**Regular Paper**

# Visualization of Two Phase Flow inside an Effervescent Atomizer

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*Abstract* : Effervescent atomization is one of the twin-fluid atomization methods while it has better performance in terms of smaller drop sizes and/or lower injection pressures. In order to investigate the effects of the internal flow patterns on droplet characteristics, a new kind of effervescent atomizer was designed and manufactured. The bubble forming process was visualized with a high-speed camera, while the droplet size was characterized with a LDV/PDA system. The experimental results show that there are three regimes of the two-phase flows inside the discharge orifice, one is bubbly flow, another is annular flow while the other is the intermittent flow. The flow patterns transfered from bubbly flow to intermittent flow and then to annular flow with decreasing of the water flow rate. In addition, with increasing of the working pressure or decreasing of the water flow rate, the SMD (Sauter mean diameter) of the droplets decreased and the axial mean velocity increased.

*Keywords* : Visualization, Water mist, Effervescent atomization, Two phase flow.

## 1. Nomenclature

| | |
|---|---|
| $A$ | cross-sectional area of the mixing tube, $m^2$ |
| $d$ | inside diameter of the mixing tube, m |
| GLR | gas to liquid mass flow-rate ratio, dimensionless |
| $j$ | superficial velocity (the volumetric flow rate of fluid moving through a pipe divided by the cross-sectional area of the pipe) , m/s |
| $M$ | flow rate, kg/s |
| $P$ | pressure, Pa |
| SMD | Sauter mean diameter, m |
| $t$ | bubble development time, s |
| $t^*$ | normalized bubble development time, dimensionless |
| $v$ | velocity, m/s |
| $v^*$ | normalized velocity, dimensionless |
| $\rho$ | density, $kg/m^3$ |
| $\tau$ | periodicity, s |
| $\tau^*$ | normalized periodicity, dimensionless |

Subscripts
$B$　　　　bubble
$g$　　　　gas
$1$　　　　liquid

# 2. Introduction

It is well known that the use of water mist for fire suppression was first studied in the 1950s, and a renewed interest in this old technology was sparked since the first version of the Montreal Protocol which was introduced in 1987. This international commitment to protecting the earth's ozone layer from further damage by chlorinated fluorocarbons (CFC's), has driven about 20 years of testing to develop alternative fire suppression technologies to replace the chlorine- or bromine-based gaseous fire suppressants known as Halons. Water mist is not associated with such dangers to people in occupied areas and has received considerable attention as one of the potential methods for replacement of Halon 1301 and 1211(Alpert, 1993; Jones et al., 1995).

　　　The fire extinguishing mechanisms of water mist primarily are heat extraction, oxygen displacement, and blocking of radiant heat. In theory, small droplets are more efficient in fire suppression than large droplets, because of their larger total surface area available for evaporation and heat extraction. They are more effective in radiation attenuation. The research results show that Class 1 mist (90 % of the volume of the spray within drop sizes of 200 microns or less) has better suppression effectiveness to Class B fires (fires of flammable liquids and gases) and obstructed fires. Besides these, the droplets also need enough momentum to penetrate into the fire plume. However, traditional water mist nozzles, such as pressure jet nozzles, impingement nozzles and twin-fluid nozzles, either need relatively higher pressure, or produce coarser mist droplets and lower spray momentum, while effervescent atomization can generate fine water mist under relatively lower pressures and can well avoid the cost problem.

　　　Effervescent atomization is one of the twin-fluid atomization methods for water mist generation while it has better performance in terms of smaller drop sizes and/or lower injection pressures(Roesler, 1988). The principle of effervescent atomization has been investigated experimentally by Lefebvre and Sojka et al. Roesler and Lefebvre conducted experiments to visualize the two-phase flow of the effervescent atomizer as it approaches the exit orifice and the near-nozzle liquid break-up mechanism(Roesler et al., 1988 and 1989). The mechanisms of effervescent atomization had been also discussed by Sovani et al (2001).

　　　Flow visualization techniques were widely used for studying of fluid flows, and Fujisawa et al. (2007) reviewed the recent progress in flow visualization techniques. Arosio et al. (2006) visualized the flow structure fields of a gas-liquid flow, Ninomiya et al. (2006) visualized the flow around and inside a falling droplet. Lin et al. (2001) used a transparent aerated-liquid injector with several interchangeable square final discharge orifices to investigate the structures of internal two-phase flow inside the aerated-liquid injector. They found that the aerated-liquid spray is related to the structure of the internal two-phase flow inside the discharge passage. But they didn't investigate the effects of injection pressure, liquid velocity, arrangement of aerating holes, and nozzle passage design, etc.

　　　Therefore, a new kind of effervescent atomizer was designed and the two-phase flow pattern inside the atomizer was visualized under different operation pressures and GLR (gas to liquid mass flow-rate ratio), etc.

# 3. Experimental Apparatus

## 3.1 Effervescent Atomizer

As shown in Fig. 1, a single-hole plain-orifice 'Gas-outside-fluid-inside' effervescent atomizer was designed, manufactured and characterized in this paper. The mixing and containment tubes are made from clear acrylic to permit visual observation of the internal two-phase flow. The overall length of the atomizer is approximately 160 mm. The containment tube has an inside diameter of 40

mm and a wall thickness of 5 mm. The mixing tube has an inside diameter of 6 mm and a wall thickness of 2 mm. Six rows with four holes, each with 1 mm diameter, designed for injecting gas into the mixing tube are perpendicular to its axis. Each row is spaced 8 mm apart and rotated 45° from the neighbor one. The last row of these injection holes is located 80 mm upstream of the exit orifice with 1.5 mm diameter. Figure 2 gives the schematic diagram of the water mist generation system that consists of some valves, flowmeters, pressure sensors and an effervescent atomizer, etc. The atomizing gas is nitrogen in all experiments.
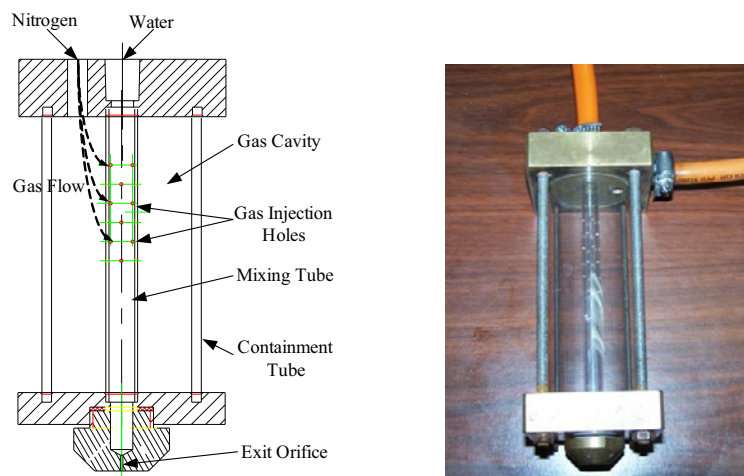


Fig. 1. Schematic diagram of the effervescent atomizer and its practical picture.
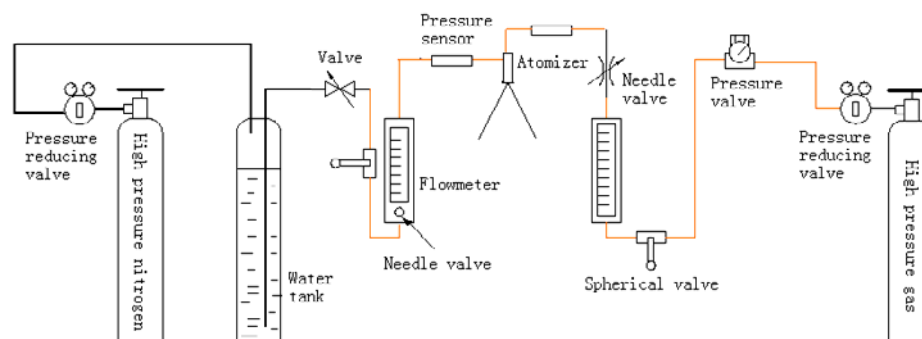


Fig. 2. Schematic diagram of the water mist generation system.

## 3.2 Characterization and Visualization Equipments

In order to characterize the mist droplets produced by the effervescent atomizer, a LDV/PDA system (as shown in Fig. 3) is used for droplet size and velocity measurement. In addition, a Fastcam Ultima APX high-speed camera (manufactured by Photron Inc.) was used to visualize the internal flow structures and the atomizing processes. With a highly light-sensitive mega-pixel CMOS sensor and one million enormous 17 µm pixels, the APX camera can provide full resolution up to 2,000 frames per second (fps), and reduced resolution up to a phenomenal 100,000 fps. A 800 Watts iodine-tungsten lamp with 2,000 fps shoot speed was used as compensatory lamp-house during the two-phase flow visualization. Figure 4 gives the schematic diagram of the visualization system.

# 4. Results and Discussion

## 4.1 Bubbly Flow Patterns inside the Atomizer

Figure 5 shows the two-phase flow patterns inside the atomizer at 0.4 MPa pressure and 60 kg/h water flow rate. In this flow regime, gas bubbles with diameter about 2 mm are generated one after another through the gas-injecting holes, and move downward with the water flow. These orderly generated bubbles broke up due to the low gas flow rate. And the bubble development time is about 6 ms. The normalized bubble development time ($t^* = j_l t/d = M_l t/\rho_l A d$) is about 0.59. Although more bubbles exist at the lower-part of the mixing chamber and crowd each other, few of them coalesce and form a bigger one. So the two-phase flow inside the atomizer is very steady. The flow patterns also show that the velocity of the moving bubble increases from 0.8m/s at the upper-part to 1.9 m/s at the lower-part. Correspondingly, the normalized velocity of the moving bubble ($v_b^* = v_b/j_l$) increases from 1.36 to 3.22. The bubbles accelerate mainly due to drag effect of the fluid flow. The liquid velocity also increases with increasing the void fraction at the lower-part.
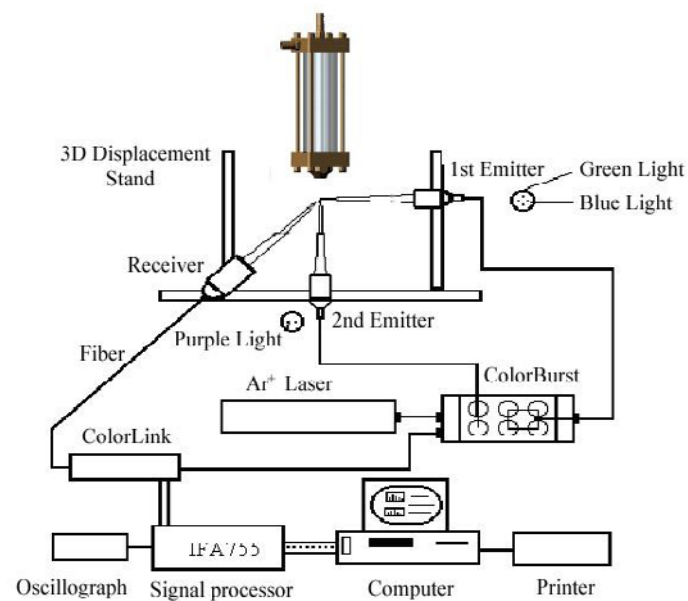


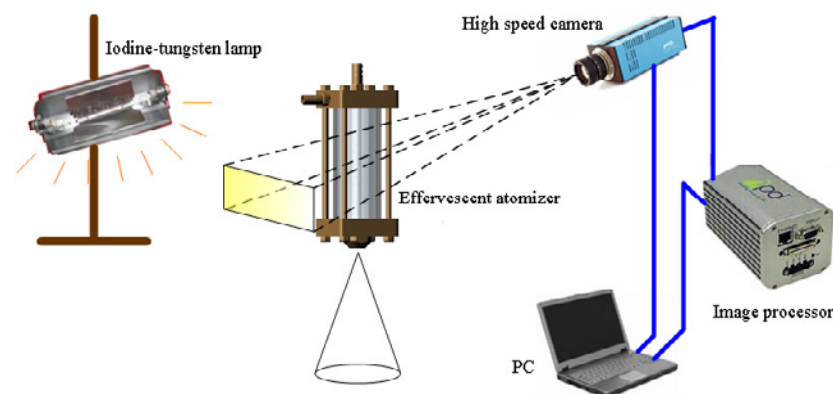Fig. 3. Schematic diagram of droplet characterization with LDV/PDA system.



Fig. 4. Schematic diagram of the system for the internal two-phase flow visualization inside the effervescent atomizer.
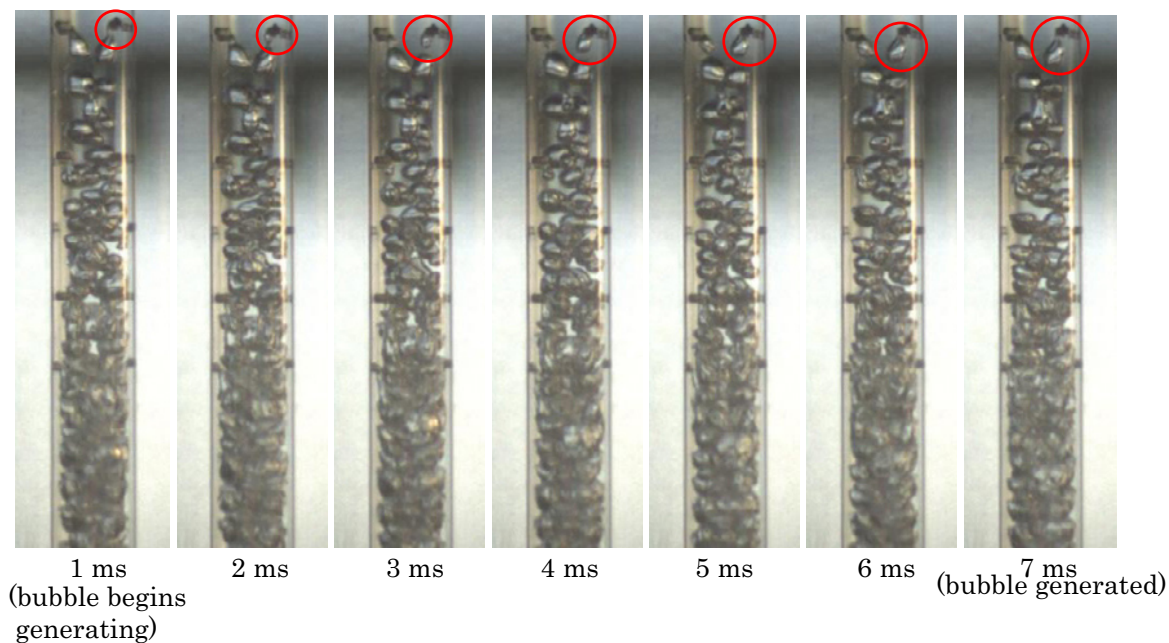
| 1 ms (bubble begins generating) | 2 ms | 3 ms | 4 ms | 5 ms | 6 ms | 7 ms (bubble generated) |

Fig. 5. Typical bubbly flow patterns (P = 0.4 MPa, $M_l$ = 60 kg/h, GLR = 0.025).

Figure 6 gives the bubbly two-phase flow patterns under different conditions. In Fig. 6(b), the water flow rate is reduced to 55 kg/h, i.e., the gas flow rate increases. Therefore, the generation rate of the bubbles becomes faster and the average bubble development time decreases to 5.5 ms ($t^* = 0.50$). However, it should be noted that the bubble development process isn't uniform under this condition. For instance, some bubbles need 8 ms to form ($t^* = 0.72$). When the gas pressure is reduced to 0.3 MPa (Fig. 6(c)), the gas flow rate decreases and the bubble generation rate decreases either. At this condition, each bubble needs about 6.5 ms to form ($t^* = 0.64$), which leads to reduction of bubble number. In addition, as the pressure of the mixing chamber decreases, the size of bubble increases.
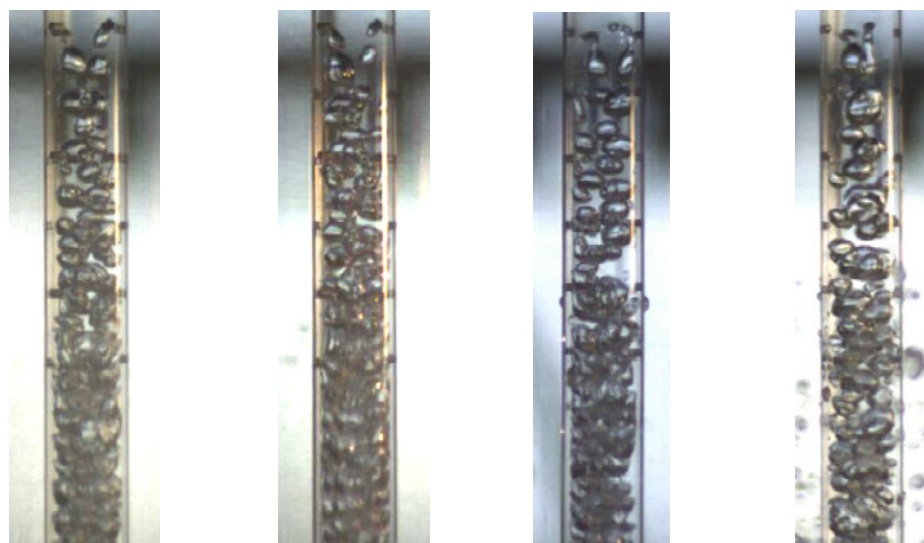


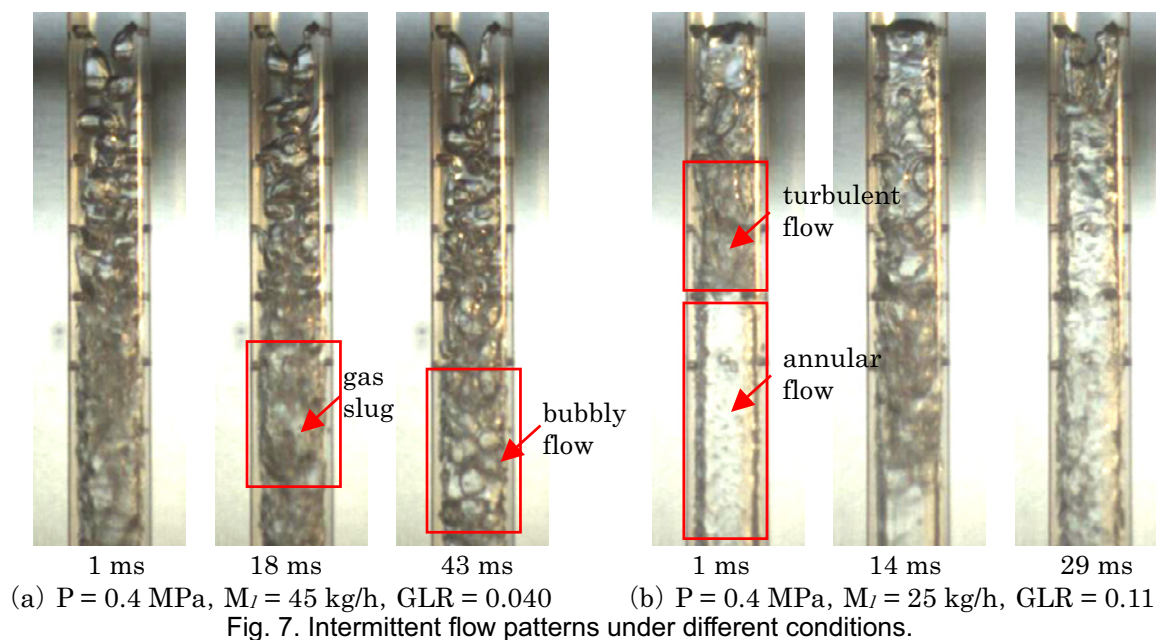| (a) P = 0.4 MPa $M_l$ = 60 kg/h GLR = 0.025 | (b) P = 0.4 MPa $M_l$ = 55 kg/h GLR = 0.027 | (c) P = 0.3 MPa $M_l$ = 60 kg/h GLR = 0.016 | (d) P = 0.1 MPa $M_l$ = 60 kg/h GLR = 0.005 |

Fig. 6. Bubbly flow patterns under different conditions.

## 4.2 Intermittent Flow Patterns inside the Atomizer

When the liquid flow rate decreases to a certain point, the two-phase flow inside the mixing chamber can not maintain uniform as a bubbly flow. As shown in Fig. 7(a), when the liquid flow rate decreases to 45 kg/h, most bubbles need 10 ms to form ($t^* = 0.74$) and some of them even need 15 ms ($t^* = 1.11$) to form. The long bubble development time makes the bubble volume increases. Then the bubbles start to coalesce and form voids in the bottom of the mixing chamber just as shown in Fig. 7(a) at 1 ms and 18 ms. However, the two-phase flow inside the mixing chamber will return to bubbly flow at 43 ms (Fig. 7(a)). Therefore, the flow exhibits unsteadiness and the flow pattern changes with time. In other words, the bubbly and the annular flow appear alternately in the intermittent flow regime.

When the liquid flow rate decreases further, for instance, from 45 kg/h to 25 kg/h (Fig. 7(b)), the bubbles coalesce before they move away from the gas injection holes and no single bubble can be generated. The bubbles mutually squeeze and merge to form disorderly and turbulent flow at the upper-part of the mixing chamber. At the same time, a steady annular flow structure which comprises a round jet of gas surrounded by a thin annular film of liquid exists at the lower-part, as shown in Fig. 7(b) at 1 ms. Then the turbulent flow runs forward to the exit orifice and the annular flow structure is destroyed at 14 ms. However the annular flow rebuilds in the mixing chamber at 29 ms. The annular flow region only can extend to the second row of the gas injection holes, and then the unsteady turbulent flow will occur again. The flow structure transition shows periodicity and the periodicity is about 39 ms. The normalized periodicity ($\tau^* = j\pi/d = M\pi/\rho_l A d$) is about 1.60.



1 ms          18 ms          43 ms               1 ms          14 ms          29 ms
(a) P = 0.4 MPa, $M_l$ = 45 kg/h, GLR = 0.040        (b) P = 0.4 MPa, $M_l$ = 25 kg/h, GLR = 0.11
Fig. 7. Intermittent flow patterns under different conditions.

## 4.3 Annular Flow Patterns inside the Atomizer

As shown in Fig. 8, if the water flow rate reduced further, the injected gas from different gas injection holes will merge together and occupy most space of the mixing chamber, while the water will be squeezed to liquid film. Then the two-phase flow pattern transits to annular flow. However, the annular flow observed here is not a steady flow as Lefebvre described before. Since the middle of the mixing chamber is occupied by gas, water can only flow around the gas plug and then a gas-liquid interface forms around the gas plug. This interface will move up as the water flow rate reduces, and become invisible when the water flow rate reaches 10 kg/h. After the water flow is obstructed by the gas slug for a while, water pressure at the interface will increase until break the balance of pressure between gas and water. Then the water will flow in the middle part of the mixing chamber for seconds and an unstable flow pattern appears. After that, a new interface will re-form with the water pressure decreased, and these process occurs periodicaly. Compared with the unsteadiness of the

intermittent flow regime, annular flow regime has a longer steady period. And with the decrease of the water flow rate, the period becomes longer. Figure 8(c) shows that as the water flow rate reduces to 10 kg/h, internal flow structure maintains steady as annular flow for about 106 ms until the pulsation begins at 107 ms. And at the time of 119 ms, internal flow structure returns to steady annular flow. The normalized periodicity is about 1.13 at 15 kg/h water flow rate and is about 1.93 at 10 kg/h water flow rate.
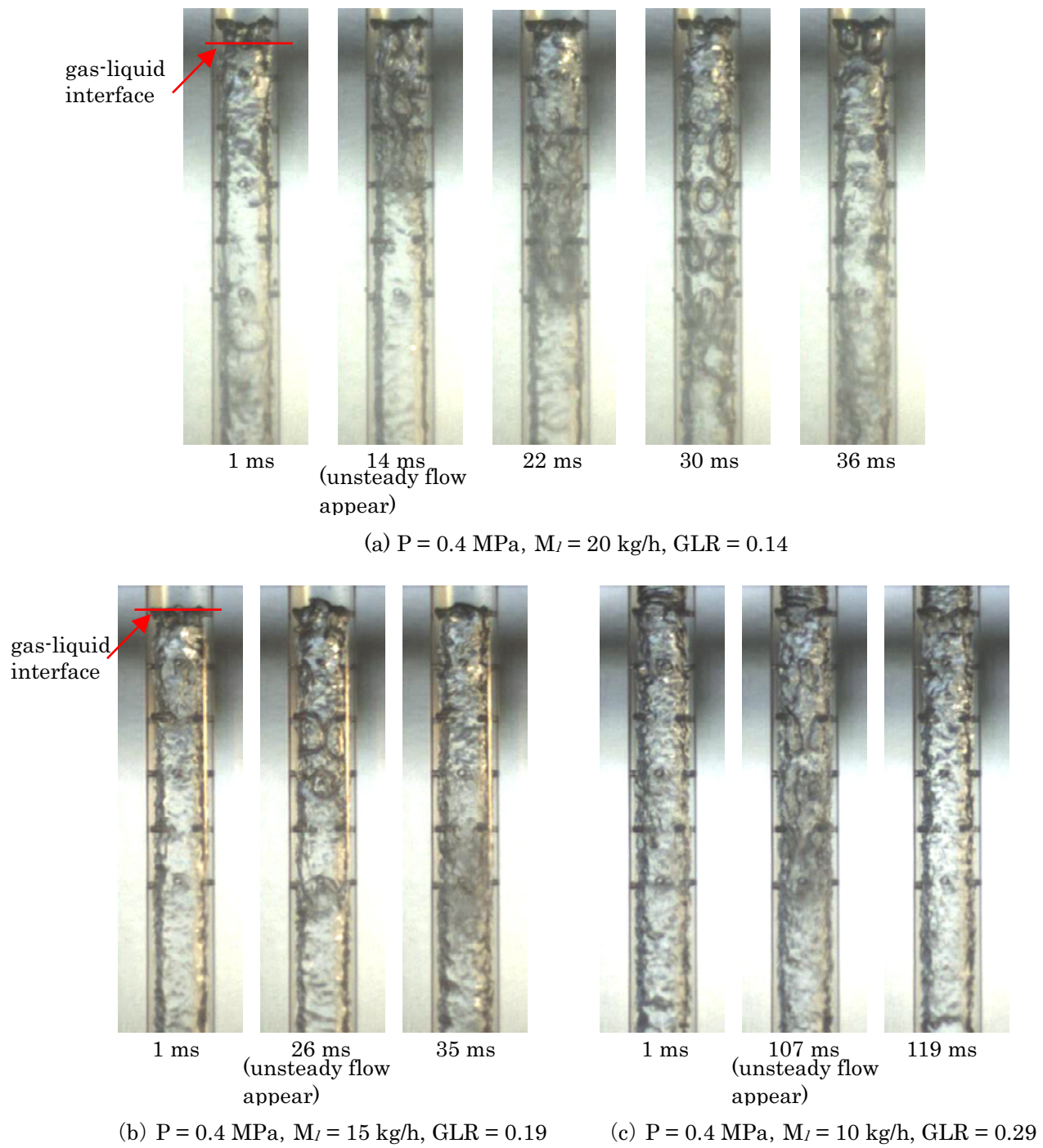


gas-liquid interface

| 1 ms | 14 ms (unsteady flow appear) | 22 ms | 30 ms | 36 ms |

(a) P = 0.4 MPa, $M_l$ = 20 kg/h, GLR = 0.14

gas-liquid interface

| 1 ms | 26 ms (unsteady flow appear) | 35 ms |

(b) P = 0.4 MPa, $M_l$ = 15 kg/h, GLR = 0.19

| 1 ms | 107 ms (unsteady flow appear) | 119 ms |

(c) P = 0.4 MPa, $M_l$ = 10 kg/h, GLR = 0.29

Fig. 8. Annular flow patterns under different conditions.

## 4.4 Summary of the Flow Patterns Transition

Figure 9 shows the influence of pressure and water flow rate on flow patterns. Reducing the pressure will induce decrease in gas flow rate. So the amount of the bubbles decreases but the size of the bubbles increases. Due to decrease in amount of the bubbles, the twin-fluid flow will maintain bubbly flow pattern more easily and transit to annular flow pattern under lower water flow rate. However, if the size of the single bubble enlarges to fill full cross section of the mixing chamber as a gas slug, the twin-fluid flow will transit to intermittent flow although water flow rate is still high. As shown in Fig. 9, the flow pattern is intermittent flow at 0.1 MPa and 50 kg/h water flow rate. Figure 10 shows the flow patterns obtained through the present experiments, and the superficial velocities of gas and liquid are chosen as the representative velocities.
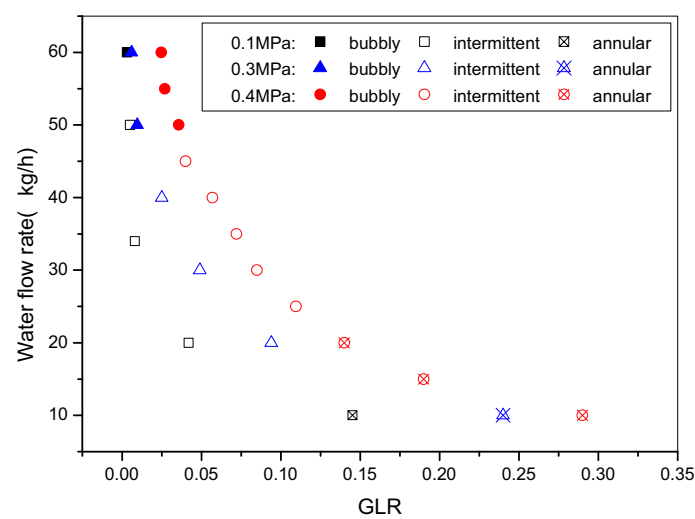


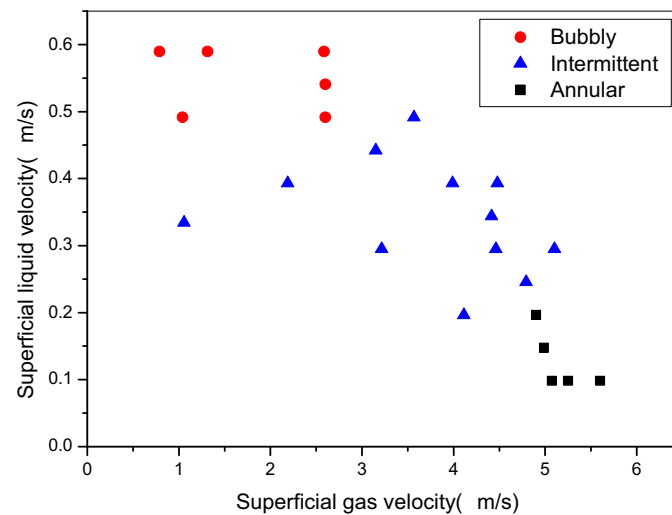Fig. 9. Effects of pressure and water flow rate on flow pattern.



Fig. 10. Effects of the supperficial velocity on flow patterns transition.

## 4.5 Water Mist Characteristics

The droplet size and velocity produced by the effervescent atomizer were measured by the LDV/APV system at the cross-section 1.0 m away from the atomizer exit. The SMD and axial mean velocity of

the droplets are given in Fig. 11 and Fig. 12, respectively. The figures show that the effervescent atomizer can produce water mist with droplet diameter less than 100 µm at low operation pressure ($\leq$ 0.4 MPa) and the droplet velocity is larger than that produced by single-fluid atomizer at the same pressure. The figures also show that the SMD decreases and the axial mean velocity increases with an increase in operation pressure. And in the bubbly flow regime, the droplet size is larger and the droplet velocity is lower, although the mist spray is the steadiest one. As GLR increases and flow pattern transits to intermittent flow, SMD decreases and axial mean velocity increases. However, the mist spray is not steady at this flow pattern. In the annular flow regime, the best atomization and highest spray velocity can be achieved and the influence of GLR on atomization becomes weak. However, the required high gas flow rate will induce high cost and the low water flow rate will reduce the fire suppression effectiveness. Therefore, under high operation pressure and bubbly flow pattern the achieved steady water mist would be the most appropriate for fire suppression. However, this point should be further confirmed by fire suppression experiments.
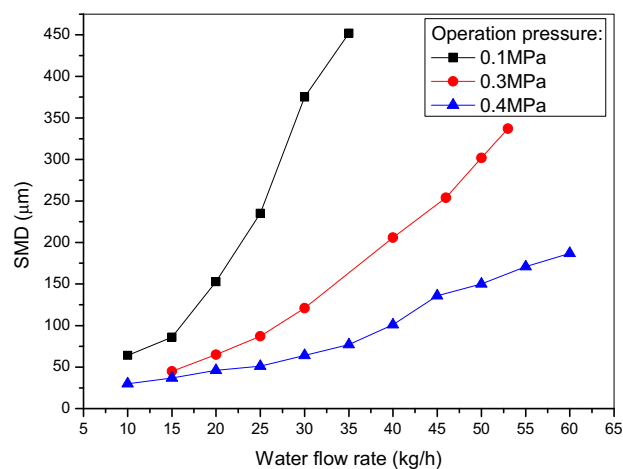
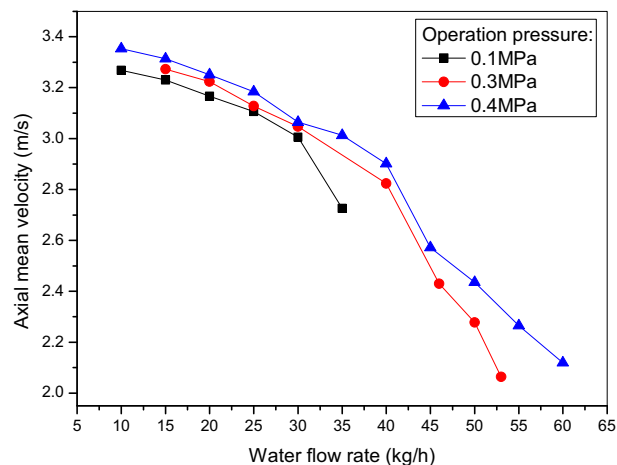Fig. 11. Influence of water flow rate on SMD.

Fig. 12. Effects of water flow rate on droplet axial mean velocity.

## 5. Conclusion

A new kind of effervescent atomizer was designed and the internal flow structure was visualized with a Fastcam Ultima APX high speed camera. In addition, a LDV/PDA system was employed to

characterize the water mist generated by this effervescent atomizer under various conditions. Following conclusions can be drawn from the experimental results: (1) There are three regimes of the two-phase flows inside the effervescent atomizer, one is bubbly flow, another is annular flow, and still another is intermittent flow. (2) The SMD is smaller and axial mean velocity is larger under higher operation pressures. (3) The SMD increases and axial mean velocity decreases with an increase in water flow rate. In the future, fire suppression experiments should be done to evaluate the fire suppression effectiveness of effervescent water mist produced in different internal two-phase flow regimes.

## Acknowledgements

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