Influence of Internal mixing region on spray fluctuation in twin-fluid atomizer

P Watanawanyoo1, H Mochida1, T Furukawa1, M Nakamura2 and H Hirahara2
1Graduate School of Science and Engineering, Saitama University, Saitama, Japan
2Division of Human Support and Production Sciences, Saitama University, Saitama, 338-8570, Japan
E-mail: s09dh052@mail.saitama-u.ac.jp

Abstract. A twin-fluid atomizer with internal mixing chamber was developed and its performance was tested. The primary breakup took place in the internal mixing chamber, so the mass flow rate of air and water was measured and those ratios were presented vs. supplied pressure. In the present report, the oscillatory behavior of the spray produced by the developed twin-fluid atomizer was investigated to explore the stabilities of the spray. An optical observation was conducted to analyze the unsteady spray images with a high speed video camera. The images were inspected with FFT analysis and stream-wise oscillation spectrum was discussed for various supplied-air pressures and the length of the internal mixing chamber, L. When L is small, a strong resonance took place so that the spray is influenced by this phenomenon. However, the oscillation was suppressed then a stable atomization was provided by adjusting L.

1. Introduction
Many types of atomization techniques for the combustion systems have been contrived. According to the refining techniques of liquid, the atomizers are classified into several types, e.g. single-fluid pressure atomizer, two-fluid atomizer, rotary atomizer, electrostatic and ultrasonic atomizer [1], etc. These different types of nozzles are widely used for the specified purpose. Among them, single and twin-fluid atomizers are widely used in combustion systems. In the twin-fluid atomizer, liquid is disintegrated into droplets and ligaments by the interaction between the gas and liquid to lead to spray. This process will proceed more easily if the liquid is introduced as liquid sheets which have higher surface energies or higher instabilities [2], and thus are more susceptible to disintegration. Aerodynamic forces promote the disruption by exerting external distorting forces to the bulk liquid [3]. A breakup occurs when the magnitude of the disruptive force exceeds the consolidating surface tension force [4].

So far, we have been involved in the development of an atomizer, which is categorized into the twin-fluid type of a micro gas turbine system as a local on-site power generator. The developed atomizer has an internal mixing chamber where air and fuel are mixed, which are separately introduced through specified inlet ports. Mixing of the air and fuel causes a primary breakup within the chamber, whereby achieving production of fine droplets at the exit of the nozzle. In the previous study, we investigated fundamental characteristics of the developed nozzle including spray angle and

1 To whom any correspondence should be addressed.
spray penetration length. The results demonstrated an abrupt increase in a discharge coefficient, defined as a ratio of the actual air flow rate of the isentropic flow rate, at a certain air supplied pressure. Through the detailed analyses, this jump was probably attributed to transonic flow instability produced by barrel shock within the internal mixing chamber. In order to achieve a stable and safe operation of the atomization, it is necessary to understand spray fluctuations [5] produced by the developed atomizer.

The aim of the present study is therefore to explore the oscillatory behavior of the spray produced by the developed twin-fluid atomizer. The effects of the length of the internal mixing chamber on the spray characteristics were also examined to obtain fluid mechanical insights into the optimum design of the nozzle in terms of spray stability.

2. Method
Figure 1 presents a cross-sectional illustration of the air-assisted atomizer developed in the present study. Pressurized air supplied from the primary nozzle expands in the internal mixing chamber. The air flow develops into a supersonic jet in the internal mixing chamber if the plenum pressure is larger than a critical pressure. The dimensions of nozzle geometry and experimental condition of atomization used in the present study are summarized in Table 1.

Table 1. The dimensions of nozzle geometry and experimental condition

| Parameter                                | Value                  |
|------------------------------------------|------------------------|
| Diameter of primary nozzle               | $D_1 = \phi 1.0 \text{ mm}$ |
| Diameter of secondary nozzle             | $D_2 = \phi 2.5 \text{ mm}$ |
| Length of secondary nozzle               | $L_2 = 10 \text{ mm}$   |
| Length of internal mixing chamber        | $L = 7, 10, 12 \text{ mm}$ |
| Test liquid                              | Distilled water        |
| Driving gas                              | Air                    |
| Diameter of air inlet port               | $\phi 9.2 \text{ mm x 1}$ |
| Diameter of water inlet port             | $\phi 9.0 \text{ mm x 1}$ |
| Air supply pressure                      | 170-790 kPa abs.       |
A pressurized air was supplied through the air inlet port. Its flow rate was measured with a digital flow meter. The air pressure was regulated by the controller. The water, used as a model liquid for fuel, was fed from a storage tank placed at the same altitude of the nozzle. The water stored in a tank was conveyed due to the ejector effect to the atomizer. The water flow rate was regulated by controlling the supplied air pressure. The data of pressure and flow rates of air and water were transferred to the computer for post-analysis. The nozzle was mounted on an aluminum frame placed 0.42 m above the drain tank. A honey comb was established in a drain tank situated far below the nozzle to minimize air circulation within the tank.

An experimental setup is illustrated in Figure 2. Flow in the downstream of the nozzle was visualized with a shadowgraphic technique. A continuous Nd-YAG laser with 532 nm in wavelength (Spectra Physics, Millennia Pro) was used for illuminating the flow [6]. The laser was controlled by a pulse generator. Speckle noises resulting from the coherency of source light were minimized with a speckle killer (Nano photon, SK-11) and a ground glass. The laser beam passing through the ground glass was collimated with a lens of 100 mm in diameter. The shadowgraphic images were captured with a high speed CMOS camera (IDT, XS-5). The focal length was 200 mm and the spatial resolution was 1280 x 1024 pixels. All image data acquired in the experiment were stored in a PC via data logger.

Experiments were conducted to investigate the effects of the length of the internal mixing chamber and the air-supply pressure on the spray characteristics. The length of the internal mixing chamber, L, was varied at \( L = 7, 10 \) and 12 mm, while the air-supply pressure was varied in 170, 307, 514, 652 and 790 kPa in absolute. In the present liquid feeding line, the liquid tank was released to the atmosphere, so the liquid was sucked by the vacuum pressure of air ejection and delivered to the atomizer. Capturing the spray images, if liquid completely blocks a laser light, liquid appears in black on the images. On the other hand, if a laser light passes through air without any losses, the air appears in white. Although noises are always accompanied, the oscillatory behavior of the spray could be investigated by an image analysis. Figure 3 gives a schematic representation of the method to analyze the spray fluctuation. A region of interest (ROI) with the size of 0.043 mm x 2.5 mm was placed at 2.5 mm downstream from the nozzle exit. The grayscale intensity (black to white) over the ROI was averaged. In order to offset a fluctuation of the net intensity of an image resulting from instabilities of a laser, the averaged intensity of the ROI was normalized with the grayscale intensity of the pixel far enough away from the nozzle, which no sprays can reach. The fast Fourier transform was then applied for a time-series data of the normalized grayscale intensity to obtain the frequency spectrum of the spray.

![Experimental setup for visualization of the spray](image-url)
3. Results

3.1 Air-liquid mass flow ratio and discharge coefficient

An air liquid mass flow ratio, $\text{ALR}$, is one of the important factors for assessing the nozzle performance and combustion efficiency. $\text{ALR}$ was obtained as a ratio of the mass flow rate of air to that of water. $\text{ALR}$ vs. air-supply pressures for 3 different lengths of the internal mixing chamber is plotted in Figure 4. Macroscopically, the $\text{ALR}$ tended to increase as the air-supply pressure became larger. A comparison of $\text{ALR}$ between different lengths of the internal mixing chamber shows that $\text{ALR}$ changed more widely for longer internal mixing chamber. This suggests that more flexible adjustment of $\text{ALR}$ can be made for a longer internal mixing chamber. It should also be noted that $\text{ALR}$ became smaller as the internal mixing chamber became shorter. Since smaller $\text{ALR}$ means that more volume of the fuel can be atomized given the same air-supply pressure, the shorter internal mixing chamber would produce better performance in terms of efficiency.

Figure 5 plots a discharge coefficient, $C_d$, against the air-supply pressure. The discharge coefficient, $C_d$, was calculated as a ratio of the flow rate of the air to that of an isentropic flow [7] which gives a standard estimation of the flow rate in dry test. The flow rate of the isentropic flow was estimated with the room temperature of 288 K, gas constant of 287.1 J/kgK, and a specific heat ratio of the air of 1.4. The isentropic gas flow gives a standard estimation of the flow rate in dry test. Overall, the discharge coefficient increased with elevation of the air-supply pressure for all lengths of the internal mixing chambers. A significant gap in the discharge coefficient was observed between the air-supply pressure of 170 kPa and 310 kPa. This was caused by transonic instabilities within the nozzle due to choking. Beyond this pressure, the discharge coefficient increased monotonically as the air-supply pressure became larger.
3.2 Spray fluctuation

Figure 6 presents snapshots of the flow near the exit of the nozzle with the length of the internal mixing chamber of 7 mm operated under the air-supply pressure of 171, 516 and 791 kPa. The formation of a spray begins with the detaching of droplets from the outer surface of a continuous liquid core extending from the orifice of the injection nozzle. While some ligaments are partially observed for 171 kPa, the ejected liquid promptly disintegrated into droplets once the flow is ejected from the nozzle. Droplets were quite dense near the nozzle, but scattered as they moved downstream. For all conditions, no core flow was found. Although Figure 6 does not give any insights into the oscillatory behavior of the ejected flow, the spray fluctuation was clearly observed.

![Figure 4. Plot of the ALR against the air-supply pressure](image)

**Figure 4.** Plot of the ALR against the air-supply pressure

![Figure 5. Plot of the discharge coefficient against the air-supply pressure](image)

**Figure 5.** Plot of the discharge coefficient against the air-supply pressure

![Figure 6. Snapshots of the flow near the exit of the nozzle with the length of the internal mixing chamber of 7 mm operated under the air-supply pressure of (a) 171, (b) 516 and (c) 791 kPa.](image)
A frequency spectrum of the grayscale intensity of the ROI defined as 2.5 mm downstream of the nozzle exit was shown in Fig. 7. Figure 7 (a), (b) and (c) present the data for the air-supply pressure of 171, 516 and 791 kPa, respectively. In looking at Fig. 7 (a), when the air-supply pressure was 171 kPa, we found the prominent peak at the frequency of 81 Hz for $L = 7$ mm, and 75 Hz for $L = 10$ mm. In contrast, for $L = 12$, the frequency spectrum did not show remarkable peaks. Rather, the intensity monotonically decayed with an increase in the frequency. The peaks observed for $L = 7$ and 10 mm at the air-supply pressure of 171 kPa shifted to a high-frequency side when the air-supply pressure was 516 kPa (Fig. 7 (b)). In addition, another peak was observed in the frequency of 483 Hz for $L = 7$ mm, which is possibly the second harmonics. At this pressure, a small peak appeared at the frequency of 40 Hz for $L = 12$ mm. A further increase in the air-supply pressure caused an intensification of the peak values and a small shift of the peak frequency towards a higher frequency side for $L = 7$ and 10 mm. At the air-supply pressure of 791 kPa, the primary and second peaks were found at the frequency of 253 Hz and 483 Hz for $L = 7$ mm as in Fig. 7 (c). For $L = 10$ mm, the peak was presented at the frequency of 214 Hz. For $L = 12$ mm, the frequency spectrum seems to be flat, although a small hump was observed in the frequency of 39 Hz.

These instabilities may be attributed to the jet resonance in the internal mixing chamber. A subsonic or supersonic jet forms a shock cell structure and self-excited oscillation was induced in it. When $L$ is small, a strong resonance took place so that the spray is influenced by this phenomenon. However, the oscillation was suppressed then a stable atomization was provided by adjusting $L$.

![Figure 7](image_url)

**Figure 7.** Frequency spectrums of the grayscale intensity of the ROI defined at 2.5 mm downstream from the nozzle exit; the air-supply pressure of (a) 171, (b) 516 and (c) 791 kPa.

4. Concluding Remarks

In the present study, we visualized the flow ejected from a twin-fluid atomizer with internal mixing chamber which was developed in the present research. The air supply pressure was regulated of 170 kPa to 790 kPa (abs). The results demonstrated that ALR got smaller as the length of the internal mixing chamber became shorter. In this sense, a shorter internal mixing chamber would produce better performance, since more fuels can be drawn with smaller air-supply pressure. However, in looking at the frequency spectrum of the spray, we found the shorter internal mixing chamber caused the prominent oscillation in the spray, indicating unstable atomization, which is inherently included in the jet flow generated in the internal mixing chamber. When the internal mixing chamber is long, the disintegration will be prompted due to the extension of the mixing time in the internal mixing chamber. On the other hand, the performance of loading of liquid may be decreased. Therefore, thecompromise of the disintegration enhancement and fuel loading performance should be optimize in the nozzle design.
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