Sadatomi and Kawahara (2012)

- it is easy to manufacture because of the simple structure, e.g. straight tubes, orifice and porous pipe are cut off and assembled easily (Sadatomi *et al*., 2012)
- Very small droplets (about 80% of their diameters are less than 20 μm), i.e., fine mist, can be generated with low air pressure, because water is discharged into a highly turbulent air flow tube via a fiber porous pipe with small holes of 25 μm in diameter (Yao *et al*., 2013)

In the previous study, experimental and analytical results for the atomizer of small size with outlet of 7 mm i.d. were reported (Sadatomi *et al*., 2010; Yao *et al*., 2013). In the present paper, similar experiments have been conducted for that of medium size with outlet of 14 mm i.d. In order to maximize the spray performance of the atomizer, a series of outlet parts and propellers were tested to find the best specification. After that, comparisons are made between the small size and middle size. From this, we tried to understand the capacity for scaling of the atomizer, in order to provide design flexibility.

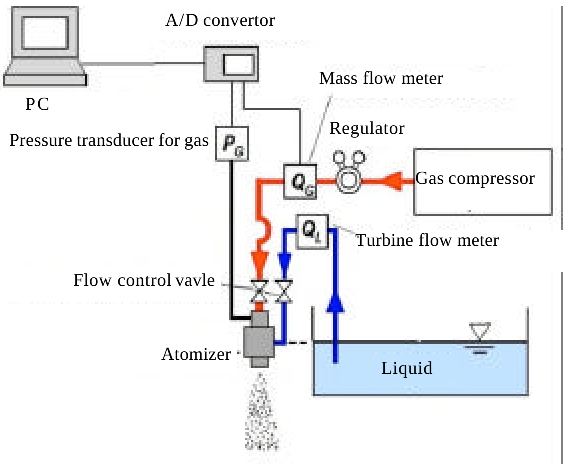

Fig. 2: Schematic diagram of experimental apparatus

Table 1: Specifications of small and middle sized atomizers

Name	D (mm)	d_0 (mm)	□ ($d_0 2/D_2$)	Porous pipe
SO4.58-FP	7	4.58	0.429	Fibre
MO9.16-FP	14	9.16		

EXPERIMENTS AND METHODS

Experimental setup: Two sizes of atomizers with the same proportion were manufactured based on the patent of (Sadatomi and Kawahara, 2012) as listed in Table 1. In the present experiments, we focus on studying MO9.16-FP. Here, M means the middle sized atomizer with the mixing chamber diameter of 14 mm, O the orifice-type atomizer, 9.16 mm the orifice diameter, FP the fibre porous. The confirmed specifications of MO-9.16-FP atomizer includes outlet diameter (inner diameter of the mixing chamber), D, the orifice diameter, d_o, the opening area ratio, β^2, water penetration diameter in the fibre porous, d_H, and the thickness of the fibre porous pipe, t_p, and the porous material. Effects of other parameters, like the length of outlet, the spray angle, etc., are studied in the present experiments.

The schematic diagram of experimental apparatus for the hydraulic performance test is revealed in Fig. 2. The apparatus is composed of atomizer, gas supply system, liquid supply system and measurement system. In the gas supply system, an air compressor is utilized to supply an appropriate air pressure. The liquid supply system only contains a water tank and a vinyl tube without pressure source. The level of water surface in the tank is the same as that of the water suction port of the nozzle to eliminate the effects of the level difference. The output signals from the flow rate and pressure sensors are acquired by a personal computer via an A/D converter.

Atomizers with outlets in different lengths: The length of the mixing chamber of an atomizer was proved to have an influence on spray characteristics, such as droplet size (Kushari, 2010; Ferreira *et al*., 2009), spray cone angle (Shafaee *et al*., 2012). For the present atomizer, except for these influences, another factor should be considered.

Table 2: Specification of atomizers with different outlet lengths

Name	Outlet l_{out}(mm)
MO9.16-FP-34.0	34.0
MO9.16-FP-41.0	41.0
MO9.16-FP-44.5	44.5
MO9.16-FP-48.0	48.0

Table 3: Specifications of PET propellers

Name	Blades (-)	Outer dia. (mm)	Core dia. (mm)	Thickness (mm)
b3d50	3	50	1.2	0.5
b4d50	4			
b3d60	3	60		
b4d60	4			
b3d70	3	70		
b4d70	4			

That is, the water flow rate is influenced by the length of outlet (mixing chamber, l_{out}), since the water is sucked by the negative pressure induced by the orifice. The outlet of the present atomizer is also the mixing chamber, and there exists the optimum length (l_{out}) since too long l_{out} means larger pressure loss, while too short l_{out} means zero or shorter vacuum pressure region. Consequently, different lengths of the outlets (l_{out}) results in different water suction capacity. So we need to test the different lengths of the outlet and find the optimum l_{out}. The specifications of outlets are listed in Table 2.

Propellers for expansion of spray angle: A spray angle is the opening angle of the atomized droplets jet from the outlet, which is one of the fundamental parameters for the choice of atomizers. The present atomizer has a spray angle of 24°, it is better to expand the spray angle for the application of air cooling, CO_2 absorption, etc. (Dimiccoli *et al*., 2000).

In the present study, six types of PET (Polyethylene Terephthalate) propellers with different number of blades and outer diameters are tested in order to seek for the optimum one with the best spray angle expansion effect. The specifications of six PET propellers are listed in Table 3. The name of propeller b3d50 for example, stands for a PET propeller with 3 blades, and 50 mm in outer diameter. Figure 3 shows the photograph of the six propellers.

Figure 4 shows the schematic of the spray angle expansion. The propeller is set about 80 mm downward from the nozzle, which can be rotated automatically by an action of the air stream with mist. In order to collect and obtain the radial distribution of the mist, 22 test tubes each 13 mm apart in centre to centre distance are arranged in line in four radial directions at 500 mm downward from the nozzle.

RESULTS AND DISCUSSION

Lefebvre (1989a) concluded some general characteristics an ideal atomizer should possess:

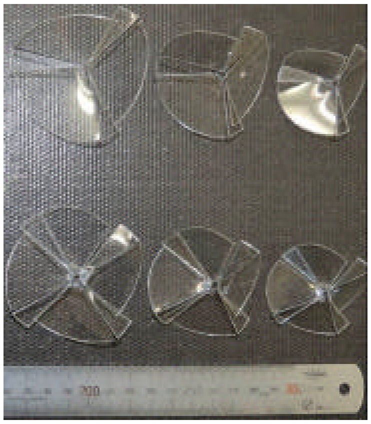

Fig. 3: Photograph of six PET propellers

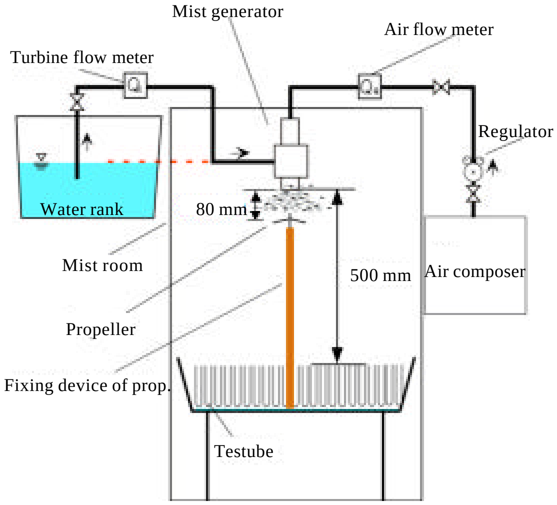

Fig. 4: Schematic of the spray angle expansion

- Ability to provide good atomization over a wide range of liquid flow rates
- Rapid response to changes in liquid flow rate
- Freedom from flow instabilities
- Low power requirements
- Capability for scaling, to provide design flexibility
- Low cost, light weight, ease of maintenance, and ease of removal for servicing

The atomizer studied in this paper is mainly applied to gas absorption and air cooling, so except for the above features, this atomizer should have features as follows:

- Large spray angle, in order to enlarge the contact area between droplets and ambient gas

- Small droplets, which have a relativelower sedimentation velocity, in order to increase the contact timebetween droplets and ambient gas

Based on the above evaluation criterion for the atomizer, the experimental results were presented and discussed.

Optimum length of outlet part: The atomizers with four different outlet parts in Table 2 were tested to find the optimum length of the outlet part.

Since gas/liquid flow rate ratio (GLR) is an important parameter for drop size, a larger range of GLR means a larger candidate range of SMD for different applications. As a consequence, the atomizer with the proper outlet generating the largest liquid flow rate should be considered as the optimum one. As is described before, the water can be automatically sucked by the vacuum pressure produced behind the orifice. Hence the suction performance is compared in Fig. 5, which presents the relationship between the volume flow rate of water sucked (QL) (i.e., the total mist generation rate) and the volume flow rate of gas (QG0) under the standard conditions for the atomizer with four types of outlet parts. The liquid flow rates of all the cases increases with the increased gas flow rate on a linear scale. In particular, the outlet in lengths lout = 41.0 mm and 44.5 mm generates the largest water flow rates (QL) with different gas flow rates (QG0). A potential explanation is: a shorter outlet makes the region of negative pressure too near to the ambient pressure, and the negative pressure is limited to decline; while, a longer outlet leads to much more pressure loss, and then the pressure drop induced by the orifice is decreased, so more negative pressure is difficult to obtain.

The liquid atomization efficiencies (ηM) of the atomizers with different outlet lengths are compared in Fig. 6. Here, the pneumatic power, LG, and the mist generation efficiency, ηM, were calculated from Eq. 1 and 2:

$$L_G = \left(P_{G1} + \frac{\rho_{G1}}{2} v_{G1}^{\ 2}\right) Q_{G1} \qquad (1)$$

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

In the calculations, experimental data on QG1, QL, pG1 and the mean air velocity at the atomizer inlet, vG1, were substituted. In Eq. 2, the mist velocity is assumed to be equal to the mean air velocity at the atomizer exit. From an economical point of view, a larger pneumatic power consumption leads to a higher atomization efficiency; specially, the liquid atomization efficiencies of atomizers with lout = 41.0 mm and 44.5 mm are superior to those of others.The differences of the atomization efficiencies induced by the four outlets are mainly due to different liquid flow rates and different air pressures induced by the varying lengths of the outlets.

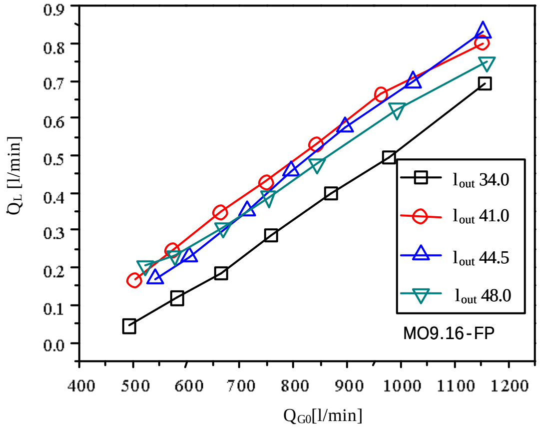

Fig. 5: Comparison of water suction flow rates for the atomizers with different outlet lengths against the gas flow rate

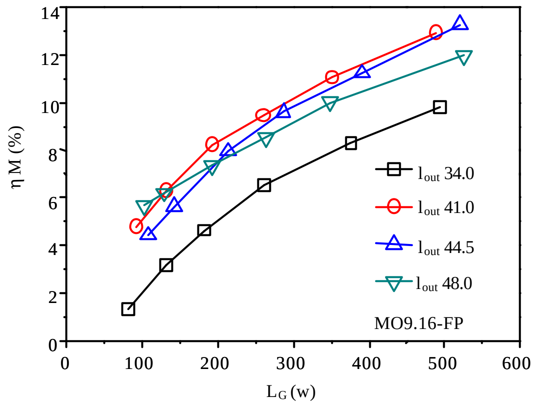

Fig. 6: Comparison of liquid atomization efficiencies for the atomizers with different outlet lengths the pneumatic power

The Sauter mean diameter is probably the most commonly used mean as it characterizes a number of important processes. Chin and Lefebvre (1986) suggest that it is the best measure of the fineness of sprays. In consequence, for clarifying the optimum outlet of MO9.16-FP, we collected 1000 droplets in the centre of the spray cone area, 500 mm downward from the nozzle. The result showed that the atomizer with l_{out}44.5 gave the smaller droplets than l_{out} 41.0, as listed in Table 4.

Table 4: Drop size comparison among different outlets

Diameter	l_{out} 41.0	l_{out} 44.5	vG (m sec^{-1})	vL (m sec^{-1})
d10 (µm)	21.2	15.3	133.1	0.042
d32 (µm)	51.4	46.7		

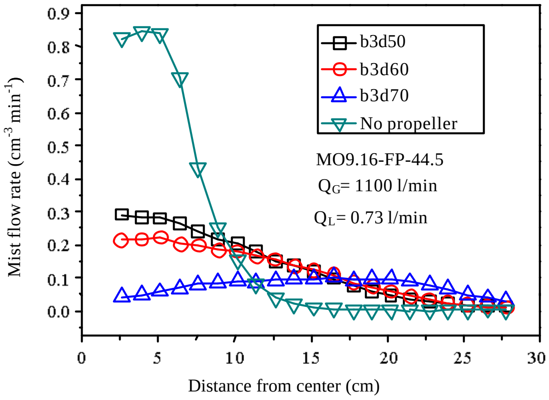

Fig. 7: Comparison of radial distribution of mist flow rate measured at 500 mm downstream from the nozzle exit with 3-blade propellers and without a propeller

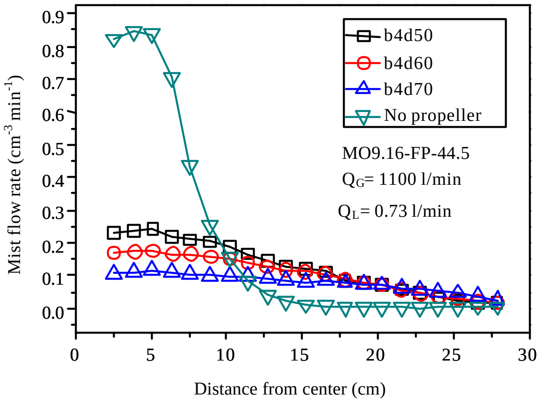

Fig. 8: Comparison of radial distribution of mist flow rate measured at 500 mm downstream from the mist nozzle exit with 4-blade propellers and without a propeller

Actually, the drop size is also remarkably influenced by gas/liquid flow rate ratio (GLR). Generally, an increasing ratio of gas/liquid flow rate generates a smaller drop size. This regularity is also confirmed by (Elshanawany and Lefebvre, 1980) for their airblast atomizers.

Optimum propeller for expanding the spray angle: In this section, we name the atomizer with l_{out}= 44.5 mm as MO9.16-FP-44.5, which was used to test the spray angle expansion effect.

Figure 7 and 8 compare the radial distribution of mist flow rate collected by the test tubes for MO9.16-FP-44.5 atomizer with a series of propellers listed in Table 3 and without a propeller. The abscissa stands for the radial distance from the centre of mist dispersion at 500 mm downward from the atomizer exit. Air and water volume flow rates in the test are Q_G = 1100 l min^{-1} and Q_L= 0.73 l min^{-1}.

For all cases, the mist flow rates decrease from centre to rim. When we only use the generator, most of the mists are distributed around the centre, however, when we use the propellers, the flow rates around the centre are reduced lower than 0.3 cm^3 min^{-1} and displays good expansion effect.

From a comparison of six propellers, we found that b4d70 propeller provides the lowest flow rate as about 0.1 cm^3 min^{-1} at the centre, and keeps this value even at about 27 cm away from the centre. In other words, b4d70 propeller shows the best performance of spray angle expansion.

However, in practical operation, propellers with large outer diameter lead to unstable rotation causing dropout from the rotating shaft. Therefore, we judge b3d50 and b4d50 propellers are enough to expand the spray angle. In fact, b3d50 and b4d50 propeller can expand the spray dispersion well with a stable rotating action, and reduce the mist flow rate from 0.85 cm^3 min^{-1} to lower than 0.3 cm^3 min^{-1} around the centre and keep a flow rate in 0.08 cm^3 min^{-1} even at 27 cm away from the centre. On the other hand, by using b4d50 propeller, the spray angle of the atomizer was measured, which was expanded from 24° to 111° (test position is at 500 mm downward from the nozzle).

Ageneral approach to expand the spray angle was employed by a pressure swirling atomizer (Chen *et al*., 1992). Though it has an enough spray angle for many applications, a major drawback of this type is that its flow rate varies as the square root of the injection pressure differential. Thus, doubling the flow rate demands a fourfold increase in injection pressure. Therefore, besides the complex structure of the swirl atomizer, it also consumes much higher pneumatic power than twin-fluid types. From this point of view, we considered that the PET propeller is quite a quite convenience approach to expand the spray angle without consuming more power.

Figure 9 compares the Sauter mean diameters (d_{32}) of the droplets for b3d50 and b4d50 propellers. We found that the atomizer with b4d50 propeller provides a smaller d_{32} than that of b3d50 propeller from centre to rim, only about 25.0 µm in diameter.

On the viewpoint of atomization process, for many internal-mixing, twin-fluid atomizers, especially when operating at high air-liquid ratios, primary atomization occurs either just upstream of the discharge orifice or in

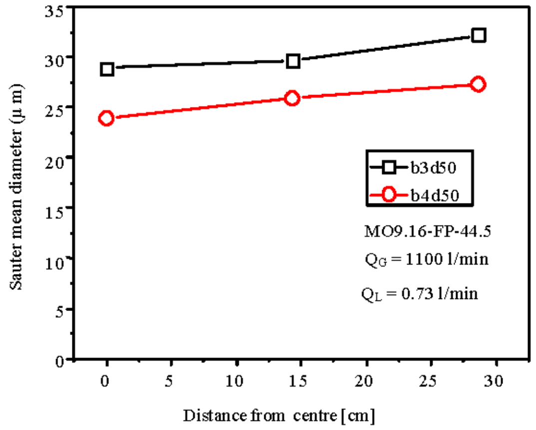

Fig. 9: Radial distribution of droplet size d_{32} for b3d50 and b4d50 propellers

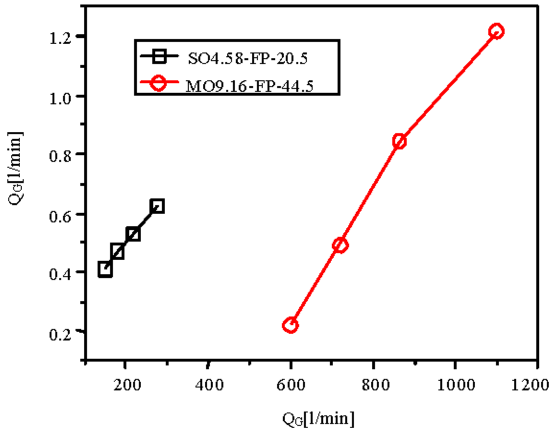

Fig. 10: Comparison of liquid volume flow rates (Q_L) against gas volume flow rates (Q_G) of two types of atomizers

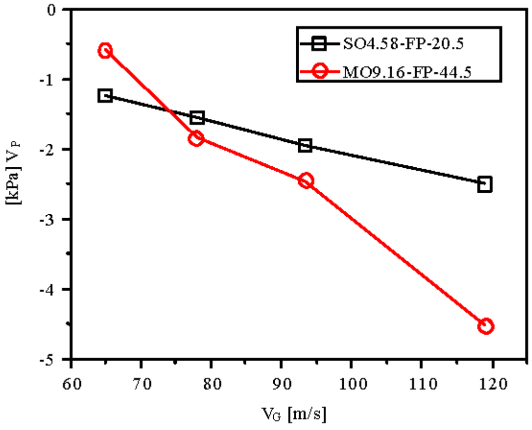

Fig. 11: Vacuum pressure for water suction (p_{Lin}) against gas velocity (v_G)

the orifice itself. Further droplet breakup (secondary atomization) occurs downstream of the nozzle exit, in the region where the nozzle efflux first encounters the surrounding air (Chin and Lefebvre, 1993). The final range of drop sizes produced in a spray depends not only on the drop sizes produced in primary atomization but also on the extent to which these drops are further disintegrated during secondary atomization (Lefebvre, 1989b). The propeller explored not only expands the spray angle but also produces a violent collision between drops and blades, leading to a much stronger second atomization and generates smaller droplets.

It should be further noted that in Figure 9, the Sauter mean droplets diameters increase with the radial distance. Similar behaviour has been reported earlier by Kushari (2010), which is attributed to the formation of annular or dispersed two-phase flow inside the atomizer due to the penetration of air to the centre of the tube owing to its high momentum with respect to the liquid momentum.

According to the above analyses, MO9.16-FP-44.5 atomizer with b4d50 propeller shows a good spray angle expansion and stable rotating action, and also provides droplets with much smaller Sauter mean diameter of 25.0 μm, being smaller than 46.7 μm for the atomizer without a propeller. The decrease in the diameter means that a stronger secondary atomization can be produced by the propeller.

Performance comparison of small and middle sized atomizers: Since MO9.16-FP is twice the size of SO4.58-FP, in the performance test, the gas volume flow rate Q_G for the middle atomizer was set at four times of that for the small size, which makes for the same gas velocity (v_G).

Figure 10 compares the experimental results of liquid volume flow rates (Q_L) of two types of mist generators in different gas volume flow rates (Q_G). Q_L in each type increases with Q_G, for the middle sized atomizer, it generates liquid volume flow rate as twice as the small size, except in the low gas volume flow rate. An explanation for the large liquid atomization rate of the middle sized atomizer is, a larger size of porous pipe of the atomizer can suck water in a larger contact area, leading to a larger liquid flow rate.

Figure 11 shows the negative pressure, p_{Lin}, at the annular space for two different size atomizers against the mean air velocity at the water inlet, v_{G1}. The stronger the negative pressure, more the water suction rate. Besides at the lowest velocity of v_G = 65 m sec^{-1}, the negative

Table 5: Drop size comparison of the two sizes of the atomizers at specified flow rate

	No propeller		With propeller	
Name	d_{10} (m)	d_{32} (m)	d_{10} (m)	d_{32} (m)
SO4.58-FP-20.5	13.1	39.8	8.90	20.8
MO9.16-FP-44.5	15.3	46.7	11.5	24.0

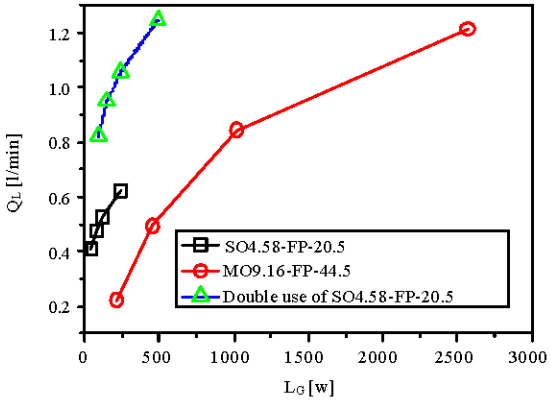

Fig. 12: Liquid volume flow rate (Q_L) against pneumatic power consumption (L_G)

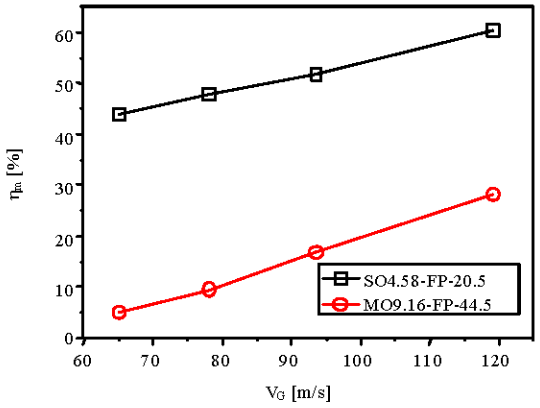

Fig. 13: Liquid atomization efficiency against gas velocity

pressure of the middle sized generator is stronger than that of the small size. This indicates for the middle sized one to supply higher air velocity in order to realize stronger water suction performance.

Figure 12 compares the water suction rate, Q_L, of different sized atomizers against the pneumatic power consumption, L_G. The ratio of the water suction rate to the pneumatic power, Q_L/L_G, decreases with increasing of pneumatic power. The middle sized one can generate twice mist flow rate than the small sized one, but it consumes about 10 times energy than the small sized one. Thus, if say, 1.2 l min^{-1} of mist generation rate is required, double use of the small sized one is recommended from an energy saving point of view, because the power consumption can be reduced to about one fifth.

In Figure 13, the abscissa is the air velocity in the inlet section of the atomizer, and the ordinate is the liquid atomization efficiency. It shows that the mist generation efficiency $\eta_M$of each atomizer increases with the increase of gas velocity. It can be also seen that, $\eta_M$of the middle sized atomizer is much lower than that of the small sized one, lower than 30%. This suggests that we should choose the smaller sized atomizer as well as possible.

In addition, mist diameters of the two types of atomizers are compared in Table 5 at the following conditions: small size, Q_G = 300 l min^{-1}, Q_L = 0.2 l min^{-1}, with b4d25 propeller; middle size, Q_G = 1100 l min^{-1}, Q_L = 0.73 l min^{-1}, with b4d50 propeller. For the two atomizers, by using the propellers, the arithmetic mean diameter (d_{10}) and Sauter mean diameter (d_{32}) of the droplets decrease significantly. In particular, for all the cases using a propeller or without a propeller, d_{10} and d_{32} of the mist sprayed by the small sized atomizer are always smaller than that of the middle size. That means the small sized atomizer generates finer mist than the middle sized one at the same condition of gas velocity and liquid velocity.

The comparison results in Table 5 is roughly the same with the study by Elshanawany and Lefebvre (1980), who conducted a series of experiments for an airblast atomizer and concluded that, spray quality deteriorates with increase in atomizer scale, such that the mean drop diameter increases with approximately the 0.43 power of the atomizer linear dimension. They also derived a dimensionally correct equation for relating the experimental data on mean drop size to the flow variables and atomizer dimensions. The applicability of the equation to the present atomizer has to be studied near future.

Incidentally (Barreras *et al*., 2006) obtained a similar Sauter mean diameter by using industrial twin-fluid atomizers, so the present atomizer can be applicable to industrial purposes.

CONCLUSION

This study reported the experimental study of an air assisted atomizer (liquid siphon type) patented by Sadatomi and Kawahara (2012). Two sizes of atomizers in different inner diameters of outlets were manufactured. In the present study, the performance of the middle sized atomizer was optimized and compared with that of the small sized one. The experimental results are concluded as follows:

- MO9.16-FP atomizer with l_{out} = 44.5 mm expressed the best spray performance i.e., high water suction rate, fine mist with droplets of 15.3 μm in arithmetic mean diameter, 46.7 μm in Sauter mean diameter
- Six propellers with different blade numbers and outer diameters were tested, and the MO9.16-FP-44.5 atomizer with b4d50 propeller shows a good performance of spray angle expansion and stable rotating action. The Sauter mean droplets diameter can be decreased from 46.7 μm to 24.0 μm, which is attributed to the secondary atomization produced by the propeller
- Two sizes of atomizers, SO4.58-FP-20.5 and MO9.16-FP-44.5, were compared in atomization performance. Although MO9.16-FP-44.5 can generate mist as a maximum flow rate in 1.2 l $\min^{-1}$, as twice of the small size, it has much lower efficiency than the later one. From the perspective of energy saving, we should choose small sized atomizer as well as possible
- The present atomizer has a low capacity for scaling, and the liquid atomization rate does not increase with the size of the atomizer on a linear scale. In practical applications, multiple use of the small sized atomizer is recommended from the viewpoint of energy saving

As practical applications, the atomizer with the optimum specifications is applicable to air cooling in greenhouse (Sadatomi *et al*., 2010), humidification in living room, and some industrial purposes (Barreras *et al*., 2006).

Nomenclature

d_{10}	Arithmetic mean diameter of droplets in mist (m)
d_{32}	Sauter mean diameter of droplets in mist (m)
d_o	Orifice diameter (m)
D	Diameter of outlet (m)
l_{out}	Length of outlet part (m)
L_G	Pneumatic power (W)
p	Pressure (Pa)
p_{Lin}	Water suction pressure at the annular space (Pa)
Q	Volume flow rate (m3 s-1)
Q_{G0}	Gas volume flow rate under standard condition (m3 sec^{-1})
v	Velocity (m sec^{-1})
Greek letters	
□	Area ratio of orifice to mixing chamber (dimensionless)
□	Density (kg m^{-3})
η_M	Liquid atomization efficiency (%)
Subsripts	
G	Gas
L	Liquid

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REFERENCES

Barreras, F., A. Lozano, J. Barroso and E. Lincheta, 2006. Experimental characterization of industrial twin-fluid atomizers. Atomization Spray, 16: 127-146.

Chen, S.K., J. Rollbuhler and A.H. Lefebvre, 1992. Factors influencing the effective spray cone angle of pressure-swirl atomizers. J. Eng. Gas Turbines Power, 114: 97-103.

Chin, J.S. and A.H. Lefebvre, 1986. Some comments on the characterization of drop-Size distribution in sprays. Proceedings of the 3rd International Conference on Liquid Atomization and Spray Systems, Volume 2, July 8-10, 1985, London, UK.

Chin, J.S. and A.H. Lefebvre, 1993. Flow patterns in internal-mixing, twin-fluid atomizers. Atomization Spray, 3: 463-475.

Dimiccoli, A., M. Di Serio and E. Santacesaria, 2000. Mass transfer and kinetics in spray-tower-loop absorbers and reactors. Ind. Eng. Chem. Res., 39: 4082-4093.

El-Shanawany, M.S. and A.H. Lefebvre, 1980. Airblast atomization: Effect of linear scale on mean drop size. J. Energy, 4: 184-189.

Ferreira, G., J.A. Garcia, F. Barreras, A. Lozano and E. Lincheta, 2009. Design optimization of twin-fluid atomizers with an internal mixing chamber for heavy fuel oils. Fuel Process Technol., 90: 270-278.

Kushari, A., 2010. Effect of injector geometry on the performance of an internally mixed liquid atomizer. Fuel Process. Technol., 91: 1650-1654.

Lal, S., A. Kushari, M. Gupta, J.C. Kapoor and S. Maji, 2010. Experimental study of an air assisted mist generator. Exp. Therm. Fluid Sci., 34: 1029-1035.

Lefebvre, A.H., 1989. Atomization and Sprays. Hemisphere Publishing, New York, USA.

Lefebvre, A.H., 1989. Properties of sprays. Part. Part. Syst. Charact., 6: 176-186.

Liu, H., 1999. Science and Engineering of Droplets: Fundamentals and Applications. William Andrew Publishing, New York, USA.

Sadatomi, M. and A. Kawahara, 2012. Fluids mixer and fluids mixing method. Japanese Patent, No. 5103625.

Sadatomi, M., A. Kawahara, H. Matsuura and S. Shikatani, 2012. Micro-bubble generation rate and bubble dissolution rate into water by a simple multi-fluid mixer with orifice and porous tube. Exp. Therm. Fluid Sci., 41: 23-30.

Sadatomi, M., A. Kawahara, K. Fukamachi, F. Matsuyama and N. Tanaka, 2010. Development of a new large-flow-rate and efficient mist generator, and its application to air cooling in greenhouses. Multiphase Sci. Technol., 22: 79-93.

Shafaee, M., S.A. Banitabaei, V. Esfahanian and M. Ashjaee, 2012. An investigation on effect of geometrical parameters on spray cone angle and droplet size distribution of a two-fluid atomizer. J. Mech. Sci. Technol., 25: 3047-3052.

Watanawanyoo, P., H. Mochida, T. Furukawa, M. Nakamura and H. Hirahara, 2012. Experimental study on the spray characteristics of an air assisted atomizer with internal mixing chamber. Eur. J. Sci. Res., 84: 507-521.

Yao, J.F., A. Kawahara, M. Sadatomi, E. Sakurai and S. Furusawa, 2013. Expansion of mist jet generated by a special twin-fluid atomizer for CO_2 capture. WIT Trans. Eng. Sci., 80: 495-506.