Spray characterization for coal mine dust removal

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Dust scrubbing using water sprays is one of the most common techniques for airborne respirable dust control in the mining industry. Measurement of spray characteristics such as drop size and velocity using state-of-the-art laser instruments (Phase Doppler Particle Analyzer) will provide detailed information for a better understanding of wet scrubbing mechanisms such as inertial impaction, interception and turbulent diffusion. All previous wet scrubber performance calculations were based on measurements of dust size and concentration as a function of water flow rate, water pressure, and average drop size. The real spray process undergoes dynamic changes so that it is necessary to determine spray characteristics such as drop size and velocities in both radial and axial directions.

1. Introduction

Prolonged exposure to airborne respirable coal dust is responsible for the prevalence of coal workers' pneumoconiosis (CWP) in the United States. Health research studies have identified that the severity of CWP is directly related to the amount of respirable dust exposure and the coal rank [1-4]. Wet collectors or wet scrubbers are devices that use a liquid spray for removing particles or polluted gases from exhaust gas streams. Water sprays can be injected into the gas stream; gas can be forced to pass through sheets or films; or, the gas can move through beds of plastic spheres covered with liquids. Wet collectors are designed to incorporate small dust particles into larger water droplets. Droplets ranging from 25 to 500 μm in diameter are produced and brought into contact with particulates.

To increase the understanding and efficiency of currently used wet scrubbing units in the coal mining industry it is necessary to determine 1) spray characteristics such as drop size and velocity measurements by using state-of-the-art laser instruments; 2) spray interactions with the ambient air flow; and 3) the influence of turbulent spray dynamics on the dust collection. The aim of this experimental study is to compare the spray characteristics of a hollow cone spray (Spraying Systems Co., Model 3/8 BD3[+], Wheaton, IL) and a full cone air atomized spray (Spraying Systems Co., Model ¼ J-SU42[+], Wheaton, IL) nozzles which were previously studied for coal mine dust suppression [5, 6, 7]. The spray measurements were made at two different axial downstream locations from the nozzle exit. At each axial location measurements were taken radially from the spray center to the outer edge of the spray. This information is necessary to determine the spray entrainment and penetration with the dust particles. The spray characterization at each measurement point includes the drop size and two velocity components. Drop size and velocity information are necessary to understand dust collection mechanisms and dimensionless dust control parameters such as Stokes number (between particle and drop collector), droplet Weber number (how the droplets react to external forces resulting in secondary breakup) and Reynolds numbers.

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The most useful information for mathematical or empirical modeling of wet scrubber efficiency is the droplet velocity and the size distribution of the spray. The non-invasive Phase Doppler Particle Analyzer (PDPA) instrument (TSI Inc., TSI PDPA System, St. Paul, MN) is capable of measuring the size and velocity of each droplet as it passes through the micron-size probe volume formed by a pair of laser beams (vertical and horizontal).

2. Mathematical Modeling of Dust Removal Efficiency

The capture of airborne coal dust particles by liquid sprays is directly related to the spray characteristics. The velocities of liquid (and air for twin-fluid nozzle) exiting the nozzle and the nozzle internal geometry determine the spray characteristics. The breakup of liquid is dependent upon the momentum, viscous and surface tension forces. Drop size and velocities change very significantly in the axial and radial directions. Airborne dust particles are captured by the spray droplets as a result of different collection mechanisms (such as inertial impaction, interception, gravity, and turbulent diffusion). The mathematical modeling described below illustrates the importance between spray droplet size, velocity, distance, and dust particle capture.

The mathematical modeling of a wet scrubber can be described as follows based on the average droplet size (see [8, 9]). Assuming that the droplets are moving with V_d (droplet velocity) in a particle laden gas flow (V_g, gas velocity). The swept volume or cleaning volume of a droplet (the volume of air that flows through the hypothetical tube having the frontal area of the droplet) during the time dt is

$$\frac{\pi}{4} D_d^2 \left| V_g - V_d \right| dt \qquad (1)$$

Now the volume from which all particles are removed in a traveled distance $dx = V_d dt$ by a single droplet is

$$\eta_d \left(\frac{\pi}{4} D_d^2 \right) \left| V_g - V_d \right| \frac{dx}{V_d} \qquad (2)$$

where η_d is the single-drop collection efficiency. The inertial impaction efficiency of a single-drop, $\eta_{d,II}$, can be approximated with the Stokes number as recommended by Calvert (1970) [8]: $\eta_{d,II} = Stk^2 / (Stk + 0.35)^2$. Stk is the Stokes number defined as the ratio of the stop distance of a particle (product of the particle relaxation time and the relative velocity) to the drop radius as the characteristic length of the system: $Stk = \tau_p \left| V_d - V_p \right| / r_d$. The single-drop efficiency for the flow-line interception can be given as function of interception parameter, ratio of the particle radius to the drop collector ($N_R = r_p / r_d$) [10]. Beizae and Tien (1980) studied numerically 3-D particle trajectory line around a sphere collector for the combined effects of inertial impaction, interception, and gravitation and gave a correlation equation for the combined single collection efficiency as function of Stokes, interception parameter, and gravitation parameter ($N_G = \tau_p g / \left| V_d - V_p \right|$) [11].

The mass balance for dust particles in a differential volume element of the wet scrubber gives with assumption that dust particles moves with the gas velocity

$$V_g N_p A - V_g \left(N_p + dN_p\right) A = \eta_d \left(\frac{\pi}{4} D_d^2\right) \left|\left(V_g - V_d\right)\right| N_p N_d \frac{dx}{V_d} \tag{3}$$

where N_p is the dust particle concentration in the gas and $N_d = 6\dot{Q}_d / \pi D_d^3$ is the total number of injected droplets per unit time into the gas stream with the volumetric flow rate $\dot{Q}_d$. The reduction in the dust particle concentration for the volumetric gas flow rate in the scrubber ($\dot{Q}_g = V_g A$) and the overall collection efficiency $\eta_{overall}$ of the wet scrubber with a scrubber length (L) will be

$$-\frac{dN_p}{N_p} = \eta_d \frac{\dot{Q}_d}{\dot{Q}_g} \frac{3}{2D_d} \left|\left(V_g - V_d\right)\right| \frac{dx}{V_d} \quad \text{and} \quad \eta_{overall} = 1 - exp\left(-m \dot{Q}_d / \dot{Q}_g\right) \tag{4}$$

where $m = \eta_d \frac{3}{2D_d} \left|\left(V_g - V_d\right)\right| \frac{L}{V_d}$ is the *specific cleaning volume*. But all nozzles used in the wet scrubbing processes generate poly-disperse droplets in the spray and it is necessary to consider the droplet distribution as well as the dust particle size distribution for the overall efficiency calculation. For each dust particle size class the collection efficiency can be written over all spray droplets size classes with the droplet volume size distribution $q_{3,d}\left(D_d\right)$:

$$\eta_{D_p} = 1 - exp\left(-\frac{\dot{Q}_d}{\dot{Q}_g} \int_{D_{d,min}}^{D_{d,max}} m\left(D_d, D_p\right) q_{3,d}\left(D_d\right) dD_d\right) = 1 - exp\left(\frac{\dot{Q}_d}{\dot{Q}_g} \overline{m}_{D_p}\right) \tag{5}$$

where $\overline{m}_{D_p}$ is the *mean specific cleaning volume* for the dust particle size D_p. Furthermore, the overall collection efficiency for all dust size classes with the particle volume size distribution $q_{3,p}\left(D_p\right)$ becomes (see [12, 13, 14, 15]):

$$\eta_{overall} = \int_{D_{p,min}}^{D_{p,max}} q_{3,p}\left(D_p\right) \eta_{D_p} \, dD_p \tag{6}$$

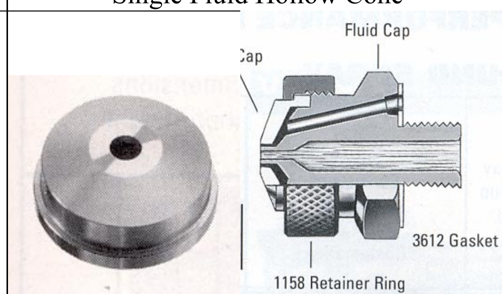
The PDI measurement provides information of both drop size and velocity distributions at each measurement point (the probe volume). Moving the probe volume along the radial plane on the spray region at each downstream axial location from the nozzle exit provides a spray map of the size and velocity distributions. This detailed characterization of water spray droplet size and velocity at various distances from particular nozzles is needed for understanding their influence in spray dust capture experiments.

3. Experimental Setup for Spray Nozzle Characterization

Spray droplet measurements were made along two cross sectional planes of each spray at axial distances of 25 and 50 cm from the nozzle exit. Table 1 gives the list of the two tested nozzles with the operating test conditions. The experimental setup of the PDI measurement is given in Fig. 1. The 300 liter liquid tank was pressurized to obtain the maximum liquid pressure of 1100 kPa (160 psi) gauge pressure at the nozzle inlet. The liquid volumetric flow rate was measured with an in-line flow meter (Cole-Parmer Instrument Co., Model# HC205B-020, Vernon Hills, IL). The liquid pressure was measured at the nozzle inlet pipe with a pressure gauge. The nozzle was located in a traversing mechanism to change the location in axial and radial directions above the PDPA probe volume. The spray collecting container was located 90 cm downstream of the probe volume to minimize splashing.

The Phase Doppler method is based upon the principles of light scattering interferometry. Measurements are made at a small, non-intrusive optical probe volume defined by the intersection of two laser beams. As a particle passes through the probe volume, it scatters light from the beams and creates an interference fringe pattern. A receiving lens strategically located at an off-axis collection angle projects a portion of this fringe pattern onto several detectors. Each detector produces a Doppler burst signal with a frequency proportional to the particle velocity. The phase shift between the Doppler burst signals from the different detectors is proportional to the size of the spherical particles. For PDPA measurements the receiver was set at 45 degrees forward scatter with a 1000 mm focal length front lens. This transmitting lens was used with approximately 1 W of laser power. For this optical setup the dynamic range of PDPA size measurement is between 13 μm and 671 μm which had optimally covered the spray size range of tested two nozzles. Each PDPA measurement was based on 60,000 particle attempts with an accepted size percentage of 85%.

Table 1 Test parameters. (Spray pictures courtesy of Spraying Systems, Wheaton,IL).

Spraying Systems Nozzle No:	**Nozzle Type**	**Liquid Pressure (Gauge) [kPa]**	**Liquid Flow Rate [liter/min]**
WhirlJet 3/8 BD3	 Single Fluid Hollow Cone	550	3.06
		1100	3.78
Air Atomizing ¼ J-SU42 Fluid Cap #100150 Air Cap #1891125	 Twin Fluid Full Cone	172 at P_{air}=172 kPa	0.98
		345 at P_{air}=345 kPa	2.50

4. Experimental Results

The spray measurements of two different nozzles include both drop size and two velocity components. The hollow cone nozzle is a single-fluid whirljet 3/8 BD3 nozzle from Spraying System which is widely used in the coal dust suppression [5]. The water injection pressures (measured at the nozzle inlet) were 550 kPa and 1100 kPa, giving the volumetric flow rates of 3.06 liter/min and 3.78 liter/min, respectively.

Fig. 2 shows the distribution of the axial droplet velocity as a function of the droplet size at Z=30 cm downstream axial location from the nozzle exit and at the spray center (R=0 cm) for the water injection pressure P=1100 kPa. At this probe volume location 47,121 droplets are counted for the axial velocity measurement. The average axial velocity is V_x=9.545m/s and the average drop diameter as Sauter Mean Diameter (SMD, D_{32}) is 37.8 μm. This distribution shows clearly that most droplets are in the size range between 13 and 50 μm and their axial velocities are intensified between 5 and 12 m/s. Some droplets have negative axial velocities because of some back splashing effect of the spray from the collecting container.

Figs. 3, 4 and 5 demonstrate the SMD, Volume mean diameter (D_{30}), and the average axial velocity at different probe volume measurements (as average values of Fig. 2).

Fig. 3 shows the SMD variation as a function of the radial distance from the spray center at two downstream locations from the nozzle exit for two liquid flow rates (3.06 liter/min and 3.78 liter/min for the nozzle BD3 and 0.98 liter/min and 2.5 liter/min for the nozzle J-SU42). For all cases of the hollow cone nozzle (BD3 in the left frame) SMD increases gradually with the radial distance from the spray center (a finer spray in the center area and a coarser spray at the outer edge of the spray cone). The spray cone diameter does not increase dramatically for this nozzle type. For the low injection pressure case the spray cone radius was 7.5 cm where the cone radius for the high injection pressure case didn't increase visibly. Increasing the injection pressure two-fold (resulting in higher injection velocity) increases volumetric flow rate 23% and decreases the SMD size at all radial distances for both axial distances. This is as a result of an increase in breakup processes from an increase in the injection velocity at the nozzle exit. At Z=30 cm downstream, for the 550-kPa case, there is a gradual increase in SMD from 51 μm at the spray center (R=0 cm) to 93.5 μm at the outer edge of spray (R=7.5 cm). Also the SMD increases by increasing the downstream location of the measurement point from the nozzle exit from 30 cm to 60 cm. This is as expected because of high coalescence between droplets forming larger droplets as a result of turbulent spray flow and its entrainment within the ambient.

The air-atomized nozzle from Spraying Systems (¼J-SU42) was also tested for coal dust suppression and it had dramatically reduced the water consumption in full scale model mine dust control experiments [6]. The right frame of Fig. 3 demonstrates the SMD changes for the full cone twin-fluid nozzle (¼J-SU42) where this time SMD decreases as the radial distance increases from the spray center to the outer edge in contrast to the BD3 nozzle. This SMD decrease with the radial distance is more noticeable at Z=30 cm where the SMD becomes almost flattened at Z=60 cm for both flow rates. At the spray center region SMD is in the range between 159 and 206 μm. The spray cone is spreading out with the axial distance from the nozzle exit. At Z=30 cm the spray cone radius is 3.75cm where at Z=60 cm the radius is 8.75 cm for the 345 kPa liquid and air injection pressures. At the Z=30 cm location the outer edge spray region has droplets with a SMD of 136 μm for the low injection pressure and 117 μm for the high injection pressure.

In the wet scrubbing characterization the volume mean droplet size of a spray is also a useful variable to consider for dust collection efficiency calculations. The same tendencies of SMD can be seen in the volume mean size variation with the radial distance and the injection pressures (see Fig. 4). But the D_{30} increases faster than SMD with the radial distance from the spray center for the BD3 hollow cone nozzle (the left frame in Fig. 4). The D_{30} also decreases with radial distance for the ¼J-SU42 (the right frame of Fig. 4). At Z=30 cm the D_{30} diameters for both flow rates become very close to each other.

Fig. 5 shows the average axial velocity change with radial distance from the spray center. The general tendency of average axial droplet velocity is as follows. The spray core region moves faster than the spray outer edge for both nozzle types even though their droplet sizes show different tendencies. When compared with previous figures the small droplets are moving faster in the spray core region and the average axial velocity decreases with the radial distances from the spray center to the outer edge for the BD3 hollow cone nozzle. The average axial velocities at the spray center (core) region for the single-fluid nozzle (BD3) are between 4 and 9.55 m/s where as expected the higher injection pressure results in higher injection velocities (see the left frame in Fig. 5). The twin-fluid nozzle (J-SU42) has axial droplet velocities in the spray center region (R=0cm) in the range between 14 and 33.8 m/s which is relatively higher than the BD3 nozzle.

The spray droplet characterization of these two nozzles has provided some valuable insight into prior empirical water spray dust suppression systems for coal mine dust control. Previous dust control experiments in a full scale model mine have shown that a better than 24 percent respirable dust capture improvement was achieved with the J-SU42 nozzles with about half of the water flow rate as compared to the BD3 nozzles [6]. The notably different spray droplet characteristics measured and discussed above for these nozzles provide some valuable insight in what dust capture mechanisms may be more dominant in reducing dust around a mining machine in an underground opening. The larger size and higher velocity of the J-SU42 generated water droplets suggest that internal impaction efficiency may be a more dominant mechanism in airborne respirable coal dust capture rather than interception and turbulent diffusion.

5. Conclusions

The performance criteria of wet scrubbers need~~s~~ detailed information of droplet size and velocity at the cross sections of the spray pattern to more adequately describe empirical airborne dust control studies. The PDPA measurements can provide all necessary detailed spray information for the determination of dust removal efficiency principles. Water droplet size and velocity characteristics were measured for a BD3 hollow cone nozzle and a J-SU42 full cone air atomized nozzle and showed noticeably different water droplet characteristics. These different spray characteristics suggest the key components in dust capture performance criteria measured during previous empirical studies. Future research in water spray dust capture should empirically study the dust capture mechanisms with regard to detailed spray characterization measurements of drop size and velocity.

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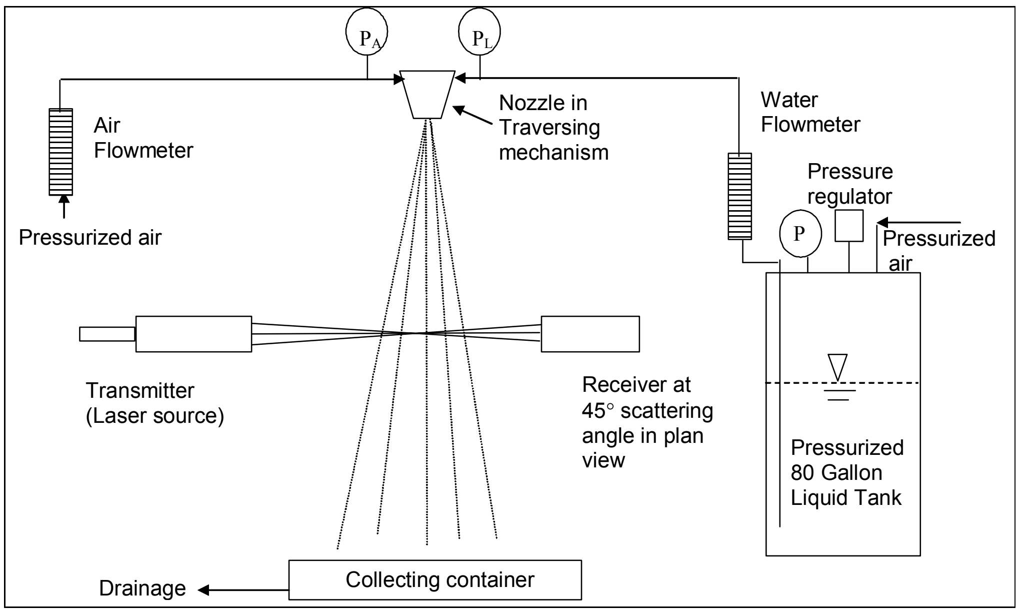

Fig. 1 PDPA experimental setup for spray nozzles used in coal mine dust control.

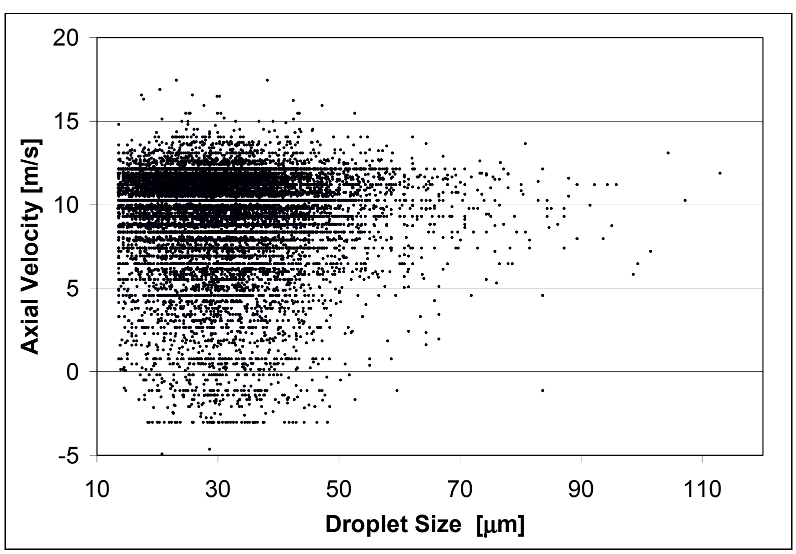

Fig. 2 Axial velocity vs. drop size of the BD3 nozzle at Z=30 cm and R=0 cm for P=1100 kPa. The lower limit of the dynamic size range of the used PDPA optical setting is 13 µm.

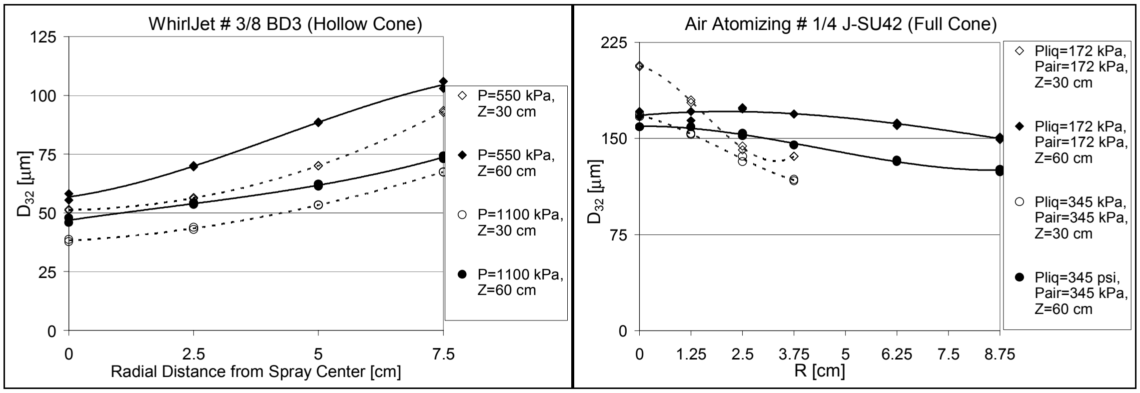

Fig. 3 D_{32} vs. radial distance from the spray center at Z=30 cm and 60 cm for the nozzle 3/8BD3 (left) and the nozzle ¼J-SU42 (right).

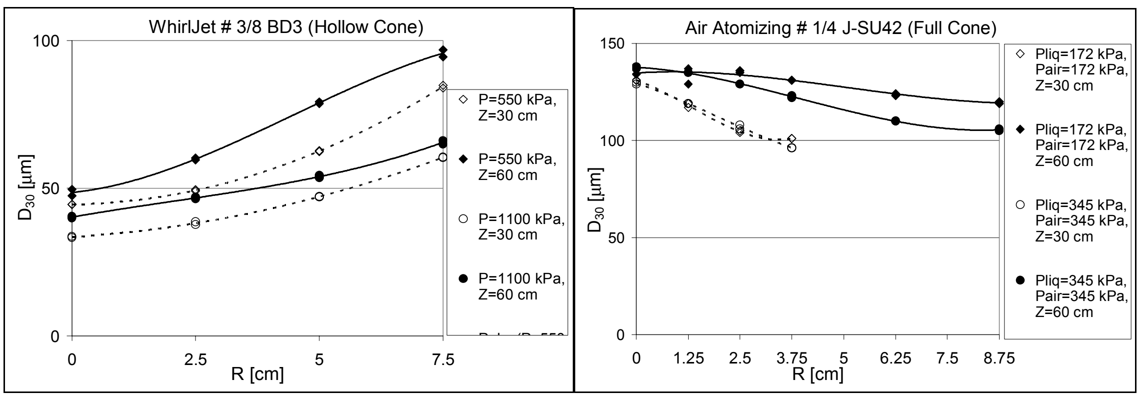

Fig. 4 D_{30} vs. radial distance from the spray center at Z=30 cm and 60 cm for the nozzle 3/8BD3 (left) and the nozzle ¼J-SU42 (right).

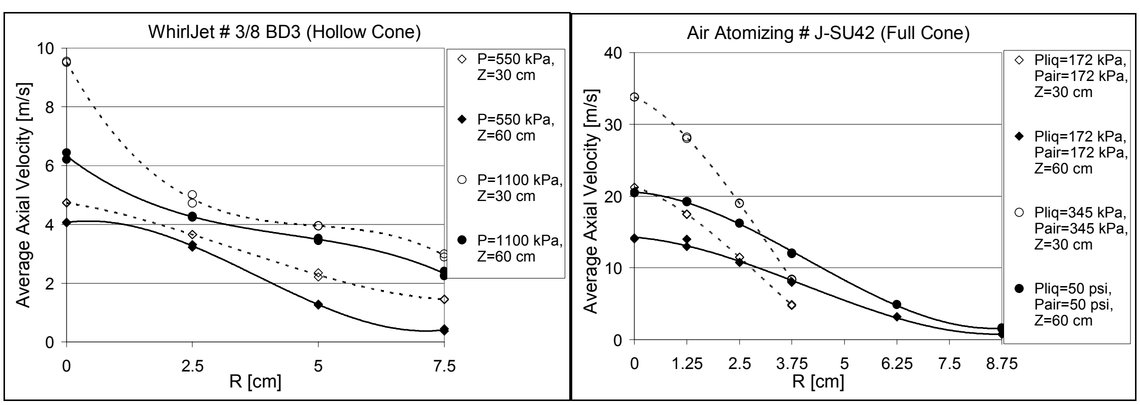

Fig. 5 Average axial velocity of spray droplets versus radial distance from the spray center at Z=30 cm and 60 cm for the nozzle 3/8BD3 (left) and the nozzle ¼J-SU42 (right).