DETAILED STUDY OF CONFINED SPRAY CHARACTERISTICS WITH VARIABLE CO-FLOWING AIR VELOCITIES

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ABSTRACT

The characteristics of sprays within a confinement tube with a co-flowing airflow, as used in a wide range of applications such as combustion, spray drying and cooling systems, have been studied experimentally by using the phase Doppler technique. The objective of the present research is to set up a controlled experiment in which initial and boundary conditions are controlled and measured as accurately as possible for better understanding the characteristics of such spray cases and to obtain initial conditions with enough detail to provide the essential input data for modern CFD codes. The characteristics of sprays produced by a hollow-cone atomizer acting within a confinement tube have been presented and discussed. Moreover, the air velocity profiles with and without the main sprays have been obtained by measuring the behaviour of the fine droplets produced by using a twin-fluid atomizer. The interactions between the two phases have been discussed. The lower co-flowing airflow velocity gave a wider spread of the spray and greater wall deposition. Droplet sizes became more homogeneously distributed across the tube with increasing downstream distance. A strong initial correlation between droplet size and axial velocity exists with larger droplets maintaining higher velocities, but once the droplets have lost their excess momentum correlation between size and axial velocity is no longer significant.

1. INTRODUCTION

With applications such as in combustion, dust capturing, spray drying, coating and cooling systems, spraying of liquids into ducts or tubes in co-flowing air has been studied by a number of research workers. Understanding of the transport and exchange mechanisms within and between phases is important in designing optimized spray systems in processes in such aforementioned spraying systems. However, detailed knowledge of confined spray behaviours under different running conditions is still unsatisfactory especially in producing detailed controlled measurements to provide the essential initial condition for modern *CFD* codes which is the main objective of the current study.

Abduljalil [1] presented the data on which this paper is based where the structure of the confined sprays under a number of different running conditions were studied in detail. These running conditions include; liquid injection pressure, liquid mass flow rate and co-flowing air velocities. It appears that studying the cold-flow characteristics is very important to the understanding of the behaviour of confined sprays, before going into heated flow conditions, because of difficulty of obtaining predictions of vaporisation or mixing performance without a better understanding of the atomizing process and initial spray structure. Studying the behaviour of confined spray directed into a cold and hot airflows was carried out by Trichet et al. [2]. They concluded that the spray structure evolves to be more homogeneous with some medium size droplets along the centreline with downstream distance. In the mining industry, confined sprays (mainly hollow-cone sprays) are used to both entrain air and flammable gases and to capture dust. A spray ventilator which essentially acted as a jet pump (ejector) where the spray pumped the air was studied by a number of researchers such as Mellor et al. [3] , Jones [4] and Widger [5] who concluded that the air/water entrainment ratio increases with increase in supply pressure and hence, water flow rate, up to an optimum value above which "entrainment saturation" is reached and the addition of excess water is no longer beneficial to air-movement. The entrainment ratio was seen to reduce greatly with increase in orifice diameter of the atomizer. This may be mainly due to increase in drop size, but spray angle also increases with orifice diameter and this may have an effect. Schelling and Reh [6] investigated experimentally the influence of atomizer design and coaxial air velocity on entrainment for coaxial and confined sprays. The influence of coaxial air velocity on the spray width was found to be significant when comparing the free spray with coaxial and confined cases. There is, to date, very little published work on sprays confined in simple axi-symmetric tubes with a uniform air flow and little attention has been paid to measuring initial conditions with enough detail to provide the essential input data for modern *CFD* codes.Thus an objective of the present research is to set up a controlled experiment in which initial and boundary conditions are controlled and measured as accurately as possible.

A hollow-cone spray atomizer with a nominal spray cone angle of 80^o and capacities of 0.36 and 0.51l/min at liquid injection pressures of 1 and 2MPa (Lechler GmbH.) was used throughout the current investigation. This atomizer was held by a 3-dimensional holder and positioning assembly positioned in a front chamber, with dimensions 410mm (width) x 440mm (height) x 880mm (length) to enable aligning the spray centrally relatively to both the confinement tube (Acrylic tube of 192mm internal diameter, 4mm thickness and 800mm in length) and the air-inlet tube (202mm internal diameter and 600mm length). Both tubes have bell-mouthed contractions at their inlet ends to assist uniformity and streamlining the flow into them to prevent the separation of the flow due to the sharp edges at the upstream inlet, which cause unwanted turbulence and non uniform air velocity profiles. A Kranzle HD13-230 high-pressure water pump was used to deliver the required water flow rate via a hose of 9.5mm bore diameter, which is much greater than the orifice diameter of the nozzles (1mm) to avoid excessive pressure drops. For the flow to be uniform in the pipeline, a surge tank was fitted to damp out fluctuations. The gas-out end of a droplet-gas separator cyclone, is connected to a powerful fan via a plastic tube of internal diameter of 150mm and a total length of about 27m. In addition, a twin-fluid atomizer, purchased from Spraying Systems Co., was mounted vertically downward in the front chamber to produce fine droplets with negligible axial velocity component to enable measuring the air velocity profiles with and without existence of the main spray produced by the swirl atomizer. This is achieved by averaging the velocity of droplets having diameters of $D \leq 10\mu$m.

A Dantec-*PDA* (phase Doppler anemometry) measurement system was used to measure the drop sizes and the mean axial velocity of the spray droplets simultaneously. This system has transmitting optics of 400 mm focal length with beam separation of 38 mm and the laser beam diameter is 1.35 mm and this gives number of fringes 37 with fringe spacing of 4.815 µm. The phase-Doppler receiving optics of 310 mm focal length is mounted at 30^o off the axis from the forward scattering direction. The effect of curvature of the tube wall on both the transmitting and the receiving beams were considered. The *PDA* measurements were carried out at 12 different downstream axial locations 25, 50, 75, 100, 125, 150, 175, 200, 250, 300, 400, and 500 mm. However, for the purpose of clarity the results presented in this paper show only the results for a working distance up to a point where there are no more significant changes in the flows taking place. The measurements of the air velocity were carried out separately due to the limitations in the equipment used. The air velocity was measured at each point by running the twin-fluid atomizer to produce a fine spray and the measurements were carried out at the condition where the main spray was off and also with the presence of the main spray. A maximum error in positioning the *PDA* measuring point of ± 0.25 mm in r and x directions was accepted. The estimated maximum errors in size and velocity measurements were ±5µm and ± 0.3 m/s respectively. This is based on comparisons between randomly replicated tests throughout the data acquisition. Finally, errors in the co-flowing air velocity values and water supplied to the experimental apparatus by the fire main due to change in ambient properties from day to day were considered.

2. RESULTS AND DISCUSSIONS

2.1. Spray Characteristics

As is typical of pressure swirl atomizers, near the atomizer the spray is hollow with larger droplets at the periphery, where they tend to remain due to their higher momentum/drag ratios, and smaller droplets in the middle of the spray, due to entrainment towards the centreline. The mean droplet size is getting smaller with increasing liquid injection pressure which causes the liquid to be discharged at a higher velocity. This raises the Weber number, thereby promoting finer atomization. The profiles of D_{32} shown in Fig. 1 are wider and flatter with increasing downstream distance x for the three presented spray cases which could be due to the entrainment of medium drop sizes into the centre of the spray, causing the mean diameter in the centre to increase with downstream distance x. One can also see that at the spray edges, the mean droplet diameter increased with downstream distance till the spray hits the wall of the confinement tube. This could be due to removal of smaller drops by entrainment toward the centre of the spray, as also concluded by Bachalo and Houser [7].

Figure 1 shows, generally, that smaller drop sizes are produced at P =2 MPa and the higher drop momentum gives less deflection and spread of the main cone of larger droplets. The D_{32} was observed to increase towards the "spray sheath", which is the radial point showing the maximum flux value as defined by Tokouka et al. [8], at any downstream section and reaches maximum near the spray sheath. These maximum values of D_{32} at the first

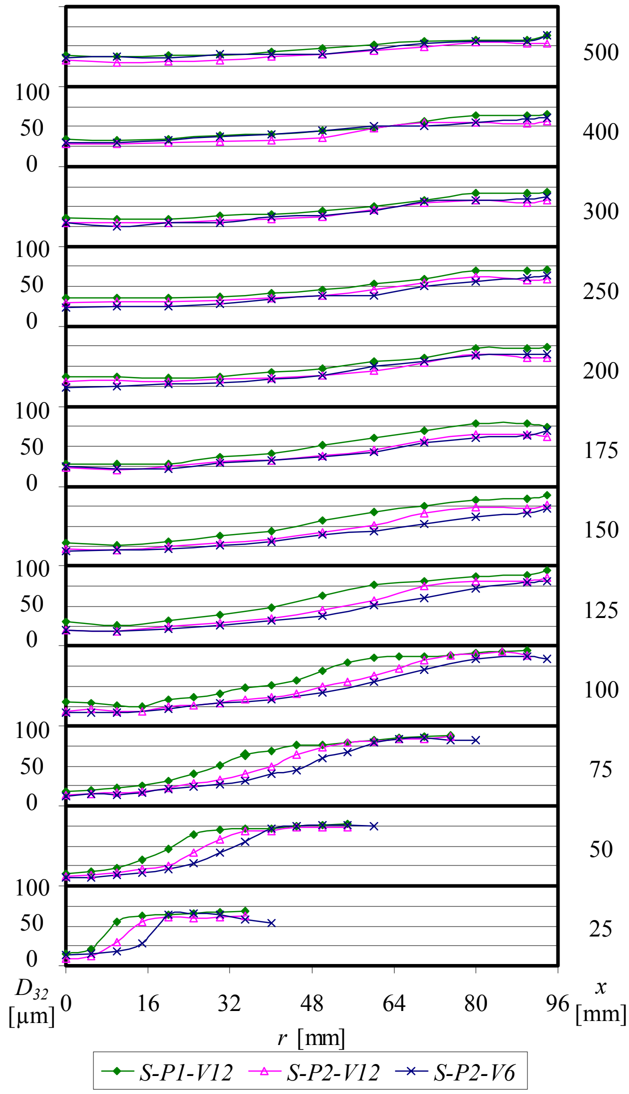

Fig. 1: Sauter mean diameter D_{32} distribution along the confinement tube at P=1 and 2MPa and V=12 and 6m/s.

downstream measurement location (x =25 mm) were seen at r =10 and 15 mm at liquid injection pressures of 1 and 2 MPa respectively and V =12 m/s. This could be due to the smaller droplets being induced to the centre by entrained flow, leaving the larger droplets, which have larger momentum, moving linearly along the spray sheath but with higher rate at lower liquid injection pressure. This figure also shows that the core of smaller mean drop sizes is narrower and disappears more rapidly at P =1 MPa than at P =2 MPa with downstream distance x. This may be due to the number density of smaller droplets at P =1 MPa being less than those at P =2 MPa, and as a consequence the mean drop size values are skewed toward a larger value as relatively more medium drop sizes are entrained toward the centreline of the spray. Moreover, one can see that larger droplets appear further downstream which could be partly due to droplet collisions. However, the mean drop size profiles at 500 mm downstream are within ± 7 μm for all the three cases at the centreline and ±12 μm close to the tube wall.

The principal cause of mean drop size profiles varying with co-flowing airflow velocity is likely to be because small droplets can accelerate or decelerate more rapidly than larger droplets. Studying the drop size profiles should thus be carried out with consideration of the velocity profiles. It can be seen from Fig. 1 that, as expected, the sprays spread more rapidly at the lower co-flowing air velocity, and that at this velocity the local values of mean droplet size are slightly larger at the edges of the spray, probably due to the removal of fewer small drops by the 'winnowing' effect. The spray at lower V hits the wall sooner and there is a detectable downstream deflection of the larger droplets for higher V. Thus larger droplet size can be seen further downstream at V =12 m/s. The profiles of mean droplet velocity for the three spray cases are presented in Fig. 2. This figure shows that the mean velocity values for the droplets at P =2 MPa are higher than those at P =1 MPa, as expected. This difference in the velocity values is seen most clearly close to the atomizer. It is noted that a simple average velocity for all drop sizes is generally biased towards the velocities of the smaller droplets at any position because these are very much greater in numbers than larger drops, although the larger drops contain a high proportion of the local spray mass flow. Near the atomizer the smaller droplets have not decelerated completely to the local air velocity, particularly in the main initial spray cone. Smaller droplets around the centre of the spray have lost, their initial velocity, to the air, more quickly. This figure shows that as expected, the droplets of sprays at P =1 MPa exchange their initial momenta to the air over shorter distances than those at P =2 MPa as will be discussed in detail.

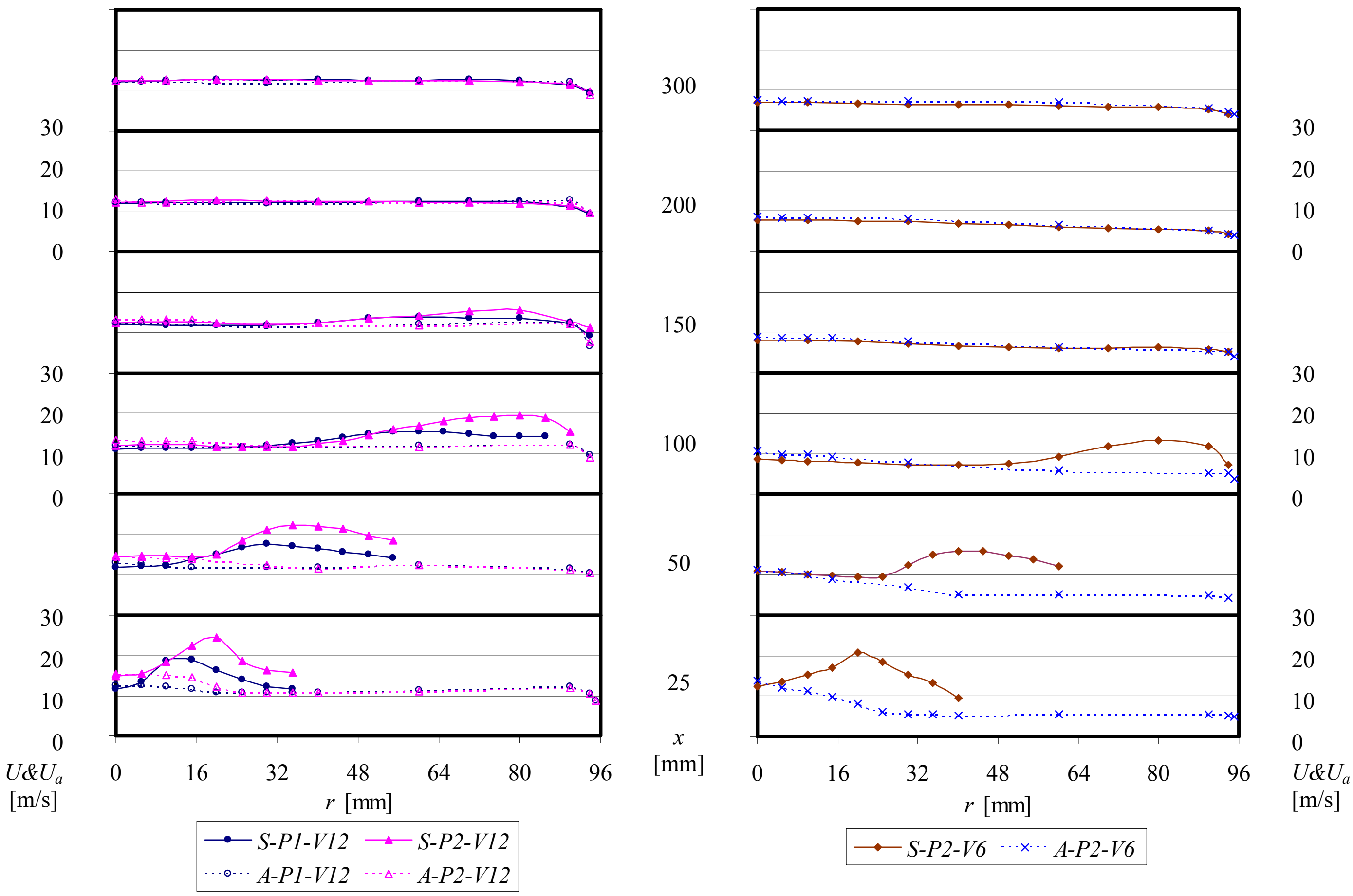

Fig. 2: Profiles of axial components of mean droplet U and air U_a velocities valong the confinement tube at (left) P=1 and 2 MPa and V=12 m/s and (right) P=2 MPa and V=6 m/s.

Figure 2 also shows that the differences in the mean droplet velocity profiles at different pressures, vanish gradually with increasing x. Smaller droplets dominate the average velocity near the centre and at the edges of the spray larger droplets have more contributions to the mean axial velocity values. Generally, the profiles of the average droplet axial velocity of the sprays at P =1 and 2 MPa coincide, to within ±1 m/s, at about x=200 mm, where the vast majority of the remaining droplets move with the velocity as of the airflow. Therefore, the influence of the liquid injection pressure on the spray velocity profiles vanishes for $x \geq 200$ mm. Figure 2 also shows that at the same liquid injection pressure (2 MPa) the spray spreads more rapidly at the lower co-flowing airflow velocity V. At the same liquid injection pressure the sprays should have the same initial momentum regardless of the co-flowing airflow velocity. The actual initial mean drop velocity should be obtainable by making measurements very close to the atomizer, i.e. within 5mm say. However, attempts of this showed that the spray is here too dense to make successful measurement using the *PDA* system. At the first possible downstream location, x =25 mm, one can see that the average droplet axial velocity component U has lower peak values at V =6 m/s than at V =12 m/s, showing that the effect, mainly on the smaller droplets, of the co-flowing air has already been established at this position. This figure also shows that for spray case with V =12m/s the droplets are moving with similar velocities at x =200 mm while for V =6 m/s this occurs at x=150 mm. This is because at lower V, as the spray spread more rapidly large droplets are lost sooner at the wall of the confinement tube, and the resulting higher population of smaller droplets adjusts more rapidly to air velocity.

2.2. Air Velocity Measurements and Comparisons with Droplet Mean Velocities

To enable measuring the air velocity profiles in the presence of the sprays, the airflow was seeded by small droplets using the twin-fluid atomizer mounted vertically downward in the front chamber for the spray to have negligible axial velocity component. The air velocities were determined from the velocities of droplets smaller than 10 µm, irrespective of which atomizer produced each measured droplet. The air velocity profiles measurements were carried out when the sprays of the pressure atomizers were switched on and off, i.e. to measure the airflow velocity profiles along the confinement tube with no sprays. These latter cases are known as P =0 MPa hereafter. The influences of different sprays running conditions on the air entrainment by the sprays could be deduced from the differences between these measurements, with and without the sprays produced by the pressure atomizer. It should be mentioned here that the air velocity profile measurements were carried out from 1 mm from the wall at one side off the centreline, up to 30mm of the other side of the centreline, to check symmetry of the profiles.

In Fig. 2 the mean air axial velocity profiles, obtained by averaging the velocities of droplets with diameters $D \leq 10$µm, are compared with the mean axial velocity profiles of all droplets in the sprays produced by the pressure atomizer. This figure shows that close to the atomizer, x =25mm, the liquid phase has higher velocities than the gas phase, as expected. However, at the centreline one can see that the two phases have very close velocity values to within 0.5 m/s where the gas velocity is slightly higher than the droplet average velocity, which is because the droplets at the centre of the spray are small and thus lose their initial momentum very rapidly. As downstream distance increases the droplets lose momentum to the gas phase and the high momentum large droplets impact at the wall sooner with the lower value of V. Thus the mean liquid phase velocity reduces with x and r to become almost equal to that of the air. These mean axial velocity profiles of the two phases show, generally, that the co-flowing air velocity V has a direct influence on the downstream distance required for the droplets to lose their initial excess momentum and move with same velocity as the air. This could be seen by comparing the two phases velocity profiles at x =150 mm at P =2 MPa and V =12 and 6 m/s respectively. These profiles show that the droplets have lost their initial momentum and move with same velocity as air at x =150 and 200 mm at V =6 and 12 m/s respectively. This is probably due to the lower initial axial component of velocity of the droplets for the wider spreading of the spray and hence sooner deposition of the big droplets at the wall at lower co-flowing air velocity. The droplets of the sprays produced at P =1 MPa lose their momenta sooner than those at P =2 MPa due to their lower excess initial momentum. One can see that the peak entrained air velocity values at the centreline decrease with downstream distance x, thus becoming flatter until the sprays move with same velocity as air.

Figure 3 shows that close to the atomizer the air velocity profiles for P =0 MPa (no spray) show “dips” around the centreline due to the effect of the wake of the atomizer and its holder body. The effect of the wake on the mean air axial velocity values is higher for the case at V =12 m/s than at V =6 m/s, due to its higher momentum deficit. As with all wakes, the effects reduce with downstream distance x. At higher air velocity the wake of the atomizer lasts to 150 mm downstream of the atomizer exit, while at lower air velocity the wake of the atomizer is not detected beyond 100 mm downstream. It is interesting to note the jet-like air velocity profile near the atomizer when the sprays are turned on. This is entirely due to entrained air, which is increased by increasing P due to the higher initial momenta of droplets. The peaks of the air velocity profiles at the centreline become flatter with axial distance x, as the spray becomes wider and also as larger droplets are lost to wall impacts. This figure also show that the wider spread of the spray (i. e. lower V) have relatively higher entrained air. It is remarkable that the position of the main spray cone is not clear in the results: intuitively it might be expected that peak air velocities would be found where the highest spray volume flux exists, but this is not the case. One can also see that the air velocity profiles at P =0, 1 and 2 MPa coincide at x =500 mm, to within ±0.3 m/s for the case of V =12 m/s. However, at V =6 m/s the air entrainment peaks are present further downstream. For the first measurement location, x =25 mm, one can see that the wider spray cone angle (i. e. lower V) appears to give higher air entrainment by the spray for the same pressure, as evidenced by a wider central entrainment jet. This, however, gives support to Lefebvre’s [9] proposal that maximizing spray cone “free surface area” facilitates greatest liquid to air momentum exchange. However, a narrower spray cone angle increases the interaction distance between the spray and the air before the spray hits the wall, and will tend to increase the entrainment ratio.

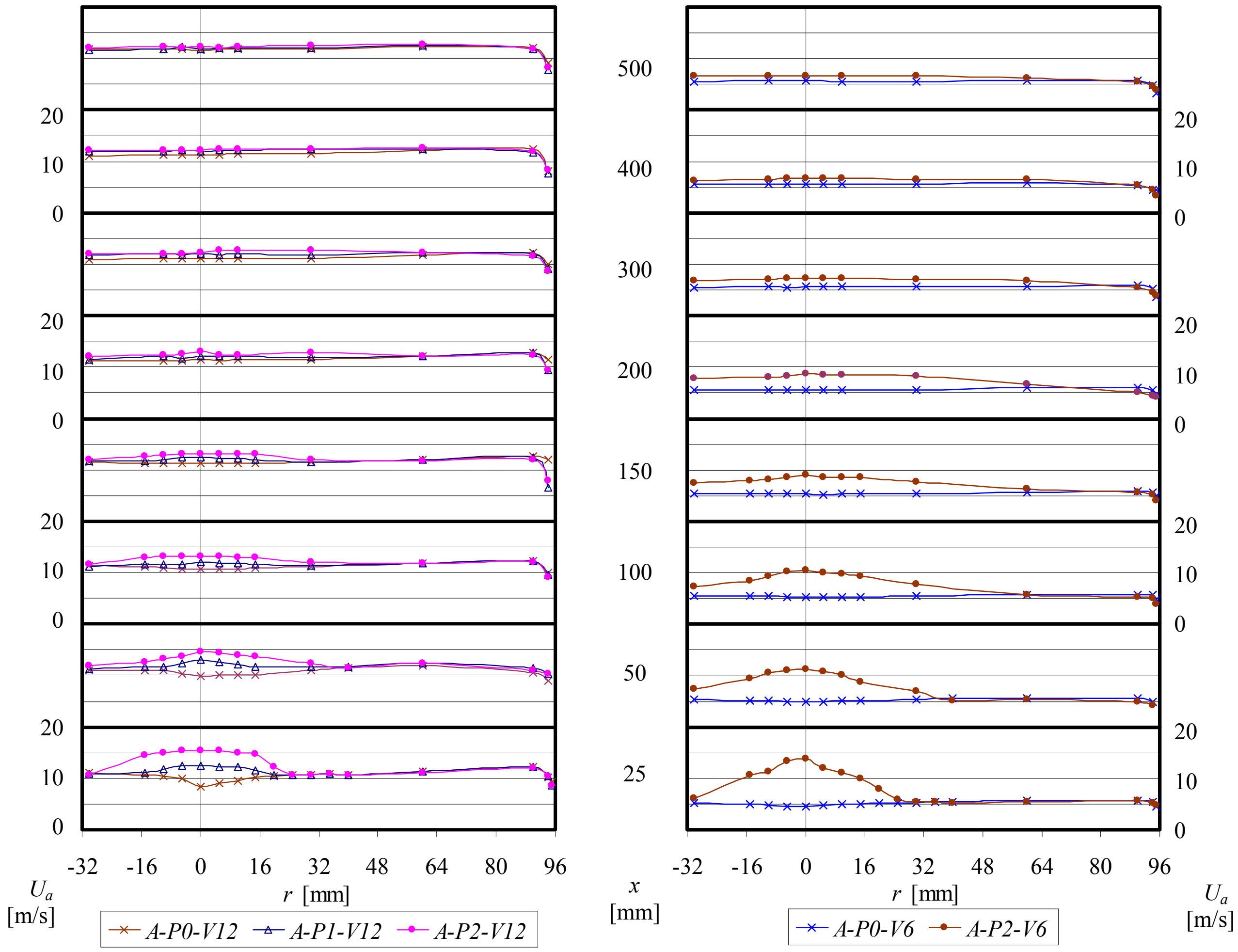

Fig. 3: Mean air axial velocity profiles along the confinement tube at (left) P=0, 1 and 2 MPa and V=12 m/s and (right) at P=0 and 2 MPa and V= 6 m/s.

2.3. Drop Size/Velocity Correlations

It is presume that the size-velocity dependent droplet size distributions influence the characteristics of confined sprays in co-flowing airflow. To enable investigating this, the droplet size spectrum at each measurement position was thus divided into size classes of 20 µm width, covering the size range 0-120 µm, there being very few droplets having diameters more than 120 µm in all cases. Three size class, small (0 µm< $D \leq$ 20 µm), medium (40 µm< $D \leq$ 60 µm) and large (80 µm< $D \leq$ 100 µm) drop sizes were obtained from the size spectrum at each measurement position and the average droplet axial velocity for each size class was obtained by averaging the individual droplet velocities within the class.

Figure 4 shows these mean velocities as a function of radial and axial distances for one spray case at P = 2 MPa and V =12 m/s with the associated air velocity profiles due to the space limition. This figure confirm that the droplets lose their initial momentum, and gain the same velocity as the co-flowing air, at rates according to their diameters. Droplets of diameters less than 20 µm appear to have lost their initial momentum by the first measurement position. The medium class of droplet size 40 µm< $D\leq$ 60 µm loses its momentum by x =150 mm. At approximately x =200 all classes of drop sizes are travelling with the velocity of the air. Generally, before these positions at any downstream location, the velocity of any individual drop is a function of its diameter. One can observe from these profiles how the larger droplets diffuse radially, both inwards and outwards, with increasing x. This figure also shows that at x=25mm droplets within the second size group, 40 µm< $D \leq$ 60 µm, exist close to the centreline of the spray. Generally, larger drop size classes exist closer to the centreline of the spray at V =12m/s, than at V =6 m/s (not presented). This could be due to more medium sized droplets being entrained towards the centre of the spray at higher V.

3. CONCLUSIONS

The characteristics of water sprays within a horizontal confinement tube with a co-flowing airflow, as used in a wide range of applications such as combustion, spray drying and cooling systems, have been studied experimentally by using the phase Doppler technique. The objective has been met, of establishing benchmark experimental data on the behaviour of confined sprays experiencing different running conditions which intended to be used to assess the capability of a commercial computational fluid dynamics code for modelling this very basic type of two-phase flow.

Results were obtained using a wide angle (80°) hollow cone atomizer at two co-flowing air velocities (6 and 12m/s) and at two liquid pressures (1 and 2MPa). The following conclusions are drawn:

- The *PDA* measurements showed a typical pattern of hollow-cone sprays with an initial zone with small droplets in the centre of the spray and larger droplets at the edges where drop sizes distribution became more homogeneously distributed across the tube with increasing downstream distance, with an increase in the mean drop size at the centre of the tube due to the inwards entrainment of medium droplets, and the loss of larger droplets at the wall.
- Further downstream D_{32} values become more uniform across the confinement tube, both because droplets lose their initial momentum and move with the same velocity as the airflow, and also because a proportion of larger droplets is lost by wall impact.
- Once this uniformity occurs, few differences between the mean droplet sizes for the different cases are observed.
- At higher liquid injection pressure the initial drop sizes showed smaller values, as expected, although the higher drop initial momentum gave less deflection and spread of the main outer cone of larger droplets. However, further downstream the drop size distributions were very similar for all atomizing conditions due to the "winnowing" effect of the co-flowing air.
- The data show that a strong correlation between droplet size and axial velocity exists, with larger droplets having the higher velocities because of their larger inertia/ drag ratios, but once the droplets have lost their excess initial momentum correlation between size and axial velocity is no longer significant.
- The velocity of the co-flowing airflow showed an influence on both the spread of the spray and the radial distributions of drop size.

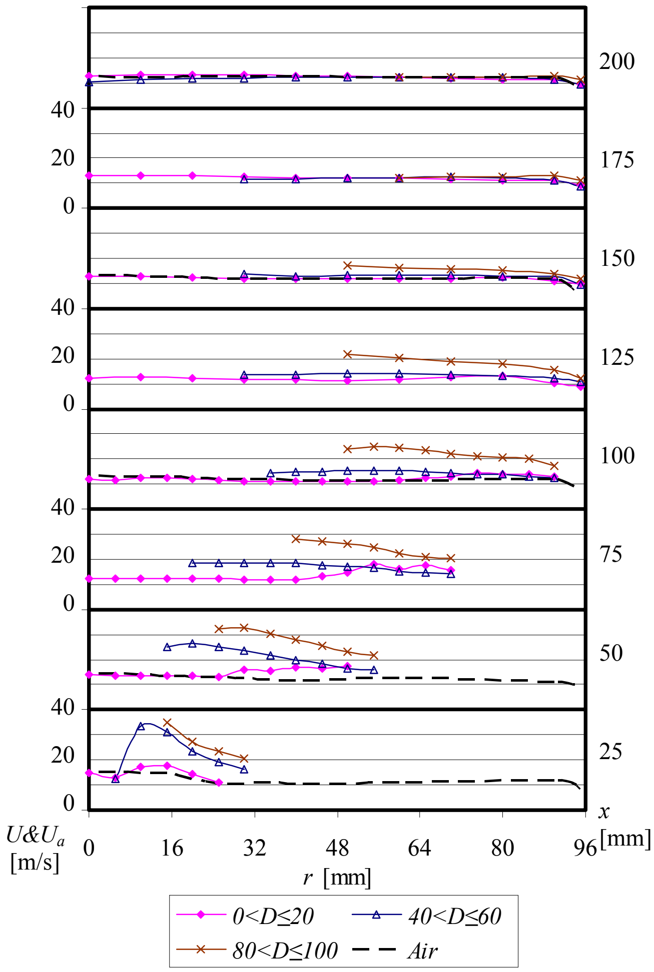

Fig. 4: Velocity profiles of different drop size classes (in microns) and mean air axial velocities at P=2 MPa and V=12 m/s.

NOMENCLATURE

D	Drop size (µm)	D_{32}	Sauter mean diamter (µm)
P	Gauge liquid injection pressure (MPa)	r	Radial distance (mm)
U	Mean drop axial velocity (m/s)	U_a	Mean air axial velocity (m/s)
V	Co-flowing air velocity (m/s)	x	Axial downstream distance (mm)

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