Investigation of the Secondary Atomization in Prefilming Air-Blast Atomizers

M. Roudini and G. Wozniak

***Abstract*—This study concentrates on the behavior of dispersed droplets after the breakup process and droplet size spatial development from air blast atomizers which use the kinetic energy of co-flowing high-velocity air. Two atomizers having different geometries were utilized to perform high-resolution local velocity and droplet size measurements using phase Doppler Anemometry (PDA). The correlation between all captured droplet sizes and droplets axial velocity at four different locations in a spray was explained. After examination several distribution functions, the log-normal distribution has been found to be well fitting in the current experimental data of droplet diameters along the spray center line. The evaluation of $D_{0.1}$, $D_{0.5}$, $D_{0.9}$ and relative span factor along the spray axial direction have been determined to explain the phenomena occurring in far field of a spray. Finally, it was observed that the effect of a small tolerance of the liquid exit tube in axial direction which may occur during manufacturing will significantly reduce the spray performance.**

***Index Terms*—Airblast atomization, droplet dynamic, phase doppler anemometry, spray characterization.**

I. Introduction

Atomizers are attracting widespread interest in many technical processes for many years due to their capability to disperse a bulk of viscous liquid into single droplets with different ranges in size and velocity. Therefore, the rapid increase of the contact surface area in a gaseous medium raises beneficially the mass transfer and the evaporation rate. In technology, the atomization contributes significantly in special applications like spray cooling and drying [1], painting and coating [2], medical inhalers [3] and fuel injection [4]. In the current study, an atomizer which uses the kinetic energy of a co-flowing high-velocity gas has been investigated. This common type of atomization is generally referred to as air-blast atomization which has many advantages over other types of atomizers, especially in their application to combustion systems operating at high pressure [5]. However, many complex mechanisms which cause the physical structure and dynamics of a spray before the dispersion of the subsequent stable droplets are not well understood. Therefore, the understanding of both local and global characteristics of a spray are essentially required for the development of air-blast atomizers.

As it is known, the production of liquid fragments and large ligaments from a bulk of the discharged liquid near field of the atomizer called the primary atomization. The primary phase has been often unnoticed and is still a topic of ongoing research [6], [7]. Ligaments and large droplets resulting from the primary atomization in the vicinity of an atomizer may disintegrate further into smaller droplets along the spray axial direction. This phenomenon addressed the secondary atomization which is usually a disorganized process includes a wide range of liquid droplet sizes downstream of a spray [8]. The secondary atomization process results final droplet sizes which are most crucial demands of industrial applications [8], therefore, it is main focus in the current study. A side view and 30-degree angle view of the spray pattern near an airblast atomizer have been shown in

Fig. 1a and b, respectively.

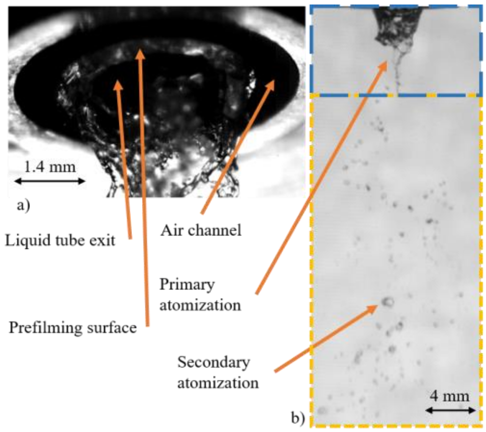

Fig. 1. The conical liquid core close to the atomizer a) 30-degree angle view and b) side view. Record rate (fps) = 40000 - Shutter speed (s) = 1/1000000).

The secondary atomization of an airblast atomizer has been investigated by several groups, (e.g., [9]–[12]). The droplet size distribution is mainly modeled empirically and analytically by the existing literature [5], [13]–[16]. However, most of the earlier investigations are performed using low accuracy measurement methods and instruments which are no longer valuable. The phase Doppler measurement technique deliver the simultaneous droplet size and velocity measurement along the spray axis and radial direction. The particle with a smaller size range and a spray region with higher density can be detected by an advanced PDA using three different apertures masks and different probe slit adjustment respectively [17].

Before investigation of the secondary atomization in airblast atomizers, several important definitions should be understood. The droplet breakup in the secondary atomization for the low viscous flow is controlled by aerodynamic and surface tension forces. Hence, the relative

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Weber number is one of the important non-dimensional numbers during the secondary atomization and is given by

$$We_p = \frac{\rho_g (U_g - U_p)^2 d}{\sigma} \quad (1)$$

where ρ_g, σ, U_g, U_p and d are the density of the continues phase, liquid surface tension, gas velocity, droplet velocity and characteristic length respectively. In order to set criteria for a drop to be transformed into smaller droplets a critical weber number has been determined by Hinze [18]. According to the Hinze investigation, the Weber number for the breakup of a drop in a constant velocity air stream is 22 and for droplets suddenly exposed to high velocity air stream is 13 [18]. Hence, the approximate location of the secondary atomization completion along a spray axial direction could be estimated using a critical weber number.

One more important parameter in far field region of a spray is sphericity of large droplets which influence the accuracy of droplet measurements. Liquid droplets tend to deform when subject to an air flow field until normal and shear stresses balance at the air-liquid interface [19]. The droplet remains under acceleration and the droplet's shape reveals a more elliptical form as long as the Bond number is high [19]. Bo represents the importance of gravitational forces compared to surface tension forces to characterize the droplet deformation and breakup. Thus, the second important dimensionless number for the secondary atomization is Bond number (Bo) which is given by

$$Bo = \frac{D^2 a \rho_l}{\sigma} \quad (2)$$

where ρ_l is the liquid density and a is the acceleration of a droplet which is given in (3).

$$a = \frac{du_p}{dt} = \frac{3\rho_g \upsilon_g C_D \mathrm{Re}_P}{4\rho_p D^2}(U_g - U_p) \quad (3)$$

To determine the acceleration of a droplet, the drop drag coefficient and particle Reynolds number can be calculated using (4) and (5) respectively.

$$\mathrm{Re}_P = \frac{\rho_l U_P D}{\mu_l} \quad (4)$$

$$C_D = \frac{24}{\mathrm{Re}_P}\left(1 + \frac{1}{6}\mathrm{Re}_P^{2/3}\right) \quad (5)$$

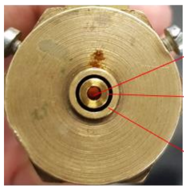
where C_D is the drag coefficient of a droplet, Re_P in the droplet Reynolds number, υ_g is the gas kinematic viscosity, μ_l is the liquid dynamic viscosity and D is the droplet diameter [20]. According to the previous studies, the droplet deforms for Bo > 0.6 for the Re_p range of 500-1000 [19]. During current experiments, the maximum of, the droplet Reynolds number is well below 1000. If the Bond number is greater than 0.6 it implies the deformation of spherical droplets into an ellipsoidal droplet with an aspect ratio of greater than 10%. Indeed, Bo gives an indication of accurate measurement locations of PDA measurements in a spray.

The droplet evaporation rate was found to be negligible during the secondary atomization process using an airblast atomizer, therefore, the spray evaporation does not affect really the evaluation of the measurement data [9].

In this study, droplet size and velocity distribution in a developed-region of a spray in the spray centre line will be analysed. The location of the secondary atomization finalization of the spray will be estimated. The level of the droplet's sphericity in the axial location was assessed to determine a region from where droplet sizing measurement results will be reliable for further spray performance investigations. Different representative diameters and spray dispersion development along axial direction will be explained. The correlation between droplet size and droplet velocity will be explained locally within the spray area. Lastly, the position of the liquid tube exit in the current airblast atomizer on the spray performance will be investigated.

II. Experimental Setup

Important geometries and definitions of airblast atomizers investigated in the present study are shown in Fig. 2. To avoid the complicated internal flows of most practical atomizers, a fundamentally important nozzle exit has been selected. The air was supplied to the nozzle by an in-house central oil free air compressor. Water was supplied using a pressurized liquid tank. The operating conditions of the spray characterization cover a range of the liquid flowrate at the exit of the nozzle from 10 to 150 ml/min and air static pressure from 0.25 to 1.5 bar for the different parameter investigations.



Geometries		N5	N6
Inner liquid tube diameter (mm)	d_i	2.2	2.2
outer liquid tube diameter (mm)	d_e	3.9	4.5
gas slit diameter (mm)	D_o	5.6	5.6

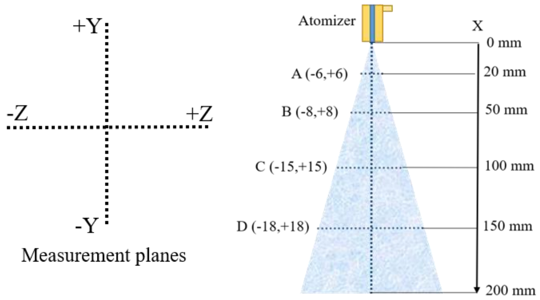


Fig. 2. Investigated atomizer geometries and measurement locations.

The experiments were performed at ambient conditions where it is possible to perform reliable Phase Doppler Anemometry (PDA) measurements. PDA as a non-intrusive local measurement technique which allows to measure the size, velocity and concentration of droplets in sprays. To investigate the evaluation of spray in front of the atomizer, the development of the droplet size and velocity is required to be inspected along the spray axis and radial direction. The measurement locations are shown at Fig. 2. The experimental setup is explained in detail in the previous publication [21]. More details about the PDA technique can be found in [22], for example.

III. Results and Discussion

A. Droplet Size and Velocity Evaluation

Since the liquid is atomized by various mechanisms of jet and sheet disintegration in the near airblast atomizer, the resulting droplets produce a wide droplet size range and the droplet size distribution could be broadly presented by a histogram plot (Fig. 3). Several distribution functions have been examined to find the best fit for the measured droplet diameters. Finally, the log-normal distribution has been found to fit well the current experimental data by the below distribution function:

$$f(D) = \frac{1}{\sqrt{2\pi} D S_g} \exp - \left[\frac{1}{2S_g^2} \left(\ln D - \ln \bar{D}_{ng} \right)^2 \right] \qquad (6)$$

where $\bar{D}_{ng}$ is the number geometric mean drop size and S_g the geometric standard deviation.

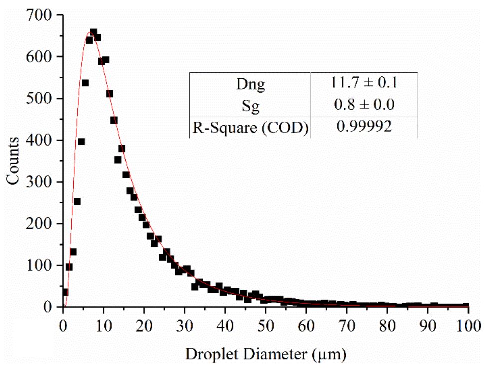


Fig. 3. Fitted function for droplet size distribution at P_a = 1 bar and Q = 50 ml/min (x=100 mm, z=0 mm).

Fig. 4 illustrates the use of the size distribution curve to demonstrate the effect of increasing air pressure and liquid flowrate on drop-size and droplet velocity distributions for a prefilming coaxial airblast atomizer (N5). It is well known that an increase in static pressure leads to a reduction in mean drop size and this reduction is accomplished mainly by eliminating the largest drops in the spray (Fig. 4a). It could be expected that the measured droplet velocity increases with increasing air pressure and reducing liquid flowrate and they are distributed as a normal distribution function (Shown in Fig. 4b).

In order to investigate the spray's development downstream of the nozzle, 3D high-resolution planar measurements have been graphically obtained in four different distances from the atomizer outlet at an air pressure of 1 bar and a liquid flowrate of 50 ml/min (see Fig. 5).

As it can be seen, the droplet mean velocity is maximum in the center of spray and the mean velocity shows a symmetric planar distribution in all four locations (see Fig. 5a). However, the generated droplets are smaller in the center of the spray and the minimum droplet size achieved at the plane located in 150 mm distance from the atomizer in this operation condition (Fig. 5b). The smallest generated volume-to-surface diameter or Sauter Mean Diameter (SMD) and the highest droplet averaged velocity appeared in the region of 60 mm < x < 200 mm and x ~ 20 mm during the current experiments which is extremely dependent on the operation conditions.

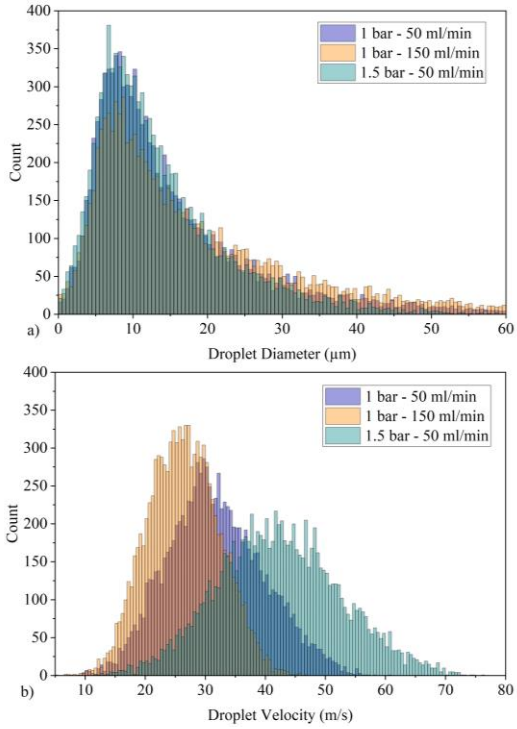


Fig. 4. a) Influence of the air static pressure on droplet size distribution at (x=100 mm, z=0 mm). b) Droplet velocity distribution at (x=100 mm, z=0 mm).

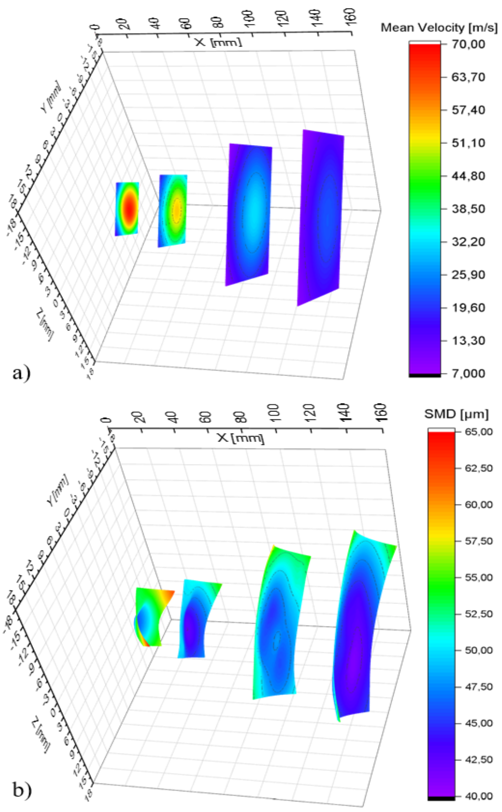


Fig. 5. 3D planar (a) droplet mean velocity and (b) SMD distributions (P_a = 1 bar and Q=50 ml/min).

B. Size-Velocity Correlations

To determine the correlation between the droplets axial velocity which is the dominant velocity component in the current study and its corresponding diameter, all captured droplet sizes were plotted with their axial velocity along different locations in the spray (shown in Fig. 6). This correlation provides the actual velocity of each droplet diameter which will be suitable for the numerical simulation and a profounder understanding of the behavior of small and the large droplets in different regions of a spray.

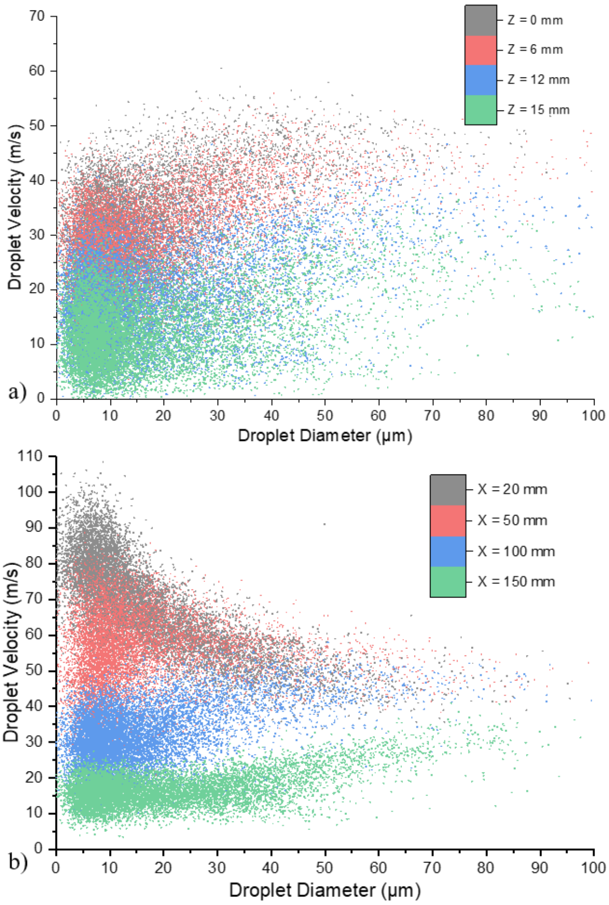


Fig. 6. Size-velocity correlation along a) radial direction (x=100) and b) axial direction (z=0).

Fig. 6. a shows the droplet size-velocity correlation at x = 100 mm and at different radial distances (z = 0, 6, 12, and 15 mm). The behavior of small and large droplets is nearly similar at different locations in the radial direction. The small and large droplets reduce their velocity with distance from the spray centerline. As it can be observed from Fig. 6b, the velocity fluctuation of small droplets is reduced by increasing the distance from the atomizer exit. In the area close to the atomizer (x = 20 mm), the small and large droplets follow their own path with higher and lower velocities. In x = 50 mm the small droplets oscillate and follow the turbulent fluctuations while the large droplets follow their own paths along the axial direction. The average velocity of the droplets increases with their size at the developed atomization area (x = 100 mm) which evidences the overshooting phenomenon. The velocity of the most droplets reaches almost 20 m/s in far away from the atomizer exit (x = 200 mm). As it generally shows, small droplets due to their small mass were able to follow the carrier air flow and accelerated faster in the initial phase than larger ones, however, they also decelerated fast while larger droplets lose their momentum slower.

C. Secondary Atomization Location

Since the location of a final range of drop sizes produced in a spray is a region where the secondary atomization in completed, the determination of this region downstream of the atomizer plays an important role in spray characteristics. As it was explained previously, the secondary atomization finalization can be estimated with a critical particle weber number. Meanwhile the maximum velocity occurred in the center of the spray in existing atomizers, the spray axial direction is selected to inspect the estimated location where from there the secondary atomization will not be present any more. The relative Weber number was calculated based on the characteristic droplet diameter $D_{0.9}$. Furthermore, the maximum relative velocity is measured from the averaged velocity of droplets less than 3 µm in size (as air velocity) and the minimum velocity of droplets (as liquid droplet velocity) using droplet size distribution data at x = 50 mm. The mean velocity of very small droplets was used similarly as a natural tracer in other studies to calculate the air velocity [23]. The relative Weber numbers from three different conditions have been shown in Table I.

TABLE I: RELATIVE WEBER NUMBERS BASED ON $D_{0.9}$ AT X = 50 MM DISTANCE FROM THE ATOMIZER ORIFICE

Air pressure [bar]	Liquid Flowrate [ml/min]	Air Velocity [m/s]	Liquid Velocity [m/s]	We_P
1	50	74	25	3.70
1	150	55	21	2.60
1.5	50	95	35	4.26

It appears that the relative droplet Weber number in all operation conditions are adequately below the secondary droplet breakup regime. Apparently, the secondary atomization will not occur beyond a spray axial location of x = 50 mm.

TABLE II: BOND NUMBER FOR DIFFERENT CHARACTERISTIC DIAMETER AT X = 25, 50, 100, 200 MM (P_A = 1.5 BAR, Q=50 ML/MIN)

x-direction	Bond No.			
[mm]	SMD	$D_{0,1}$	$D_{0,5}$	$D_{0,9}$
25	1.81	1.28	1.91	3.43
50	0.89	0.63	0.98	1.51
100	**0.34**	**0.26**	**0.38**	**0.56**
200	0.13	0.10	0.14	0.20

D. Sphericity of Large Droplets

The calculated Bond numbers in four different axial locations in the maximum air pressure condition have been shown in Table II. As it can be seen, the Bond number decreases along spray axial direction. The Bond number for all presented characteristic diameters is greater than 0.6 at x = 25 and 50 mm suggesting that a part of the droplets failed to be accepted by PDA processor at the highest air velocity test.

However, the measured droplets have Bond numbers < 0.6 at x = 100 mm, even for $D_{0.9}$, confirming an acceptable measurement location to evaluate the influence of the variable spray parameters.

E. Representative Diameter and Spray Dispersion

An attempt to indicate briefly the droplet size distribution is to use a representative diameter together with a quantity to describe the range of drop sizes. In the current study, the variation of $D_{0.1}$, $D_{0.5}$, $D_{0.9}$ and relative span factor along the spray axial direction using N5 have been determined (shown in Fig. 7). As it can be seen, $D_{0.1}$ and $D_{0.5}$ illustrated same behaviour at P_a = 1 bar and Q = 150 ml/min along the axial direction. In the beginning, an increase was observed at the location of x = 5 mm to x = 40 mm followed by a slow reduction along the axial direction. Afterwards, the values reached to a constant amount at the location between x = 40 mm and x = 160 mm. $D_{0.1}$ started to increase gradually far away from the atomizer orifice (x = 90 mm) due to the dispersion and evaporation of smaller droplets along the axial direction. Though, $D_{0.9}$ initially showed a descending trend due to the liquid secondary atomization process. It followed by a constant value at about x = 30 mm as soon as the secondary atomization is finalized.

The most commonly parameter to describe the spray dispersion is the relative span factor which is determined by (7). The relative span factor gives a direct indication of the range of drop sizes relative to mass mean diameter.

$$\Delta = \frac{D_{0.9} - D_{0.1}}{D_{0.5}} \qquad (7)$$

The span of a spray represents the range of droplets in a distribution or the spray dispersion. Firstly, as per Fig. 7, the span factor decreases along the axial direction due to the decrease of $D_{0.9}$ and in the meantime increase of $D_{0.1}$ and $D_{0.5}$. Further downstream of the atomizer, since the effect of spray dispersion is marginal the span attains a constant value.

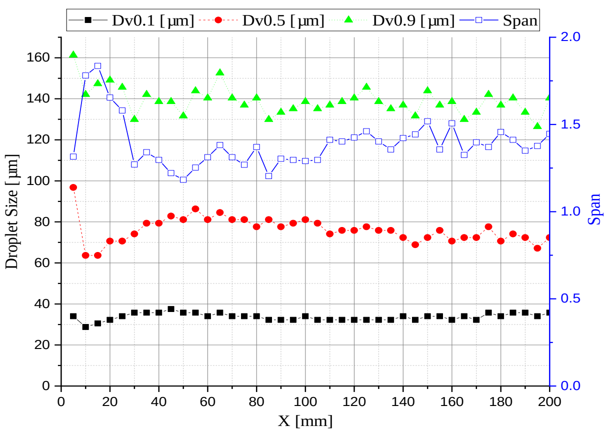


Fig. 7. The development of $D_{0.1}$, $D_{0.5}$, $D_{0.9}$, and span using N5 along axial direction (P_a= 1 bar and Q=150 ml/min).

A. Internal and External Mixing

The effect of a small tolerance of the liquid exit tube on the mean droplet velocity and SMD which may occur during manufacturing is investigated in the current section. As it is indicated in

Fig. 8, Δx is the horizontal shift of the tube axis in the x direction. This small tolerance causes the discharging liquid to be atomized inside or outside of the nozzle creating different breakup mechanisms. The air momentum reduction of the different liquid tube position setup until 50 mm distance from the atomizer exit is clearly shown in Fig. 8 There is evidence to indicate that the internally liquid atomization causes an air pressure drop before the generated droplet emerges from the nozzle exit which generate larger droplets downstream of the atomizer (Fig. 8) Furthermore, the discharging liquid interacts with the annular air flow 2 mm away in the externally setup liquid tube (Δx = +2 mm). In consequence, the air momentum with a minor reduction disintegrates the liquid to the droplets. Therefore, if the liquid tube is located in the same position in x direction as the annular air exit, the smaller droplet size appeared at downstream of the atomizer.

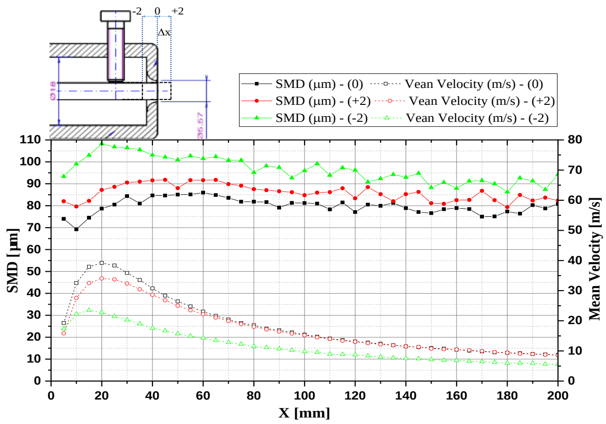


Fig. 8. Influence of the internal and external atomization on mean velocity and SMD using N6 (P_a= 0.4 bar and Q= 60 ml/min).

IV. Conclusion

The spray far field of prefilming airblast atomizer was investigated under atmospheric conditions using the Phase-Doppler measurement technique. After examination several distribution functions, the log-normal distribution has been found to be well fitted in the current experimental data of droplet diameters along the spray centre line. The correlation of the actual velocity of each droplet diameter was shown which will be suitable for the numerical simulation and a profounder understanding of the behavior of small and the large droplets in the different region of a spray. The evaluation of $D_{0.1}$, $D_{0.5}$, $D_{0.9}$ and relative span factor along the spray axial direction helped us to understand locally where important phenomena, like the secondary atomization and droplet coalescent, roughly occurring in an airblast spray. Finally, it was shown that the liquid tube located in the same position in x direction as the annular air exit generated smaller and faster droplets downstream of airblast atomizers. In future studies, these experimental investigations will be extended regarding the influence of liquid properties like viscosity and surface tension on the spray characteristic.

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