ATOMIZATION PERFORMANCE OF TWIN-FLUID MICRO-INJECTORS WITH MICRO-MIXING MECHANISMS

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ABSTRACT This paper describes the development of two types of the twin-fluid micro-injectors. One is the air-assist type micro-atomizer (AMA type) with three micro channels for the liquid and gas flows. The other is the manifold type micro-atomizer (MMA type) with four micro channels. Two of them are used to supply the atomization gas and the others supply the liquid matter. The orifice hydraulic diameters (dH) of the micro atomizers are 45µm. The aspect ratios of orifice were 20.8 and 15.8 for the AMA and MMA atomizers, respectively. The Malvern Insitec RT-Sizer is used to measure the particle size and the IDT/PIV system is used to measure the particle velocity. Flow visualization through a microscope shows that the atomizing mechanisms are related to the breakup processes due to the liquid column instability and the impinging oscillation mode for the AMA and MMA atomizers, respectively. Results also show that the dependence of the particle size on the gas-to-liquid ratio is quite different from the cases we know from the conventional atomizers. For example, the mean droplet size reduces from 14.1µm to 5.3µm with gas-to-liquid ratio ranging from 3.1 to 4.7 when the gas pressure increases from 2.0bar to 5.0bar. On the contrast, the mean droplet size was further reduced from 3.0µm to 6.0µm with lower gas-to-liquid ratio ranging from 0.13 to 0.38 under the same pressure range. This phenomenon is due to the fact that the effects of surface tension are more significant in the micro-atomization processes. It is also found that the atomization with impinging oscillation mode is more efficient as far as the design of the micro-atomizer is concerned. Moreover, the mean axial velocity of spray droplets is below 6.6m/s at a distance 20mm from the atomizer. The ultra-fine sprays with slow moving behavior can be used to the applications of the inhaled drug delivery for respiratory care.

Keywords: Micro-atomizer, Twin-fluid, Internal impinging, Atomization mechanism, Gas-to-liquid ratio

1. INTRODUCTION

The twin-fluid micro-atomizers have been widely used to produce the micro spray in medical as well as engineering applications. It aims at the production of ultra-fine sprays with relatively low flow rate. The atomization processes have been widely utilized in many applications including spray combustion in diesel engine, pulse detonation engine(PDE), gas turbines, and industrial furnaces; spray drying, food processing, spray painting, humidification, metal powder production, ceramic particle production, and spray forming techniques. It is also applied to the areas of agricultural spraying, electronic cooling, fire extinguish, and medical sprays in the delivery of drugs to the lungs, etc [1]. The control of the drop size and size distribution to meet the requirements of various applications is the important issue in the design of atomizers.

Atomizers are normally characterized as three categories based on the energy of atomization [1]: 1. Pressure atomizers: liquid is discharged through a small orifice under high pressure. The pressure energy is converted to the kinetic energy for the atomization of the liquid matter. The quality of the atomization performance depends on the relative velocity between the liquid phase and the surrounding air. Hence it is normally not easy to achieve good atomization performance at lower injection pressure. 2. Twin-fluid atomizers: liquid is injected to the air stream with high-velocity to enhance the atomization processes. For a given liquid medium, the quality of the atomization process is controlled by the dynamic pressure of the atomizing air and the relative velocity between the liquid and the surrounding air. 3. Rotary atomizers: liquid is introduced to the high-speed rotating disk. Atomization of liquid is achieved due to the action of the centrifugal force. Atomization processes can also be achieved by other energy sources such as electrostatic, ultrasonic, and piezoelectric energies, etc.

Twin-fluid atomizer is normally used to produce the fine droplets, especially for the liquids with high-viscosity [1]. There are two types of twin-fluid atomizers, i.e., the air-assist and air-blast atomizers. The interaction between the gas and liquid phases is the key issue to achieve higher performance of the atomizers. Air-assist atomizers use relatively less amount of air at a higher velocity to enhance the breakup processes of the liquid phase. On the other hand, air-blast atomizers employ large amounts of air at relatively lower velocity in the atomization process [1]. Air-Assist atomizers are usually classified as the internal-mixing and external-mixing configurations based on the location where the gas and liquid phases mix inside or outside the atomizer.

Many researchers have investigated the characteristics of the twin-fluid atomizers. For example, Rizkalla and Lefebvre [2] investigated the performance of the air-blast atomizers and found that the particle size of the spray decreases as the gas-to-liquid mass ratio (GLR) increases. Lefebvre et al. [3] further studied the performance of the plain-jet type air-blast atomizers. They showed that the increase in air velocity, air pressure, as well as air/liquid ratio tended to produce the more uniform spray and lower mean drop size.
The disintegration mechanisms of the liquid sheet were investigated by Chigier et al. and Samuelsen et al. [4, 5]. Chigier et al. first proposed two breakup modes, i.e., the mechanical and aerodynamic modes, based on the action of liquid pressure inside the nozzle and the action of air flow, respectively [4]. Samuelsen further proposed two different breakup mechanisms for the disintegration of the liquid sheet. The cellular breakup mechanism occurred at high relative velocity between air and liquid. On the other hand, the stretched streamwise ligament breakup mechanism occurred at low liquid velocity [5]. Whitlow and Lefebvre [6] further investigated the performance of the effervescent atomizer which is used to produce the fine droplets. However, its structure is more complicated than other twin-fluid atomizers.

Wang et al. [7-8] compared the characteristics of the air-assist and air-blast atomizers. They found that the air-assist atomizer has better atomization performance. It produced spray with narrower size distribution. Under the same amount of atomization air, the air-assist atomizer produced spray with smaller droplet size. Furthermore, air-assist atomizer needed only one third of air to produce the same drop size, as compared to the air blast atomizer. Nguyen et al. [9] also studied the atomization performance of the twin-fluid atomizers with the internal mixing mechanisms. They found that the atomizer produced fine water droplets with median mean diameter of 10\(\mu\)m at GLR as low as 1. Kufferath and Guo [10-11] further investigated the performance of the internal-mixing atomizers with coaxial liquid supply. The effects of nozzle design, loading and liquid and gas properties on the spray were reported. In a summary, the atomizers with internal-mixing mechanisms are preferred in terms of their high efficiency of energy transfer from atomization gas to liquid if the abrasion and fouling processes are not serious.

Recently, the applications of the micro atomizers in the medical and the cosmetic areas become popular. However, the flow rate and the droplet size are normally very low in these areas as compared to the performance of the conventional atomizers. Hence the development of the micro atomizers with special functions to meet the requirements in new applications becomes an important issue. Manufacturers of the conventional atomizers requires complicated equipments and is quite expensive for the micro-scaled machining. Furthermore, atomizers with traditional machining are difficult in producing spray with droplets size less than 10\(\mu\)m. Using micro electro-mechanical system (MEMS) technology atomizer can be built with micro scale feature or structure to obtain fine droplet. Hence recent development of the fabrication of micro atomizers tends to utilize the MEMS technique.

The pressure type micro-atomizer has been developed by many researchers. Singh et al. [12] had ever fabricated the swirling type pressure (i.e., simplex) atomizer on a 4" silicon wafer via deep-reactive ion etching (DRIE) technique. Its thickness is 400\(\mu\)m and the roughness less than 0.45\(\mu\)m. DRIE etching processes is highly anisotropic and well-controlled in the precision. They found that the mean droplet size is more than 25\(\mu\)m using this micro-atomizer.

Rajan et al. [13] further fabricate the micro-atomizer on the silicon substrate by atmospheric pressure chemical vapor deposition processes (APCVD). They used the thin film of 3C-SiC as the protective coatings in the fabrication processes to enhance its resistance to erosion.

Rajan & Mehregany [14] also fabricated the swirling type pressure atomizers on silicon carbide using DRIE and LIGA processes. They compared its performance to the nickel-based atomizers fabricated with the LIGA process. The orifice diameter of the micro-atomizer is 368\(\mu\)m. Results showed that these micro atomizers can be operated at high pressure. Tests on the performance and erosion processes demonstrated that both atomizers performed well for the pressure exceeding 25bar. However, the SiC-based atomizers exhibit better resistance to erosion. Their results also revealed that the above atomizers have better performance as compared to the silicon-based atomizers. The operation range of the latter one is limited to 14bar and is less resistant to erosion.

In an effort to develop the diesel injector, Baik et al. [15] developed the LIGA processes to fabricate the micro-injectors. They designed 14 types of the micro-atomizers with varied geometries. The micro injector has multiple orifices with orifice number from 1 to 169 and diameters from 40 \(\mu\)m to 260 \(\mu\)m. Experimental results showed that the spray angle and the penetration velocity are determined by the overall area of the orifices instead of its number and geometric configuration. The spray angle and the penetration velocity decreased when the orifice area was reduced. However, the spray angle and the penetration velocity increased when operated at a higher pressure. The droplet size decreased under high pressure conditions.

Yang et al. [16] used deep-molding processes to fabricate pressure type-swirling micro-atomizers, including the X-ray LIGA, ICP-LIGA and injection molding LIGA processes. The mean droplet size was more than 20\(\mu\)m in their tests. In an effort to enhance the atomization performance of the micro-atomizer, Snyder & Reitz [17] further developed the air-assist micro atomizer via LIGA process. They produced 4200 orifices on a nickel membrane for the gas flow. The diameter of the orifices is 7\(\mu\)m. The depths of the orifices were 84 and 160\(\mu\)m, respectively. The atomizers were designed with the external mixing mechanism. It turns out that the mean droplet size as small as 20\(\mu\)m can be obtained.

James et al. [18] designed a MEMS jet fuel atomizer based on electrostatic inkjet technologies for the pulse detonation engine. This atomizer was designed with a dual-acting single stage diaphragm as the micro-pump for fuel delivery and fabricated with the MEMSCAP Poly–MUMPs silicon-based surface-machining process. They used buffer hydrofluoric acid to remove the sacrificial layers and then dried with a supercritical CO\(_2\) process. The atomizer produced fuel spray with mean droplet size less than 10\(\mu\)m under low pressure. It can be operated at frequency higher than 100Hz.

Micro-atomizers have been widely used in the medical applications. Wissink et al. [19] had fabricated micro nozzle and micro sieve by MEMS technique for the pulmonary drug delivery devices. The orifice diameter and length of the atomizer were 10\(\mu\)m and 1\(\mu\)m, respectively, to minimize the viscous effects through the micro-channel. Results showed that this micro-atomizer produced spray with droplet size blow 20\(\mu\)m under an injection pressure less than 5Bar. Results also showed that this micro-atomizer produced mono-dispersed droplets at low
pressure, reducing the risk of macromolecular drug degeneration. Furthermore, the generation of droplets was a kinetic process hence the droplet size and size distribution were essentially independent of the viscosity and temperature of the drug-solution.

As reported in the literature, the droplet size produced by the micro-atomizer is relatively high including the pressure and the external air-assist atomizers. In an effort to produce the ultra fine particles by micro-atomizer, this paper attempts to develop the micro atomizer with internal-impinging mechanisms (see Figure 1). Two types of the twin-fluid micro-atomizers were designed. One is the air-assist type micro-atomizer (AMA type) with three micro channels for the liquid and gas flows. The other is the manifold type micro-atomizer (MMA type) with four micro channels. They were fabricated via MEMS bulk micro-machining processes. Among the micro-channels, two of them are used to supply the atomization gas and the others supplying the liquid matter. The orifice hydraulic diameters \( d_{H} \) of the micro atomizers are 45\( \mu \)m. The performance of the twin-fluid micro-atomizer under low flow rates will be characterized in this paper.

![Figure 1. Design of the micro-atomizers](image)

2. EXPERIMENTAL SETUP

2.1 Experimental Facility and Instrumentation

The experimental setup is shown in Figure 2. The test stand is designed for a down-sprayed type atomization experiment. It consists of a spray chamber, an optical table, a collection tank, and an exhaust fan. Liquid was delivered from a syringe pump and gas supplied from a compressed nitrogen tank. The liquid and compressed nitrogen are supplied through the 4 mm tubes. The mass flow rate of liquid is controlled by the syringe pump.

The drop size distribution is measured by a Malvern Insitec RT- Sizer, which uses the Fraunhofer diffraction technique and Mie scattering theory. The laser beam is expanded to 9mm diameter in the transmitter and becomes diffracted when passing through the spray. The diffracted light is received by the photo detector through the Fourier lens and transferred to digital signal by the A/D converter. From the known time difference and the measured displacement the velocity is calculated. This system works with a 10 W pulsed diode laser. The wave-length of the laser is 795nm. The laser light is then transferred to a 100 mm wide and 0.3 mm thick laser sheet through a combination of spherical and cylindrical lens. The laser sheet is used to illuminate the flow field of the micro spray. High-speed CMOS digital camera captures two frames exposed by laser pulses. Maximum frame rate is 5,145 fps with 512x512 pixels resolution. The camera is synchronized with the laser beam and the frame grabber by means of a USB-2 Timing Hub.

The particle velocity is measured by an IDT/proVISION-XS Particle Image Velocimetry (PIV) system. Particle Image Velocimetry systems provide two-dimensional velocity images of the flow using whole field techniques based on imaging the light scattered by small particles in the flow illuminated by a laser light sheet. PIV measures whole velocity fields by taking two images shortly after each other and calculating the distance individual particles traveled within this time interval. From the known time difference and the measured displacement the velocity is calculated. This system works with a 10 W pulsed diode laser. The wave-length of the laser is 795nm. The laser light is then transferred to a 100 mm wide and 0.3 mm thick laser sheet through a combination of spherical and cylindrical lens. The laser sheet is used to illuminate the flow field of the micro spray. High-speed CMOS digital camera captures two frames exposed by laser pulses. Maximum frame rate is 5,145 fps with 512x512 pixels resolution. The camera is synchronized with the laser beam and the frame grabber by means of a USB-2 Timing Hub. The images are formed by two different layers, each of them containing information about the individual particles positions. These images were then post-processed by the Tecplot software in order to extract the sub-images formed by 32x32 pixels from each layer and to perform a cross-correlation between the two corresponding sub-images. An interrogation algorithm extracts the correlation peak position from the cross-correlation domain with a sub-pixel precision, and performs the calculation of the two velocity components for those sub-images, by a pixel-to-mm conversion factor. Finally, the instantaneous velocity and average velocity plots are displayed by means of Tecplot software. Furthermore, the flow visualization technique is performed by the IDT-high speed camera system, an Olympus SZ-CVT microscope and a Nikon Coolpix 995 digital camera.

2.2 Fabrication of micro-atomizers

Figure 1 shows the design of the micro-atomizers. As shown in Figure 1(a), the liquid stream is first injected to the mixing chamber in AMA-type atomizer. The gas streams are introduced to the mixing chamber through two convergent-divergent channels. The gas-liquid mixture was discharged through the orifice to produce the micro spray. For the MMA type atomizer, as shown in Figure 1(b), the liquid stream is divided into two streams and is injected to
the gas channels separately. Atomization of the liquid streams in the high speed gas streams took place. The liquid and gas mixtures were further introduced to the mixing chamber and resulted in an impinging flow in the mixing chamber where the mixing and secondary atomization processes take place. The two phase flow is then discharged through the orifice to form the ultra-fine spray. The size of the discharge orifice is 500µm in width and 24µm in depth for AMA type atomizer. It is 380µm × 24µm for MMA type atomizer. It turns out that the orifice hydraulic diameter \(d_h\) of the two atomizers are 45.1µm and 45.8µm, respectively. We use glass material (i.e., the microscope slides) with the size of 76x26x1mm\(^3\) to fabricate the atomizers because it has high hydrophilic property as well as better mechanical property. The microchip needs high mechanical and bonding strength to sustain the high internal pressure driven by the syringe pump.

Figure 3 shows the fabrication processes of the micro-atomizers. The microscope slides were first cleaned in a boiling piranha solution. The bottom substrate was then patterned with positive photoresist AZ 4620 in a photolithography procedure including spin coating, soft bake, exposure, development and hard bake. The patterned glass substrate was further immersed in a BOE (buffered oxide etch) bath for 25 min to generate the required microchannels. After etching for 25 min with ultrasonic agitation, the microchannels attained a depth of 24µm. The upper microscope slides layer was then drilled to form the inlet holes with 2 mm in diameter using CO\(_2\) Laser. After preparing the individual glass substrates, each substrate was cleaned once again in a boiling piranha solution prior to the bonding process. The upper and bottom glass substrates were bonded in a 605°C sintering oven for 2 hour. Finally, plastic tubing with a 4 mm outer diameter and a 2.5 mm inner diameter was attached to each inlet hole using EPOXY. These tubes served to connect the microchip atomizer to the actuating syringes and pressurized nitrogen.

![Fabrication processes of the micro-atomizer.](image)

**Figure 3.** Fabrication processes of the micro-atomizer.

### 3. RESULTS AND DISCUSSION

#### 3.1 Phenomenological Description of Flow Patterns

The flow patterns of the micro-sprays are described first. Photos of the spray structure and the breakup pattern inside and outside the discharge orifice of micro-atomizer were taken by a digital camera and by a microscope and high speed camera with maximum frame rate of 5000 fps. Figure 4 (a) and (b) shows the spray pattern of AMA and MMA atomizers, respectively, under the liquid flow rate of 0.5ml/min. As can be seen from the first photograph of Figure 4(a), the micro spray of AMA atomizer presents a single stream pattern without flow expansion under single-fluid condition (i.e., \(P_g=0\)).

![Photos of the micro sprays by AMA and MMA atomizers.](image)

Figure 4 Photos of the micro sprays by AMA and MMA atomizers.

It should be noted that the spraying phenomenon was not observed during the test when the liquid supply was less than 0.4ml/min. The liquid medium forms a meniscus over a wide area outside the orifice. This indicates that the inertial force is less than the surface tension under the low liquid flow rate condition. It also implies that the influence of the surface tension becomes more significant in the micro injection processes. Hence it is not necessary to produce the finer spray by reducing the orifice size. This also explains the relatively large particles produced by the micro-atomizers as reported in the literature.

However, the above situation can be improved by simultaneously introducing the gas flow to the micro-atomizer. Figure 4(a) shows that the spraying phenomenon takes place under gas pressure ranging from 1 to 5bar. Furthermore, the micro sprays have a wide expansion angle under such twin fluid condition. For example, the micro spray has a cone angle of 35° under the gas pressure of 2bar. Moreover, the spraying phenomenon can be observed under the twin-fluid condition even though the liquid flow rate was less than 0.4ml/min. It indicates that the atomization processes under lower liquid flow conditions is due to the action of the atomization gas. It turns out that the inertial of the liquid medium under low flow rate is highly enhanced to overcome the surface tension by the momentum transfer from the gas phase. Hence the addition of the atomization gas can be used to extend the operation range to the lower liquid flow rate. The turn-down ratio of the micro-atomizer is also increased under the twin-fluid conditions. Furthermore, the increase of the momentum of the gas phase can be used as the mechanisms to control the particle size of the micro-spray that will be described later.
Gas Pressure (bar)

Spray Angle (degree)

0 1 2 3 4 5 6 7

0 20 40 60 80

AMA Atomizer
MMA Atomizer

Figure 5 Dependence of spray angle on gas pressure for MMA and MMA atomizers (Liquid flow rate 0.5ml/min).

As a comparison, Figure 4(b) further illustrates the flow structure of the micro sprays by the MMA atomizer. The micro-sprays were produced under liquid flow rate of 0.5ml/min and gas pressure ranging from 1bar to 5bar. The spray pattern of the MMA atomizer is similar to that of the AMA atomizer. The impingement of the gas flow in the mixing chamber results in the atomization process of the liquid phase. The onset of spraying processes occurred when the gas pressure reached 1bar. The particles size of the spray under such condition was large and could be observed by the naked eyes. The micro-spray became stable and particle size finer as the atomization pressure is further increased.

Figure 5 shows the dependence of spray angle on gas pressure for MMA and MMA atomizers. The spray angle reduced from 60° to 30° as the gas pressure was increased from 1.0bar to 5.0bar for AMA atomizer. While it reduced from 55° to 20° as the gas pressure was increased from 1.0bar to 5.0bar for MMA atomizer. It is also interesting to see that the micro sprays of both cases were the jet type structure instead of the liquid film structure although the aspect ratios of orifice were as high as 20.8 and 15.8 for the AMA and MMA atomizers, respectively. This indicates the strong effects of the surface tension on the micro spray structure. This also explains the single stream structure of the spray jet observed in Figure 4(a) under Pg = 0. However, the flow expansion took place when the gas flow was introduced into the micro atomizer. This phenomenon can be explained by the flow instability under the strong interaction between the inertial and the surface tension forces. The larger spray angle associated with the AMA atomizer is probably resulted from its higher aspect ratio of the orifice. Moreover, the aspect ratio may be used as the design parameter to control the expansion angle of the micro spray.

Figure 6 Atomization mechanisms of AMA and MMA atomizers

Figure 6 further illustrates the atomization mechanisms of AMA and MMA atomizers. As shown in Figure 6(a), the atomization processes associated with the AMA atomizer started from the instability of the liquid column outside the orifice. It followed with the breakup processes of the liquid column. The intact length was less than 300µm as estimated from the picture. On the other hand, the liquid column was not observed during the atomization processes of the MMA atomizer (see Figure 6(b)). Instead, the impingement of the two phase flow in the mixing chamber and at outlet of the orifice was observed. It turns out that the atomization of the MMA atomizer was essentially due to the impingement of the gas flow on the liquid phase. The oscillatory injection was also observed under the impinging mechanism. This implies the strong interaction between the atomization gas and the liquid phase. The effectiveness of the impinging mechanisms may results in the finer spray that will be described later.

3.2 Performance of the Micro-Atomizers

Figure 7 illustrates the dependence of the mean drop size on the atomization pressure for AMA atomizer. As can be seen from this figure, the mean droplet size decreases from 14µm to 7.5µm as the gas pressure increases from 3bar to 4 bar under a liquid flow rate of 0.1ml/min. It further reduced to 5.3µm as the gas pressure increases from 4bar to 5bar. Figure 7 also shows that the mean droplet size of the micro spray increased as the liquid flow rates were increased. This can be explained by dependence of particle size on the gas-to-liquid mass ratio as illustrated in Figure 8. As shown in this figure, the mean drop size decreased from 14.1µm to 7.5µm as the gas-to-liquid mass ratio (GLR) increased from 3.1 to 3.8. It further reduced from 7.5µm to 5.3µm as GLR increased from 3.8 to 4.7. It is obviously that the reduction in droplet size of the micro-spray is due to the increased atomization energy of the gas flow. However, this figure also indicates that the reduction of the droplet size approaches a limit as the gas-to-liquid mass ratio (GLR) is further increased. It turns out that the twin-fluid micro atomizer can be operated under the gas-to-liquid mass ratio ranging from 3.1 to 4.7 which is higher than that of the conventional air-assist atomizers. Operation under higher gas-to-liquid mass ratio is essentially due to the increased surface effect associated with the micro systems. However, the micro atomizer produces the spray with jet diameter less than 100µm which is not attainable with the conventional atomizers. Hence it can be used in various applications that require the spray with micro diameter.
In an effort to explain the effects of impinging mechanism on the atomization performance, Figure 9 and 10 further show the performance of the MMA micro-atomizer. As can be seen from Figure 9, the particle size ranging from 15µm to 3µm has been achieved. However, the dependence of the particle size on the gas pressure is different under low and high liquid flow rates. For example, in the tests under low liquid flow rate ranging from 0.1 to 0.2ml/min, the mean droplet size decreased from 14.5µm to 9.0µm as the gas pressure was increased from 2.0bar to 5.0bar. On the other hand, in the tests under high liquid flow rate ranging from 0.3 to 1.0ml/min, the mean droplet size increased from 3.0µm to 6.0µm as the gas pressure was increased from 2.0bar to 5.0bar. It turns out that the droplet size was larger at low liquid flow rate with the same atomization gas. Hence the atomizer has higher atomization performance under higher liquid flow rates. This phenomenon is different from that of the AMA-atomizer because its liquid supply is at the central region of the orifice.

The above results can be explained by the breakup processes associated with instability of liquid column as well as the impinging mechanisms described earlier. The characteristics of the micro spray at low liquid flow rates for MMA atomizer is similar to that of the AMA-atomizer because the breakup process is essentially due to the instability of liquid column under such conditions. However, the atomization mechanism is switched to the impinging mode when the liquid flow rate is further increased until the amount of the liquid phase occupied two sides of the orifice by the surface tension. This condition is easy to attain in MMA atomizer because its liquid supply comes from both sides of the mixing chamber, especially under the higher liquid flow rates and lower gas pressure. The atomization processes become the impingement of the high speed gas flow onto the liquid medium. The oscillatory injection under such flow condition confirms the existence of the impinging mechanism. The design of AMA-atomizer does not favor the attainment of this condition because its liquid supply is at the central region of the orifice.

Results also show that the effectiveness of the impinging mechanism for the MMA-atomizer decreases as the gas pressure is increased. For example, the atomization performance is degraded and the mean droplet size increases from 3 to 6 µm as atomizing gas pressure increases from 2 to 5bar. It can be explained by the higher gas-to-liquid mass ratios as the gas pressure is increased. The higher gas-to-liquid mass ratios imply the lower coverage of the liquid phase at the orifice area during the injection processes. It turns out that the atomization process is controlled by the instability of the liquid film instead of the impinging mode.

It is concluded that the atomization performance is better under the impinging mechanism. The ultra fine particles can be produced by the MMA-atomizer under the higher liquid flow rates and the lower gas pressure.
lowered to the range of 0.13 ~ 0.38. It results in the finer droplets because the atomization performance is controlled by the impinging mechanism.

[Image: Comparison of mean drop size on GLR for MMA-atomizer]

(a) Liquid flow 0.1ml/min. (b) Liquid flow 0.5ml/min.

Figure 10. Dependence of mean drop size on GLR for MMA-atomizer

[Image: Comparison of mean drop size on GLR for GLR 0.10 0.15 0.20 0.25 0.30 0.35 0.40]

Figure 11. Dependence of pressure difference (P_l - P_g) on gas pressure for MMA-atomizer

In order to explain the difference between the atomization mechanisms, Figure 11 further illustrates the dependence of pressure difference (P_l - P_g) on the gas pressure for MMA-atomizer. As can be seen from this figure, the pressure difference can be divided into two groups. One is the region with the pressure difference less than 0.1bar and is related to the atomization mechanism of liquid jet instability. The mean droplet size is relatively larger under these conditions. The other is the region with the pressure difference greater than 0.1bar and is related to atomization mechanism of impinging mode. One can obtain the ultra-fine spray under this condition.

3.3 Velocity Distribution of the Micro Spray

Figure 12 shows the axial velocity profile of the micro spray is essentially a jet flow structure for AMA. The peak velocity in the central region of the micro spray is similar to that of the conventional air-assist atomizer. However, the velocity of the micro spray is lower than that of the conventional atomizer under the same pressure. Figure 12(a) compares the axial velocity distribution of micro spray along the Z axis. The positive axial velocity is defined in the downward direction of the micro spray. This figure shows that the peak axial velocity of the droplets decreased from 4.0m/s to 1.0m/s at the positions from 60mm to 20mm from the outlet of the atomizer under liquid flow rate of 0.5ml/min and gas pressure of 2bar. This indicates that the micro-spray lost most of the initial momentum within short distance from the orifice. It turns out that the relative velocity between the droplets of the micro-spray and the surrounding air is reduced.

[Image: Comparison of mean axial velocity on radial distance for AMA-atomizer (Liquid flow rate 0.5ml/min)]

(a) Pg =2bar (b) Pg =5bar

Figure 12(b) illustrates the mean axial velocity distribution of micro spray along the Z axis at liquid flow rate 0.5ml/min and gas pressure 5bar. The mean axial velocity of spray droplets decreases from 6.6m/s to 3.7m/s at downstream distance from 20mm to 60mm. The axial velocity of the micro-spray under gas pressure of 5bar is slightly higher than the axial velocity at 2bar.

[Image: Comparison of mean axial velocity on radial distance for MMA atomizer (Liquid flow rate 0.5ml/min)]

(a) Pg =2bar (b) Pg =5bar

Figure 13 illustrates the profile of mean axial velocity on radial distance for MMA-atomizer. As can be seen from this figure, the axial velocity profile of the micro spray is essentially a jet flow structure, similar to the case of AMA-atomizer. The peak velocity increases from 2.7m/s to 6.3m/s at distance 20mm from the micro atomizer under liquid flow rate of 0.5ml/min and the gas pressure being increased from 2bar to 5bar. Moreover, The peak velocity decreases from 0.9m/s to 2.7m/s at distance 40mm from the atomizer. Hence the peak velocity of the MMA-atomizer is lower than that of the AMA-atomizer under the same condition. It is due to the finer spray produced by the MMA-atomizer. Therefore, the micro spray of MMA is a slow moving mist that more satisfies the medical spray applications. It can be concluded that the particle mean velocity for AMA and MMA reduced to low speed range in the downstream. The ultra-fine spray with low flow rate and slow moving velocity satisfies the requirement of the inhaling drug delivery and is useful in the treatment of the pulmonary diseases (asthma, COPD) in the medical application.
4. CONCLUSION

Performance of the twin-fluid micro-atomizers with internal impinging mechanisms is described in this paper. Results show that the twin-fluid micro-atomizer produces fine spray with particle size less than 5µm, a performance better than the micro atomizers shown in the literature. Flow visualization through a microscope shows that the atomizing mechanisms can be related to the breakup process of liquid column instability for AMA-atomizer. The atomization mechanisms of the MMA-atomizer can be related to the impinging oscillation mode with a higher liquid flow rate. It turns out that the mean droplet size reduces from 14.1µm to 5.3µm when the gas pressure increases from 2.0bar to 5.0bar for the AMA-atomizer with high GLR ranging from 3.1 to 4.7. On the other hand, the mean droplet size increased from 3.0µm to 6.0µm as the gas pressure was increased from 2.0bar to 5.0bar with much lower GLR ranging from 0.13 to 0.38. It is also found that the atomization with impinging oscillation mode is more efficient as far as the design of the micro-atomizer is concerned. Moreover, the mean axial velocity of spray droplets is below 6.6m/s at a distance 20mm from the atomizer. The ultra-fine sprays with slow moving behavior can be used to the applications of the inhaled drug delivery for respiratory care.

5. ACKNOWLEDGEMENT

This research was funded by Center for Micro/Nano Technology Research, National Cheng Kung University under contract No. NSC-94-2212-E-006-075.

6. NOMENCLATURE

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<td>AMA</td>
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<td>d_i</td>
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<td>GLR</td>
<td>gas-to-liquid mass ratio</td>
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<td>MMA</td>
<td>manifold micro atomizer</td>
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<td>r</td>
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<tr>
<td>SMD(D_{32})</td>
<td>Sauter Mean Diameter</td>
<td>[µm]</td>
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<tr>
<td>Pg</td>
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7. REFERENCES