EXPERIMENTS AND CFD PREDICTIONS OF TWO OVERLAPPING WATER SPRAYS ISSUED FROM AIR-ASSIST ATOMIZERS

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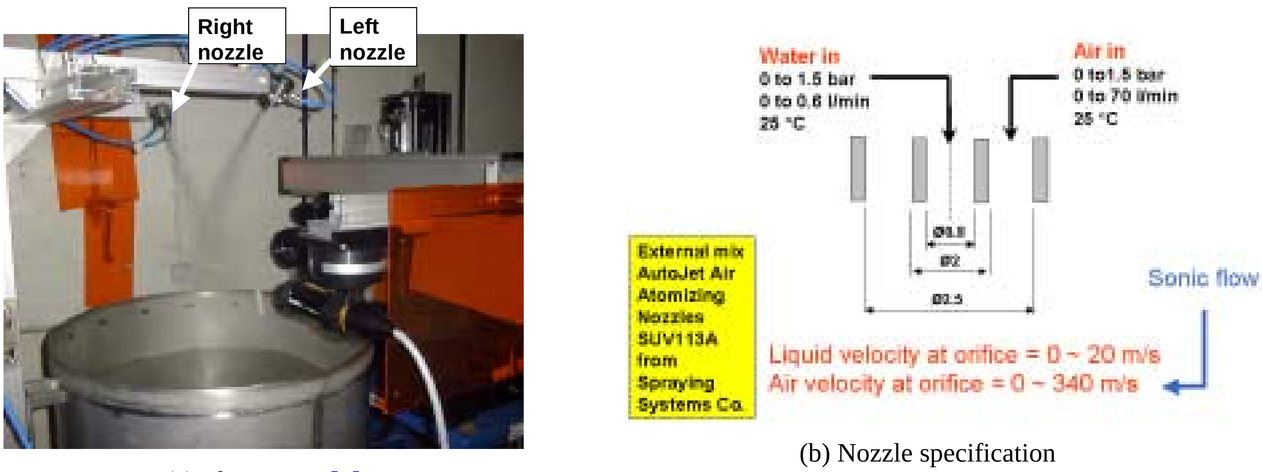
ABSTRACT

As part of an extensive EU project [1], aimed at developing and implementing an industrially validated CFD design tool, data are presented for two polydisperse water sprays that are impacted with variation of angles, momentum and initial droplet sizes with the conditions for each spray being nominally identical. Experiments, using PDA and video cameras, were carried out in references [2-4] in which the impacting sprays were produced by two twin fluid atomizers spraying downwards above a wide collection system with a uniform suction velocity across its inlet, sufficient to collect the sprays without influencing them. A novel systematic approach was adopted in order to aid interpretation of PDA data in terms of droplet collision phenomenon and to provide a unique testing ground for CFD collision submodels. This involved (a) running one spray without the other (thus giving an undeviated free spray), (b) running one spray and with only the atomising air turned on for the second atomizer and (c) operating both sprays. The simulations were carried out in an extended in-house (Spray3D) CFD code whose genesis includes applications in fire suppression systems [5] and diesel engines [6]. A reasonable agreement between experiments and CFD predictions for twin atomizers is achieved for a spray cone angle of 30º.

INTRODUCTION

Spray drying flow geometry's (as used in the EDECAD project [1]) differ considerably from the spray flows which have been analysed to date using collision modelling. For spray drying of food products, existing collision models and variants are inadequate to describe the real systems, e.g. irregular and sticky particles. Predicting the results of different modes of interparticle impacts is lacking experimental information essential for spray drying applications. It is in this perspective that UMIST carried out laboratory scale experiments to produce these data for two sprays of pure/homogeneous liquid impacted at different conditions. Two types of measurement methods were implemented, which comprised (i) video techniques using a high speed Kodak 4540 camera that allowed recording of drop-drop collisions, and (ii) Phase Doppler Anemometry (PDA) for measuring the sizes and velocities of droplets. The collected data were useful for the basic set-up (laboratory scale and pilot plant flows) of the Spray3D CFD code [6] as well as the CFD codes of other partners that undertook the testing of various sub-models generated within the EDECAD project [1] prior to their implemetation into the ultimate CFD design tool.



(a) The test rig [2]

(b) Nozzle specification

Figure 1: Experimental apparatus used in PDA and video data acquisition [2-4].

EXPERIMENTAL SET-UP

A novel experimental apparatus was designed and constructed at UMIST as shown in Figure 1 (a) [2]. This consists of two sprays impacting on each other with independent control of spray angle, momentum and drop size for each spray. Figure 1 (b) shows the nozzle specifications while Table 1 depicts the nozzle operating conditions implemented in three test cases of air/liquid pressure ratios [2-4].

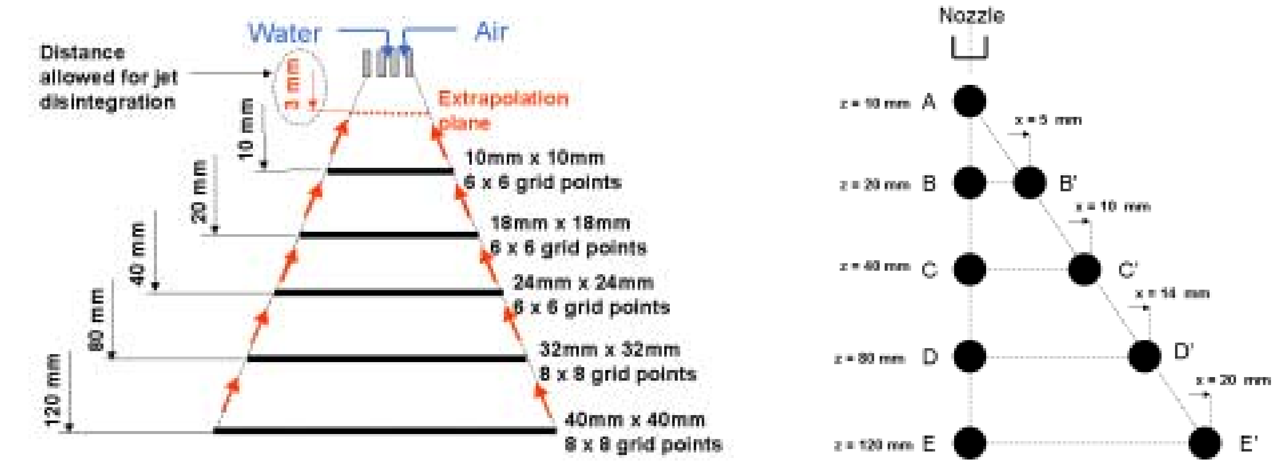
Table 1: Nozzle operating conditions.

Pair/Pliq (bar/bar)	Fluid flow	
	Air (l/min)	Liquid (l/h)
1.5/1.5 (Case A)	70	36
1.5/0.5 (Case B)	70	21
0.5/0.5 (Case C)	37	21

PDA AND VIDEO DATA ACQUISITION

Measurements for CFD initial spray data

Before PDA measurements and video records were taken with interacting sprays, there were two relevant considerations, which required individual characterisation of the atomizers. These were (i) to ensure that the two nozzles were identical in their performance and (ii) to provide initial conditions for CFD predictions. Measurements were therefore taken for each nozzle at 5 levels downstream of the exit orifices at 10, 20, 40, 80, 120 mm, with the nozzles pointing vertically downwards (Figure 2 (a)). Both the axial and radial velocity components of the spray were measured although a 1D PDA system was used. The measurement of the radial component was achieved by rotating the transmitter by 90° as well as by setting the polarization angle to match the direction of the fringes. The level z = 10 mm was the closest possible location that measurements could be taken with few spray ligaments. Hence this level has been assumed particularly relevant for the provision of initial spray data for CFD modelling, while the remaining 4 levels were used primarily to compare the performance of the two nozzles (e.g., the selected grid points shown in Figure 2 (b)).



(a) Measurement grid points

(b) Selected grid points

Figure 2: PDA measurement planes and grid points.

PDA and video data acquisition for validation of CFD predictions

As carried out in [2-4], the horizontal plane passing through the main zone of spray interaction, shown in Figure 3, was taken as the "level zero". Horizontal planes located 50 mm above and below this level were designated "level +50 mm" and "level -50 mm" respectively. It should be noted here that the reference plane at level zero does not coincide with that of the initial spray data of Figure 2, which is co-planar with the nozzles orifices. Following the test cases shown in Table 2, droplet

Table 2: Range of test conditions carried out for validation of CFD predictions.

Test No	Gauge Pair/Pliq (bar)		Remarks
	Left nozzle	Right nozzle	
1	1.5/1.5	1.5/1.5	Double spray
2		1.5/0.0	One spray & one air jet
3		0.0/0.0	Single spray
4	1.5/0.5	1.5/0.5	Double spray
5		1.5/0.0	One spray & one air jet
6		0.0/0.0	Single spray
7	0.5/0.5	0.5/0.5	Double spray
8		0.5/0.0	One spray & one air jet
9		0.0/0.0	Single spray

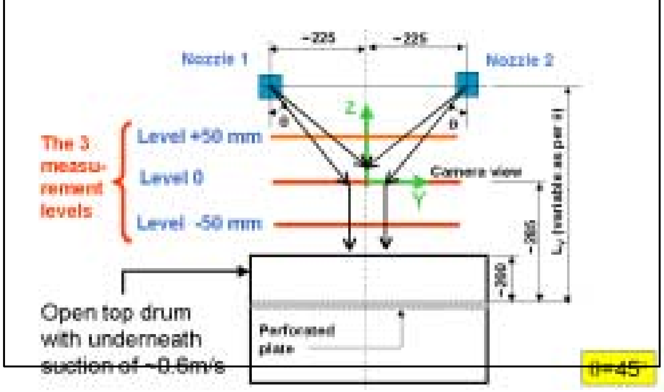


Figure 3: Illustration of measurement levels for the validation of CFD predictions.

data were recorded along the 3 planes using PDA and video techniques. Although one would expect the spray initial data to be taken with inclined sprays (i.e., not with vertical sprays as proposed in the preceding section), difficulties associated with the 1D PDA system set-up (i.e., appropriate orientation of fringes) made this approach impractical. Hence, for the axial and radial components required by the codes of other project partners, trigonometrical relations between the measured component and the spray inclination angle were implemented. These relations however were not relevant for the UMIST Spray3D CFD code [6], which uses the dominant injection velocity and direction to solve for the continuity and momenta equations in the injection cell.

PDA DATA PROCESSING

Given that the main PDA Flow and Particle Software package has been designed primarily for data acquisition [7], and offers only very limited data presentation capabilities, post processing routines have been developed at UMIST [8]. These routines process point measurement data using the PDA data export files and can provide information on characteristic diameters, PDF's of droplet number, volume, mean and fluctuating velocities, turbulence intensity, skewness and flatness. Data are dumped in the form of tables, which can readily be used in TECPLOT or any other graphics packages (e.g. Gsharp for windows and/or UNIX). Options for the desired properties, spacing of 5 or 10 µm droplet sizes and the possibility of filtering the segments in which no droplets are identified are first selected. The program filters the information relating to non-spherical particles for which the value 0 µm is assigned to the droplet diameters by the PDA system. When the fluctuating velocity component is required for a given parameter, a pseudo-classification of droplets is made: this is so because, in the first classification, one obtains the number of droplets in each size class from which the mean value of the measured velocity component is then calculated. Interactive information is provided on the computer screen while the data files are being processed and, at the end of the program, information is displayed on the computer screen while permanent data files are written to disc.

Written in FORTRAN 77, the routines are simple and comprehensive to follow. They run on ABSoft Pro FORTRAN for Windows^{TM} 95/98/NT (a few problems were encountered using Windows^{TM} 2000 because ABSoft Pro FORTRAN for Windows^{TM} 95/98/NT is a 32-bit application), UNIX and Linux environments and allow introduction of further improvements as required by the user.

Although the programs have been designed to handle distributions of up to 1,000 µm, a factor 1/10 is available, which allows processing of very narrow sprays (i.e., sprays limited at 10 µm diameter). Simple additions can also be made to allow processing of wider spray distributions. The PDA data Windows^{TM} generated files need conversion for the UNIX systems to process them conveniently. This is so because incompatibilities between the windows and UNIX *end of files* may confuse the UNIX reader. If the user does not make the necessary conversions, the program filters the false readings (these are detected through inconsistencies in the variables droplet velocities and diameters) and displays the respective warnings. Initial spray data for CFD predictions were supplied at 3 mm downstream of the nozzles exits using the extrapolation procedure as devised by [9] (see Figure 2 (a)).

RESULTS AND DISCUSSION

Spray initial data for CFD predictions

The higher pressure test Case A of Table 1 has been chosen for reporting in the present paper given that it generated data that approached the Brazier-Smith experiments [10], which are widely used in spray models. Example results are shown in Figures 4 to 6 that follow below.

It may be seen from levels z = 10 and 20 mm of Figure 4 that the sprays did not issue in entirely axisymmetric form given that the maximum droplet axial velocities of 107 m/s are only present at some spots of the horizontal cross-sections. The drag forces and the particles intercollision phenomena that take place up until the last measurement level cause a reduction of the droplet axial velocity by a factor of 3.6 (i.e. from 107 down to ~30 m/s).

Shown in Figure 5 are the volume frequency distributions of measurements carried out along the spray axis. Observable here is that the 21% peak of the volume frequency distribution at Position A resides in the vicinity of 30 µm size classes, with the SMD of the distribution being 32 µm. The profile spans up to a maximum size range of ~ 100 µm. At Position B, the peak has reduced to ~ 14%, but residing in the 100 µm size range while the SMD and the maximum sizes are 67 and 200 µm respectively.

The right-shifting shown here clearly indicates coalescence outweighing the break-up process in the window z = 10 to 20 mm. At the Positions C, D and E, the peaks slightly left-shift to size ranges in the vicinity of 75 µm with the SMD oscillating around 61 µm. This observation suggests that the coalescence and break-up mechanisms balance each other along the spray axis as the spray progresses downstream of the level z = 20 mm.

The variations of droplet volume distributions along the spray edge are illustrated in Figure 6. The coalescence is relatively less pronounced than along the spray axis as only a 39% increase of SMD is present between the planes z = 10 and 20 mm in contrast to the 110% increase in the former case. In common with Figures 5, the profiles left-shift in the subsequent positions. The size distributions are much narrower than for those along the spray axis, again indicating the relative lack of coalescences. The peaks of Figure 6 tend to stabilize at 15% volume occurrence all through the planes z = 40 and 120 mm.

For the data of Figure 6, a PDA cut-off diameter of 105 µm was set, which caused a minor truncation of the volume size distributions. This happened because the relatively poor histogram of *droplet number distribution* was used to control the cut-off diameter of the PDA system, which did not suggest the necessary adjustments identified latter when the PDA data post-processing routines were implemented to analyse the PDF's of *volume distribution*.

Additional innacurracies reflected at the right end of the profiles in Figure 6 derived from the fact that a uniform sampling time set at the spray axis was used at every measurement grid point. Hence, the time was not sufficient to allow records of enough particles at the spray edge where the droplet mass fluxes were low.

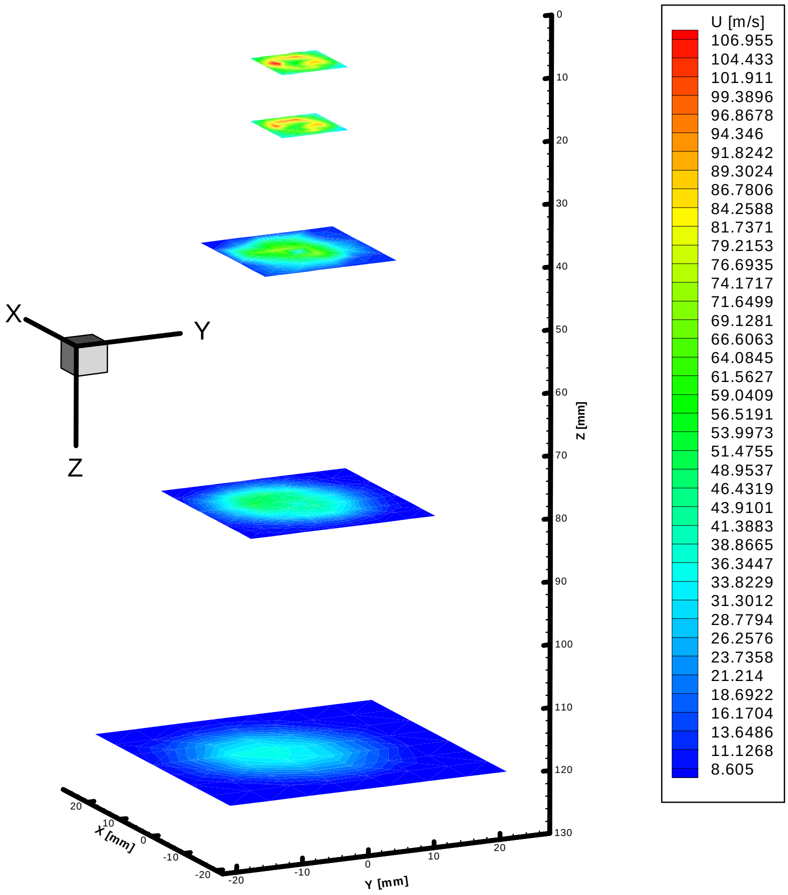


Figure 4: Droplets axial velocity contours.

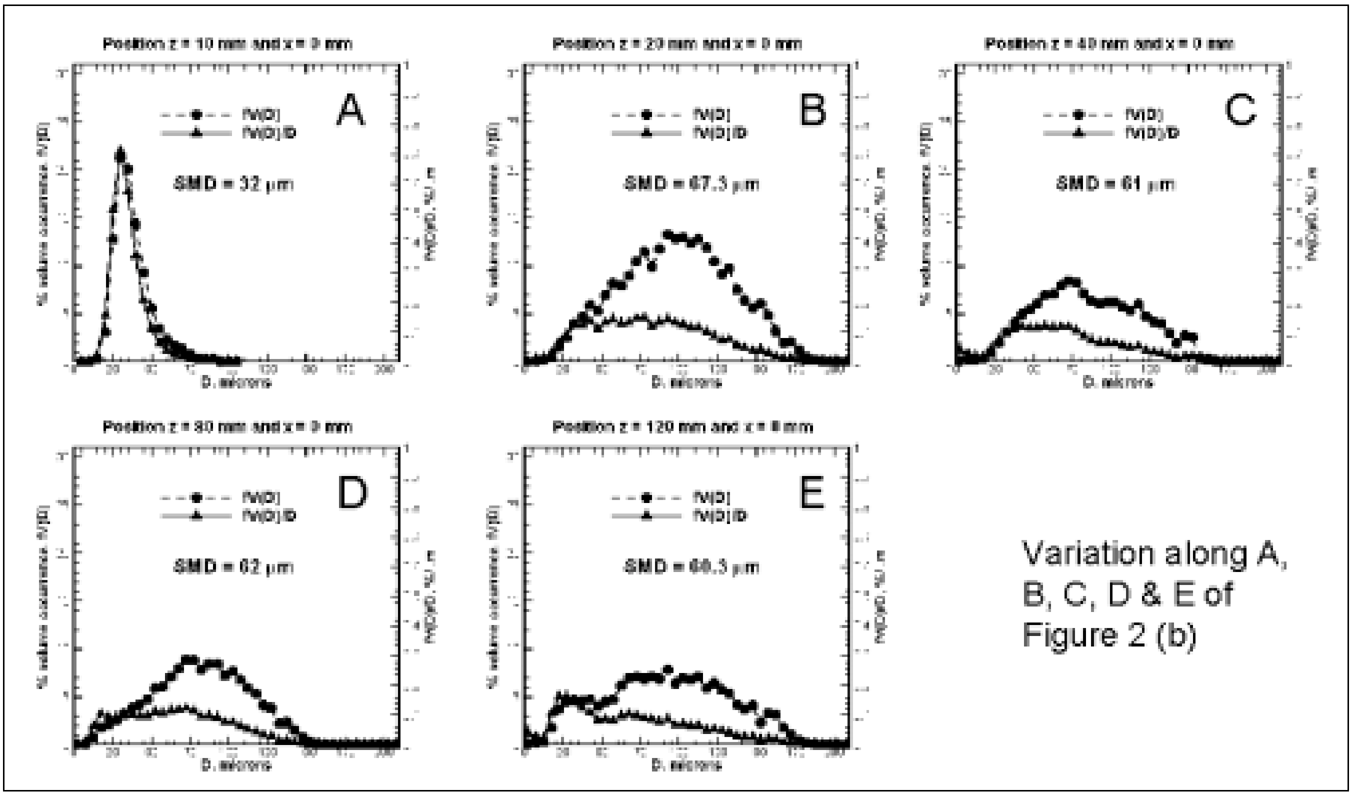


Figure 5: Variation of droplet volume distributions along the spray axis.

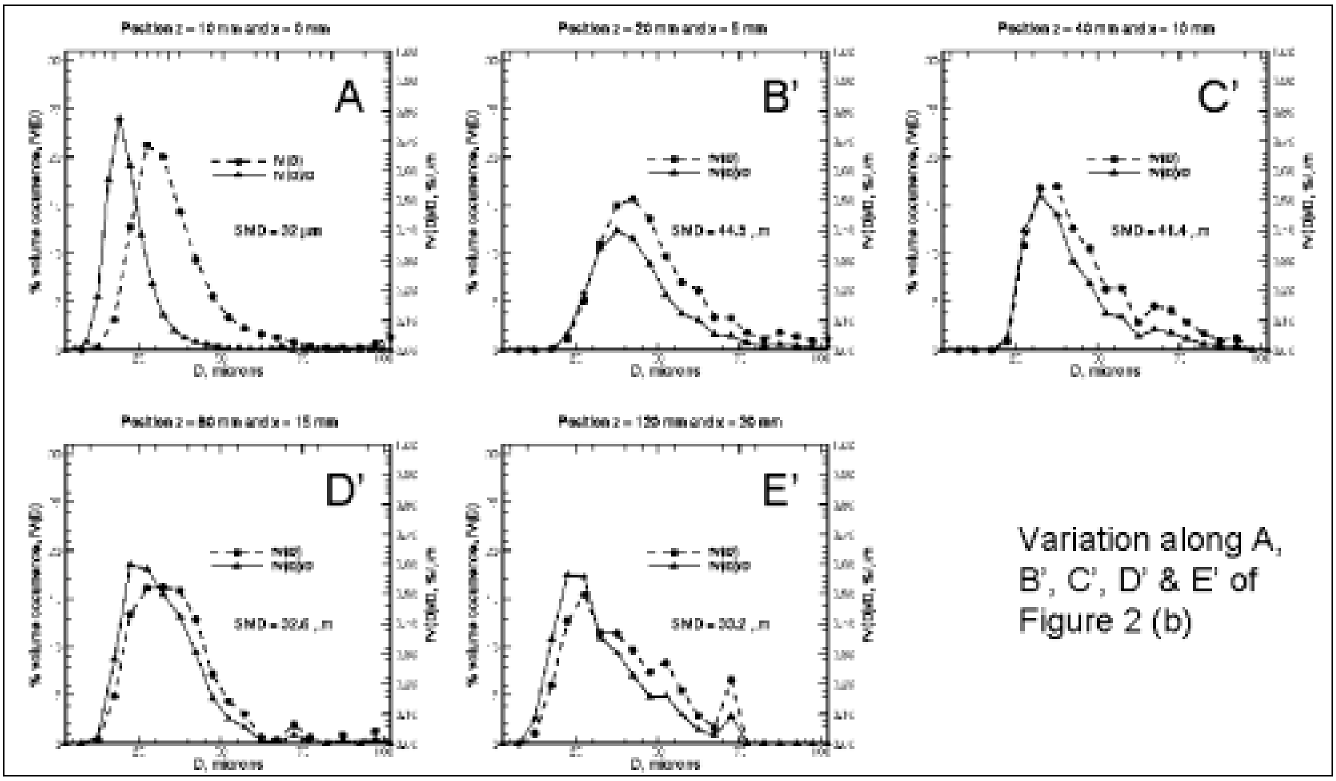


Figure 6: Variation of droplet volume distributions along the spray edge.

Validation of CFD predictions

There were considerable challenges when introducing modifications into the Spray3D CFD code while carrying out the necessary tests using the EDECAD generated sub-models. A few of the challenges included (i) difficulties associated with setting up the code so as to operate with off-axis injection, but using a cylindrical coordinate system. Here, it was required to switch between cylindrical and cartesian coordinates and vice versa. In addition, as the spray cone angle became larger than 30º, the lateral and front faces of the downstream sections of the injection cell were both wetted, which caused difficulties in the solution of the continuity and momenta equations in the injection cell; (ii) inverting the previous Spray3D injection cell settings and allow the higher momentum gas phase to accelerate the lower momentum liquid phase; and (iii) setting up one of the nozzles in order to allow blowing of air only.

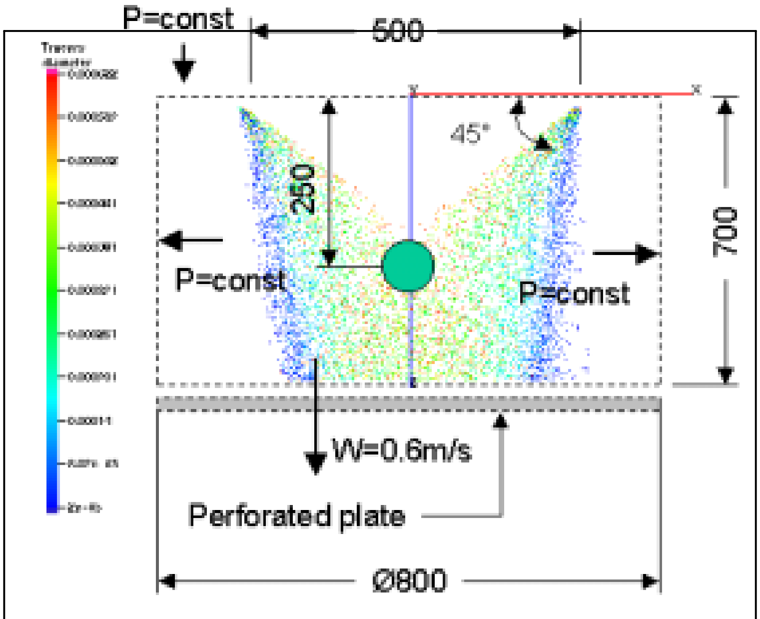
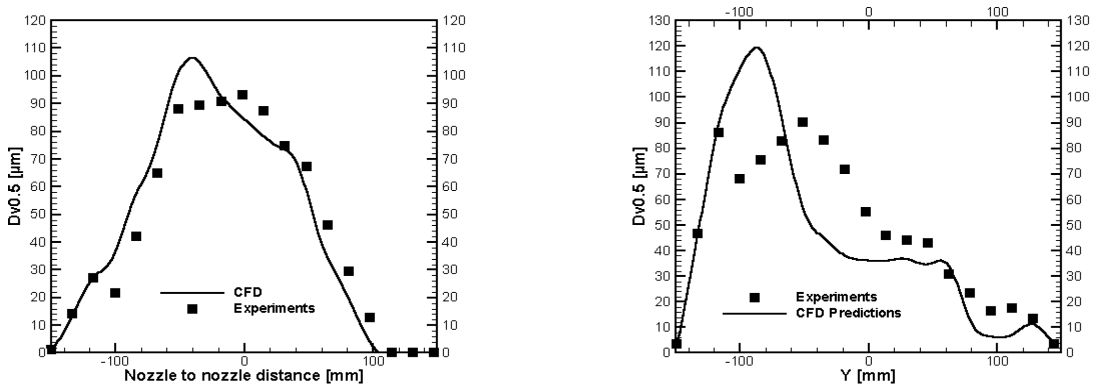


Figure 7: CFD problem set-up and droplet location by the time the flow had reached quasi-steady state for Test Case 1.

Figure 7 shows the CFD problem set-up and the droplet locations for a double spray (Test Case 1 in Table 2)). Depicted here is that the air suction through the bottom boundary causes the smaller droplets to travel along the lower edge of the spray cloud, while the larger ones travel towards the main zone of spray interaction where they may collide and eventualy result in coalescences. However, visualisation tests [4] as well as CFD predictions [11] with the conditions shown in Table 2 have shown very low collision rates in the main zone of spray interaction. In support of this observation, the experimental data and CFD data reported in Figures 8 (a) and (b) show little increase of the droplet volume median diameter ($D_{V0.5}$) between the levels 0 and -50 mm. The maximum value of the experimental $D_{V0.5}$ seems to stabilize at ≈ 90 µm, whereas that of CFD predictions shows a relative increase by only 8% between the two levels. A near axisymmetric distribution is observable at level zero while at the level -50 mm the experiments and CFD data both skew the maximum $D_{V0.5}$ to the left. The explanation for this effect is not obvious. It may be that the atomizers were not in fact identical, despite the analysis performed earlier to check this. There is some indication in Figure 8 (a) of skewness in the results. The CFD results indicate that in the subsequent convection of the drops further downstream, the larger drops are carried preferentially to the left, resulting in the observed skewness.



(a) Level 0 mm in Figure 3 (b) Level -50 mm in Figure 3

Figure 8: Validation of CFD predictions with experimental data for Test Case 1.

CONCLUSIONS

The development of two water sprays issued from twin-fluid atomizers pointing either vertically downwards or at convergent oblique angles have been investigated using air and liquid pressures of 1.5/1.5, 1.5/0.5 and 0.5/0.5 bar/bar. Selected measurement points with the sprays issuing vertically downwards were made along the spray axis and edges from which the individual nozzle performances were analysed. In the case of interacting oblique sprays, three measuement levels were defined with the reference level coplanar with the main zone of spray interaction. The individual analysis of the nozzles have shown pronounced coalescence in the first 20 mm downstrem of the nozzles exits, beyond which the drag forces combined with different regimes of particles interactions caused balanced effects between the coalescence and the break-up mechanisms. A reasonable correlation between experiments and CFD predictions was achieved for interacting oblique sprays consisting of cone angles of 30º, beyond which the CFD predictions of off-axis injection did not allow the use of cylindrical coordinate system. No significant coalescences were observed from either experiments or CFD predictions in the segment ranging from the main zone of spray interaction through to 50 mm downstream of this zone.

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NOMENCLATURE

D	Diameter, µm	U	Droplet induced axial gas velocity, m/s
$D_{V0.5}$	Droplet median diameter (diameter corresponding to 50% of cumulative volume distribution), µm	v	droplet impaction velocity, m/s
		x,y	Horizontal positions relative to nozzle axis, mm
fV(D)	Frequency volume distribution, %	z	Vertical position along the nozzle axis, mm
SMD	Sauter mean diameter, µm	We	Weber number

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