Research Article

Experimental Study of the Effect of the Expansion Segment Geometry on the Atomization of a Plain-Jet Airblast Atomizer

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In this paper, the idea of adding an expansion segment over traditional airblast atomizer is proposed to improve the spray performance. According to the systematic experiments, the Sauter mean diameter, the droplet size distribution, and the droplet axial mean velocity were obtained to evaluate the spray performance. The correlations between spray performance and four geometrical parameters of the expansion segment which include the length, the angle, the throat area, and position of liquid jet are considered. The atomizer operates at atmospheric pressure and temperature, and the air liquid ratio range is from 0.48 to 2.85. The data of the results were measured by Phase Doppler Particle Analyzer. The results show that more uniform droplet size distribution can be achieved with the addition of expansion segment, and the droplet size distribution factor $q$ of the case adding the expansion segment is 52.8% bigger than that of the case with no expansion segment. $q$ increases as the length and angle of expansion segment increase. The Sauter mean diameter can be reduced by either reducing the length or angle of expansion segment. As for droplet velocity, it is determined that the droplet velocity increases along the radial direction, which is noteworthy because opposite trend is reported for traditional plain-jet atomizers. With an increase of the length, angle, and throat area of the expansion segment, the droplet axial velocity decays.

1. Introduction

According to the characteristics of the atomization, the atomizer can be divided into airblast atomizing nozzle and pressure atomizing nozzle. Airblast atomizers have many advantages over pressure atomizers, especially in their application to combustion systems operating at high pressure. They require lower fuel-pump pressure and produce a finer spray. Moreover, because the airblast atomization process ensures thorough mixing of air and fuel, the ensuing combustion process is characterized by very low soot formation and a blue flame of low luminosity, resulting in relatively low flame radiation and a minimum of exhaust smoke. The merits of the airblast atomizer have led to its installation in a wide range of aircraft marine and industrial gas turbines.

Two basic configurations of airblast atomizer are recognized by Ashgriz and Nassseer [1]: prefilming and nonprefilming. The atomization performance of prefilming nozzles is generally supprion to that of plain-jet nozzles [2], and the same conclusion was presented in another literature review [3], but they are fully effective only when both sides of the liquid sheet are exposed to the air, and structure is complex. Plain-jet, which the fuel is not transformed into a thin sheet, but instead is injected into the high-velocity airstream in the form of discrete jet, is sometimes preferred.

The basic objective of airblast atomizer is combined effect of high kinematic viscosity and surface tension, namely, to deploy the available air, in the most manner, and to achieve the best possible level of atomization.

Plain-jet airblast atomization was systematically analyzed first by Nukiyama and Shiro [4]. Lozenzetto and Lefebvre have studied the effect of varied sizes of air atomizer on the mean drop size of the spray. They have generated a family of curves in terms of mass ratio. A general trend of reduced drop size has been reported in literature [5]. After that, Rizk and Lefebvre investigated the effects of air and liquid properties and atomizer dimensions on the spray characteristics including mean drop size and drop-size distribution with
light scattering technique. The results show that increases in air velocity, air pressure, and air/liquid ratio all tend to produce a more uniform spray and a lower mean drop size [6], and minimizing the angle of impact between the fuel jet and the high-velocity airstream improves the atomization quality [7]. Eroglu et al. investigated the effects of atomizer geometry and ambient back pressure on the intact liquid lengths of sprays using photographic experiments. The results show that when the ambient pressure is 0.1 MPa, the nozzle geometry is the important factor to spray performance. When the ambient is up to 3 MPa, there is no connection between the nozzle geometry and spray performance [8]. With the development of science and technology, up-to-date laser diagnostic techniques have been in experiment measuring downstream flow field. The Phase Doppler Particle Analyzer (PDPA) was earliest used in measuring droplet size and velocity distribution by Hardalupas and Whitelaw in 1993 [9].

In recent year, several geometrical parametric of the plain-jet airblast atomizer has been studied by Paul and Srdihar. The investigation shows the axial distance between the liquid jet and air orifice entrance results in marked difference in spray drop mean size under low air momentum flow conditions [10], and the liquid postrecess in the air nozzle cavity leads to increased drop sizes with the convergent exit and has little effect with the straight exit [11]. Charalampous et al. study the breakup length of liquid jets in airblast atomizers using different measuring method [12]. Urbán et al. used PDPA to measure the simultaneous drop size and axial and radial velocity components at various axial distances from the nozzle for a range of atomizing pressure [13]. Zaremba et al. investigated the effect of mixing process on spray formation in low-pressure twin-fluid atomization. The research shows that the spray formation process depends mainly on the internal design of twin-fluid atomizer at low ALR [14]. Inamura et al. studied the effect of prefilmer edge thickness on spray characteristics in prefilming airblast atomization which shows the effect of prefilmer edge thickness on SMD was large in the primary atomization region, but small in the secondary atomization region. In the primary atomization region, with increasing edge thickness, the droplet size distribution became broader [15]. The scholars from the University of Washington demonstrate the mechanisms of interfacial instability due to gas-liquid shear and liquid ligament acceleration that occur in the near-field of coaxial two-fluid atomizer which plays a determining role on the plain-jet airblast atomizer spray characteristics in the far-field [16]. The divergent diffusers after the expansion atomizer had been studied by Panão et al. The investigation presented an evidence of a minimum of \( H/D = 2 \) to produce larger particles through the agglomeration process depending on two flow structures, and for \( H/D > 2 \), divergent cross-section diffusers appear to enhance the agglomeration of microparticles when compared to diffusers with a constant cross-section. However, a noticeable increase in the number of agglomerate particles for \( H/D > 3 \) points this as the minimum geometric threshold to produce sprays with a higher concentration of larger particles, which is useful for cooling purposes. Although the results are very innovative, it cannot be applied to two-phase spray because the material of spray investigation is dry ice [17]. The geometric ratios \( D_s/Do \), \( Lo/Do \), and \( L_s/Ds \) had been examined of their influence on the spray cone angle and SMD [18]. The influence of atomizer exit geometry on jet instabilities during the unsteady primary jet breakup process in liquid-centered coaxial atomizer had been investigated by Kumar and Sahu. From the test result, it shows that the atomizer exit geometry plays a crucial role in triggering the interfacial disturbances as it conditions the liquid and airflow prior to their interaction [19]. Urbán et al. investigated the effect of geometric atomizer structure on the spray cone angle. It can be seen that increased liquid jet breakup length decreases spray cone angle while intense ligament formation increases it [20]. Broniaz-Press et al. studied the effect of orifice shape on the atomization process. The test data shows that the smallest droplet diameters were obtained by atomization in profiled and conical shaped orifice atomizers; however, the largest droplet diameters were achieved for plain orifice atomizers [21].

As reviewed above, numerous previous studies had investigated the spray characterization of plain-jet airblast atomizer, and all of research atomizers have the same structural features that their exit segment are always converged. However, the spray cone angle with those structures would be quite narrow, and the fuel distribution would extremely concentrate on the narrow region; collisions between liquid particles were more likely to occur which lead to large particle droplet production [22], and the same theory had been confirmed with the investigation of Shraiber et al. [23]. Yang and Chin had studied the effect of high back pressure on the spray characteristics of a plain-jet injector in coaxial airflow according to experiment. The feature of the experiment atomizer structure interestingly showed to use a

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**Figure 1:** The cross segment of investigated plain-jet airblast atomizer.
convergent-divergent nozzle. The research shows that the SMD decreases monotonically with the increase of back pressure [24].

However, there are few studies concerning the influence of the structural parameters of the atomizer with the expansion segment on spray performance in existing literature. In order to remedy that, a series of atomizer were designed which added the expansion segment to the exit of the convergent segment, and this paper focus on the effect of the different structure parameters of exit expansion segment on the spray characteristics.
2. Experimental Setup and Measurement Condition

In this section, the various atomizer geometries, the facilities, and the operating conditions adopted in the test are described in detail.

2.1. Atomizer Geometrics. Figure 1 shows the schematics of the currently investigated plain-jet airblast atomizer. The atomizer was operated at atmospheric pressure. The arrows shown in yellow color indicate airflow while blue colored arrow and face are represented for liquid. A flow straightener was constructed by four microchannels of inner diameter 1.2 mm and length 4.0 mm, which is used to reduce flow asymmetry and residual swirling motion of air. The airflow discharged from the microchannels passes through along straight pipe whose diameter is 11.0 mm into the convergent and expansion segment. The liquid was discharged from the liquid tube whose diameter is 0.4 mm and where is located in the central of the atomizer. The air-liquid interaction area is located at the convergent and expansion segment, which includes three breakup processes affecting the spray performance as shown in Figure 2. Firstly, the primary breakup process occurs in the liquid ligaments discharged from the liquid tube. The mass flow rate of the liquid and the initial liquid jet diameter are key factors influence the primary. Secondly, the convergent segment of air interacts with the liquid fragments, which causes their disintegration and the secondary breakup, and leads to the formation of the liquid film and individual droplets with various sizes. Enhancing the air aerodynamic force will promote the secondary breakup process. At last, because of the air pressure differential between the front and back edged of the liquid jet, the liquid film and droplets will turn with a circular moving to the downstream at the expansion segment. The film and droplets discharging from the exit of the expansion segment will break up again due to the interaction with the surrounding ambient atmosphere. The residence time of liquid spend in the passage and the confined space size of liquid flow area have a decisive influence on the third breakup process.

2.2. Experimental Setup. The experimental facilities consist of three subsystems including the liquid supply system, the air supply system, and the measurement system, of which schematic is shown in Figure 3. The basic constitutes of the liquid supply subsystem are fuel tank, pump, tank regulator, liquid filter, valves, and pressure gauge. The atomized liquid was discharged from the oil tank through a high-pressure oil pump which is capable to set the maximum working pressure up to 4 MPa. The liquid flow rate is monitored by the pressure gauge and which is controlled by the valves.

| Subscript | Type | Code number | Parameter |
|-----------|------|-------------|-----------|
| H         | The length of the expansion segment | H1 18.5 4 -2.7 0 |
|           |      | H2 18.5 4 -2.7 5.5 |
|           |      | H3 18.5 4 -2.7 10.5 |
| A         | The angle of the expansion segment | A1 15 4 -2.7 16.1 |
|           |      | A2 20 4 -2.7 16.1 |
|           |      | A3 25 4 -2.7 16.1 |
| D         | The throat area of the expansion segment | D1 18.5 3.2 -2.7 16.1 |
|           |      | D2 18.5 3.6 -2.7 16.1 |
|           |      | D3 18.5 4.4 -2.7 16.1 |
| h         | The position of liquid jet exit | h1 18.5 4 0 16.1 |
|           |      | h2 18.5 4 1.3 16.1 |
|           |      | h3 18.5 4 -1.3 16.1 |

Table 1: Geometrical configurations adopted in the study.

| Quantity | Parameter |
|----------|-----------|
| The temperature of air, K | 283 K |
| The mass flow rate of liquid, g/s | 1.293, 1.724, 2.155, 2.586, 3.448 |
| The mass flow rate of air, g/s | 0.482, 0.538, 0.620, 0.758, 1.068 |
| Air to liquid, ALR | 0.48–2.85 |
| The property parameter of fuel, kerosene | Coefficient of viscosity: \( \nu = 1.45 \text{ mm}^2/\text{s} \) |
| | Density: \( \rho = 0.78 \text{ g/cm}^3 \) |
| | Coefficient of surface tension: \( \sigma = 0.02300 \text{ N/m} \) |

Table 2: The operating condition adopted in the experiment.
The air supply subsystem includes the screw compressor, tank regulator, air filter, and mass flow controller. The screw compressor is capable to supply air of 5 m³/min, and the maximum exhaust pressure is up to 0.8 MPa, using the mass flow controller to control atomizing air mass flow rate, whose regime range is from 0 to 1000 standard litre per minute (SLM). The control precision of the mass flow controller is ±2%.

The Phase Doppler Particle Analyzer (PDPA) is mainly component of the measurement subsystem. The PDPA made by Dantec Dynamics was used for measuring the droplet size and axial velocity. The PDPA includes a 5 W iron laser, a beam splitter turning the laser into a monochromatic laser at three different wavelengths (514.5 nm, 488 nm, and 476.5 nm), a transmission optics, a receiving optics, and a burst spectrum analyzer (BSA) including processor and flow software. The multipoint measurement can be achieved by utilizing a 3-D traversing mechanism of which movement accuracy is 3.125 μm. The scattering angle is 85°, which is Brewster’s angle, and the reflection light is the dominant light scattering mode. The measurement system is suitable for the experiment in the dense atomization containing small particles, and the maximum particle diameter of 349.8 μm in the experiment will be reached with size resolution of ±0.05 μm. The PDPA system was set to acquire 20000 particles or measure for at least 20 seconds in low-density regions and 60 seconds in high-density regions. The measurements performed in this study are carried out at different axial location downstream of the nozzle exit as shown in Figure 4.

| Position, mm | SMD | Uncertainty, μm | RMS, μm |
|--------------|-----|-----------------|---------|
| X = 0, Z = 50 | 20  | ±0.801          |         |
| X = 0, Z = 60 | 20  | ±1.225          |         |
| X = 0, Z = 80 | 20  | ±2.457          |         |
| X = 3, Z = 50 | 20  | ±1.234          |         |
| X = 3, Z = 60 | 20  | ±1.349          | ±1.974  |
| X = 3, Z = 80 | 20  | ±2.291          |         |
| X = 6, Z = 50 | 20  | ±1.567          |         |
| X = 6, Z = 60 | 20  | ±2.253          |         |
| X = 6, Z = 80 | 20  | ±2.579          |         |

Figure 6: The accuracy of SMD obtained by the repetitive measurement measured at ALR = 1.24.
2.3. Operating Condition. A preliminary parametric study undertaken indicated that the air-liquid interaction area plays very significant role in determining flow behavior in breakup process for plain-jet airblast atomizer. Thus, for the present setup under consideration, the geometric parameters of the convergent and expansion segment which is the air-liquid interaction zone were identified for detailed studies. Variable geometric parameters are the length ($H$), the angle ($A$), the diameter of throat area ($D$) of the expansion segment, and the position of liquid jet exit ($h$). The geometric configurations adopted are shown in Figure 5, by changing these geometric parameters that change the air aerodynamic force, the residence time of liquid spend in the passage, and the confined space size of liquid flow area. The following Table 1 summarizes the geometrical configurations adopted in the study.

The experimental facility is designed for conducting experiments at atmospheric pressure and temperature. Five mass flow rates of liquid (0.482 g/s, 0.538 g/s, 0.620 g/s, 0.758 g/s, and 1.068 g/s) and five mass flow rates of air (1.293 g/s, 1.724 g/s, 2.155 g/s, 2.586 g/s, and 3.448 g/s) were...
selected for this test. Kerosene was used to atomize for test. The detailed operating condition for experiment will be given in Table 2.

2.4 Experimental Uncertainty. In this paper, in order to support the reliability of the data and conclusions, the repetitive investigation on measurement of SMD had been done based on the H3. All of the test position were carried out five times at ALR = 1.24. The results are shown in Figure 6 and Table 3.

3. Results and Discussion

This section presents and evaluates the effect of four types of expansion segment geometries on spray characteristics in terms of SMD, uniformity of droplet size distribution, and the velocity of the sprays. One of the widely used expressions for drop size distribution was originally developed for powders by Rosin and Rammler [25]. It can be represented by

\[ 1 - Q = \exp \left( \frac{D}{X} \right)^q \]  

where \( Q \) is the fraction of the total volume contained in drops of diameter less than \( D \), \( D \) is droplet diameter, \( X \) is characteristic diameter, at which \( Q = 0.632 \), and \( q \) is drop size distribution parameter. The higher the \( q \), the more uniform the spray. The velocity characteristics of spray will be referred as the mean velocity on the \( Z \) axis. In order to get the mean velocity, the value would be averaged over the particle velocity measured at each measuring point.

3.1 Influence of Expansion Segment Length. It is noted that the atomizer for \( H = 0 \) mm is a traditional plain-jet airblast atomizer, which is a typical case used to review the difference in spray characteristics between the novel atomizer with expansion segment and the traditional atomizer without expansion segment. The investigation indicates that the SMD increases, the drop size distribution becomes more uniform, and the axial velocity decreases with addition of the expansion segment.

Figure 7 shows the influence of the \( H \) in SMD characteristics. The result shows that the SMD increases with the \( H \) increases. For example, the SMD of the atomizer of \( H = 0 \)
 variation range is about 77.3 μm to 27.7 μm. Further increase of A changes the variation range into 79.4 μm to 40.4 μm. In general, with the increase of A, the maximum value of SMD is increased by about 15.5% and the minimum value of SMD is increased significantly by approximately 103.8%. Three effects are determined which are attributed to the influence. Firstly, due to the expansion segment, the downstream flow region for the liquid film and droplet discharged from the throat area is reduced, which enhances the collision and aggregation of liquid film and droplet. In addition, with an increase of the H, the distance that the liquid film and droplet discharged from the throat area rotating flow in the expansion segment increases, which leads to the increase of the time that liquid film and droplet flow in the confined space and promotes the collision and aggregation of liquid film and droplet. Thicker liquid film and larger droplet are formed. It is not conducive to the third breakup processes. Secondly, with the expansion
segment length increasing, the aerodynamic force of the airflow in the expansion segment decreases, and the liquid film and droplet lost more kinetic energy, and breakup is more difficult at third break processes. Thirdly, according to the phenomenon of overshooting [26, 27], larger liquid film maintains its velocity in the expansion segment due to its high momentum, and smaller liquid film and individual droplet decelerate because of their low momentum, thereby larger liquid film absorbs smaller liquid films and individual droplets and forms a thicker liquid film. Meanwhile, it is interesting to note that an increase in ALR decreases the SMD for $H = 0$ mm, $H = 5.5$ mm, and $H = 10.5$ mm, which indicate that the basic breakup principle of airblast atomizer is suitable for the novel atomizer with expansion segment.

Figure 8 shows the influence of $H$ on the drop size distribution, and it illustrates that with $H$ increasing, the parameter $q$ increases, with the biggest increase by approximately 52.8%. The reason is that as $H$ increases, larger liquid film nearly the wall of the expansion segment rotating flow enhances the absorption of smaller liquid film and individual droplet. Thereby, the circumferential distribution of liquid film at the exit of the atomizer becomes more uniform.

Results presented in Figure 9 confirm that for the particular atomizer for $H$ of 0 mm remains high-level downstream axial velocity, and the axial velocity decreases significantly with the increase of $H$. For instance, the axial velocity of the atomizer of $H = 0$ mm is 52.0 m/s on the test point of $X = 0$ mm and $Z = 50$ mm, and that of $H = 5.5$ mm and $H = 10.5$ mm are 31.6 m/s and 28.7 m/s, respectively. With increasing of $H$, the axial velocity drops 81.2%. It can be explained that the aerodynamic force of the airflow in the expansion segment decreases because of the expansion segment, which results in the deceleration of liquid film and droplet. It is interesting to note that the droplet axial velocity increases along the radial instead of the decrease trend of the traditional atomizer without expansion segment. The reason for this phenomenon is that the circumferential distribution of airflow velocity becomes more uniform. The droplet axial velocity decreases with the increase of the downstream distance. The reason for this phenomenon is that the droplets,
leaving the nozzle, will decelerate together with the air due to the interaction with the surrounding ambient atmosphere.

3.2. Influence of Expansion Segment Angle. Figure 10 shows that the SMD increases with increasing of $A$. For example, at the test position of $X = 0$ mm and $Z = 50$ mm, the maximum value of SMD increases from 78.9 $\mu$m to 96.2 $\mu$m and the minimum value of SMD increases from 37.4 $\mu$m to 54.6 $\mu$m with increasing of $A$. The reason for this phenomenon can be explained as follows: First of all, the aerodynamic force of the air flow in the expansion segment decreases as $A$ increases, and the kinetic energy of the liquid film and droplet decreases. Secondly, the liquid film and droplet discharged from the throat area rotate across the expansion segment, with increasing of $A$, and the liquid film and droplet rotating flow distance increase, which promotes the collision, aggregation, and absorption of liquid film and droplet. All of above factors are not benefit to the third breakup processes and lead to producing large droplets.

The effect of $A$ on the drop size distribution is presented in Figure 11. The conclusion from the figure is that as $A$ increases from 15° to 20°, the parameter $q$ decreases slightly; however, for further increase of $A$, the parameter $q$ increases...
to the maximum value. The increase of the $A$ aggravates airflow separation near the wall of expansion segment. Uniform liquid film distribution is damaged, and the flow field is distorted, which results in the decrease of drop size distribution uniformity. Meanwhile, for further increase of $A$, the airflow separation point moves to the upstream, which provides enough time for liquid film and droplet to reform uniform size distribution.

Figure 12 shows that the droplet axial velocity increases with the decrease of $A$. In Figure 11(a), the axial velocity range of $A = 15°$ is from 24.8 m/s to 28.9 m/s, and that of $A = 20°$ is from 18.4 m/s to 26.9 m/s, and further increasing of $A$ changes the axial velocity range into from 19.5 m/s to 23.6 m/s. This behavior is in agreement with previous analysis. Further analysis of experimental data shows that the droplet axial velocity decelerates gradually along the downstream and increases slightly along the radial which is consistent with previous result.

3.3. Influence of the Throat Area of Expansion Segment. The influence of $D$ on SMD is depicted in Figure 13. It is clear from this figure that the value of SMD measured by the atomizer for $D = 3.6$ mm is lower than that of $D = 3.2$ mm and $D = 4.4$ mm. For example, with various ALR, the SMD of the atomizer of $D = 3.2$ mm varies from 60.2 μm to 91.2 μm on the test point of $X = 0$ mm and $Z = 50$ mm. However, the SMD range of $D = 3.6$ mm is from 50.5 μm to 93.0 μm. As $D = 4.4$ mm, the variation range is about 53.6 μm to 105.0 μm. This phenomenon could be explained as follows: first of all, with the decrease of the $D$, the increase of the airflow velocity at the liquid-air interaction zone enhances the aerodynamic force of airflow and is conducive to the second break processes. However, because of the decrease of $D$, the kinetic energy of liquid film and droplet increases which is conducive to the second breakup processes. Moreover, the confined flow region of it narrows, which enhances collision, aggregation, and absorption of liquid film and droplet and turns liquid film into thicker and individual droplet becomes larger. It suppresses the third break processes. In addition, although the increase of $D$ decreases the aerodynamic force of airflow, the kinetic energy of liquid film and droplet decreases, and the confined flow region of it widens, which benefits for refraining from collision, aggregation, and absorption for liquid film and droplet, so that the increase in the SMD decreases.
of the $D$ is harmful to the second break processes but is beneficial to the third break processes. The combined effect of these factors causes the results of the tests.

Another interesting phenomenon from this figure is that the SMD measured by the atomizer for $D = 3.2$ mm is lower than $D = 4.4$ mm when the ALR is lower than a certain value. In contrast, as the ALR continues to increase over this certain value, the SMD measured by the atomizer for $D = 3.2$ mm is higher than the $D = 4.4$ mm, assuming that the initial liquid fragment discharged from the liquid jet remains a constant value under the same ALR. It can be speculated that this novel type atomizer affected mainly by the third breakup process at low ALR, and with an increase in ALR, the secondary breakup process is dominant, which is different from the atomizer without the expansion segment proved by Inamura et al. [15].

Figure 14 shows the influence of the throat area of the expansion segment on the drop size distribution. The $q$ of $D = 3.6$ mm is the largest indicating the worst uniformity. Increase or decrease the throat area of expansion segment makes the drop size distribution better. However, the reason for the increase of the parameter $q$ between the
atomizer for $D = 4.4$ mm and $D = 3.2$ mm is different. Firstly, due to the increase of $D$ is associated with decrease of aerodynamic force of the airflow, the time that the liquid film and droplet rotate across in the expansion segment increases, which aggravates the absorption between liquid films with droplet and makes the circumferential distribution of liquid film at the exit of atomizer more uniform. Secondly, with the decrease of $D$, the kinetic energy of liquid film and droplet increases, and the liquid film and droplet are more concentrated, which reinforces collision, aggregation, and absorption of liquid film and droplet. Thereby, the droplet size distribution becomes better.

The experimental data of the droplet axial velocity of $D$ series nozzle correlation at test position is illustrated in Figure 15. The result from figure is that the decrease of the throat area of expansion segment increases the droplet axial velocity. It can be explained that the decrease of the throat area of expansion segment increases the aerodynamic force of the airflow; therefore, the liquid film and droplet gain more kinetic energy. Meanwhile, it is worth noted that the droplet axial velocity measured by the atomizer for $D = 3.2$ mm and $D = 3.6$ mm increases along the radial direction, but that of $D = 4.4$ mm is essentially unchanged along the radial direction, which confirms that the increase of the confined region makes the circumference distribution of velocity more evenly, and it is in agreement with previous analysis.

3.4. Influence of the Position of Liquid Jet Exit. The results of SMD for the $h$ series atomizer are plotted in Figure 16. The experimental data give evidence of the minimum value of SMD is achieved with the atomizer for $h$ of 0 mm. The SMD measured by the atomizer for $h$ of -1.3 mm is the largest. Three effects are determined which are attributed to the influence. Firstly, for the $h$ of 0 mm, whose liquid jet exit is located at the throat area of expansion segment, the aerodynamic force of airflow interacts with the liquid fragment discharged from the liquid jet is the strongest. Secondly, when the liquid jet exit is situated at the front of the throat area of the expansion segment, the aerodynamic force of airflow decreases, and the streamline is contracting towards the liquid jet which facilitates the collision and aggregation. Lastly, as the liquid jet protrudes from the throat area of the

![Figure 15: The droplet mean velocity on the Z axis of h series nozzle correlation at test position (ALR = 1.24).](image-url)

![Figure 16: The droplet mean velocity on the Z axis of h series nozzle correlation at test position (ALR = 1.24).](image-url)
expansion segment, the aerodynamic force of airflow is weaker than the atomizer for \( h = 0 \) mm, and the liquid fragments generated from the secondary breakup processes have less time to flow in the expansion segment, which suppresses the absorption.

The experimental data of the drop size distribution parameter \( q \) of \( L \) series atomizer is illustrated in Figure 17. The result of the figure is that the drop size distribution of \( h = 0 \) mm is the worst, and that of \( h = -1.3 \) mm is the best. Two effects are considered to this phenomenon: Firstly, the atomizer of \( h = -1.3 \) mm, of which the liquid jet is within the throat area of expansion segment, which has the longest distance that the liquid film and droplet rotate flow distance in the expansion segment; thereby, the resident time is the longest which produces the most uniform circumferential distribution of liquid film at the exit of atomizer. Secondly, the rotating flow distance of \( h = 0 \) mm and \( h = 1.3 \) mm decreases successively. Besides, the strongest aerodynamic force of \( h = 0 \) mm leads to the highest kinetic energy of the liquid film and droplet. Moreover, the resident time that the liquid film and droplet rotate across the expansion segment is shorter than that of \( h = 1.3 \) mm. The combined effect of these factors causes the circumferential distribution of \( h = 0 \) mm is worse than that of \( h = 1.3 \) mm.

Figure 18 shows the droplet axial velocity measured at a variation of spatial position. According to this figure, it is clear to find out that the droplet axial velocity of the atomizer for \( h = 0 \) is the highest. When the liquid jet protrudes from the throat area expansion segment, the droplet mean velocity will be reduced slightly. As the liquid jet is situated at the front of the throat area of expansion segment, the droplet axial velocity decreases significantly. According to the previous analysis, the expansion segment makes the liquid fragments decelerate, and the longer the time that the liquid film and droplet rotate flow in the expansion segment, the more rapidly the droplet axial velocity decay. More detailed explanation of this part has already been described above. In addition, the rule of the droplet axial velocity distribution along the radial direction and downstream is similar to the previous, which is the droplet axial velocity increases along the radial direction and decays along the downstream.

4. Conclusion

In this paper, the idea of adding an expansion segment over traditional airblast atomizer is proposed to improve the performance of the droplet size distribution. The expansion segment length (\( H \)), the expansion segment angle (\( A \)), the throat area of the expansion segment (\( D \)), and the position of liquid jet (\( h \)) are considered. And systematic experiments are carried out to reveal the effect of those geometric parameters on the droplet diameter, size distribution, and axial velocity. Overall, the droplet size distribution becomes more uniform and other spray characteristics show significant difference with addition of expansion segment. The main conclusions are as follows:

1. The parameter \( q \) increases 52.8% comparing \( H = 0 \) mm with \( H = 10.5 \) mm, which indicates the droplet size distribution had positive values in the test region owing to the existence of expansion segment. Meanwhile, the droplet axial velocity increases along the radial instead of the decrease trend

2. The smaller Sauter mean diameter can be achieved by reducing \( H \) or \( A \). The atomizers for \( D = 3.6 \) mm and \( h = 0 \) mm are optimal geometries to minimize the Sauter mean diameter

3. The increase of droplet size distribution is associated with increasing of \( H \) and \( A \). Under the same air liquid ratio, the lowest Sauter mean diameter is obtained by the atomizer for \( D = 3.6 \) mm or \( h = 0 \) mm

4. With an increase of \( H \), \( A \), and \( D \), the droplet axial velocity decays. When \( h = 0 \) mm, the droplets have a high-level mean velocity

Nomenclature

\[ A: \] The angle of the expansion segment
\[ q: \] Drop size distribution parameter
\[ ALR: \] Air to liquid ratio
\[ SMD: \] Sauter mean diameter
\[ D: \] The throat area of the expansion segment, mm
\[ T: \] The temperature of air
\[ D_{f}: \] Droplet diameter
\[ X: \] Characteristic diameter
\[ H: \] The length of the expansion segment, mm
\[ h: \] The position of liquid jet exit, mm
\[ Y: \] Spanwise coordinate
\[ m_{l}: \] The mass flow rate of liquid, g/s
\[ Z: \] Axial coordinate
\[ m_{a}: \] The mass flow rate of air, g/s
\[ \rho: \] Density, kg/m\(^3\)
\[ PDPA: \] Phase Doppler Particle Analyzer
\[ \sigma: \] Surface tension factor, N/m
\[ Q: \] The fraction of the total volume
\[ v: \] Dynamic, Pa\(\cdot\)s.

Data Availability

All data were generated and analyzed during the study and appear in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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