Radial Analysis of Fine Sprays Using Phase Doppler Anemometry (PDA)

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Abstract

A mobile fine spray unit, utilising a Spill Return Atomiser (SRA) has been developed for the purpose of decontamination within healthcare environments. The unit must be able to spray uniformly onto any given surface, providing 'mist like' coverage. Any uneven coating would jeopardise the efficiency of delivering the decontaminant fluid. Thus it is pertinent to understand and analyse the characteristics of the spray at various radial and downstream locations within the full cone patternation produced by the SRA.

PDA equipment was used to acquire Sauter Mean Diameter (SMD), droplet velocity and mass flux data at set radial positions across the spray and at various distances downstream of the atomiser. The results provided a comprehensive analysis of the spray and were used to determine the most effective coating distance to achieve 'mist like' coverage for delivering a decontaminant fluid.

Introduction

Hospital Acquires Infections (HAI's) are a major problem for worldwide. Inefficient cleanliness and hygiene practice has lead to a steep rise in infection rates, with subsequent increases in HAI associated illnesses and fatalities. MRSA (Methicillin Resistant Staphylococcus Aureus) has become synonymous with these problems as the appearance of organisms resistant to antibiotics has, in some cases lead to patient mortality. Other similar infections includes VRSA (Vancomycin Resistant Staphylococcus Aureus) and Clostridium Difficile. A mobile fine spray system has been developed [1-2], producing droplet sizes 15 μm< D_{32} <25 μm. This is achieved by providing an effective and efficient delivery system for specified disinfectant agents, which have been proven to kill infection-causing organisms. These disinfectants function by coming into contact with the organisms present on a surface, and remaining in contact for a certain length of time (typically minutes) so as to kill any harmful organism present. The efficiency of the disinfection process depends mostly upon the correct application of disinfection solution in providing maximum surface coverage, without any streaking. It is therefore important to gain a comprehensive understanding of the behaviour of droplets impacting on various surfaces and the occurrence of streaking.

The Spray Research Group cooperated with relevant industries in collaboration with a major international company [3] in developing a portable surface coating disinfection system, which uses a high-pressure, spill-return atomiser [4]. The main aim of this investigation is to utilise the spill-return atomiser, which can produce similar spray patterns and surface coverage to the existing ultrasonic system. Furthermore, despite the requirement of a mains power supply, neither compressed air canisters nor a pressurised liquid reservoir would be required. Thus the system will be more cost effective and it is as efficient as an ultrasonic system.

Previous experiments [5] with the existing Hughes Ultrasonic Atomiser (HUSA) system showed that it successfully coated surfaces (walls, furniture etc.) using flow rates of the order of 0.1 l/min and drop sizes with SMD<20 microns. Excessive flow rates or larger drop sizes could result in disproportionate localised surface wetting and poor coverage. If flow rates are too low, coating times will be excessive and the finer droplets may not penetrate to the required surface. An investigation of high-pressure swirl atomisers, with spill-return features, has shown that they are capable of producing both similar flow rates and drop sizes to ultrasonic atomisers at a supply pressure to the order of 10 MPa [6]. Without a spill return facility flow rates can be high, whilst its addition reduces flow rate with minimum effect on drop sizes, providing a better penetration and subsequently enhanced coverage. Moreover, the 'spilled-off' liquid is not wasted as it is returned to the liquid reservoir.

This paper provides the results of a number of spray performance tests which were carried out using the spill-return atomiser and focuses particularly upon the findings of the liquid's Sauter Mean Diameter (SMD), droplet velocity and mass flux data at set radial points across the spray, and at various distances downstream of the atomiser.

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Apparatus and Procedures

To obtain radial positions throughout the flow the atomiser mounting trolley is traversed horizontally relative to the beams with the transmission optics fixed. The radial positions were situated at 15mm intervals from the centre of the atomiser orifice. Taking into account the estimated cone angle of the spray, the outer boundaries on the left and right peripheries of the radial scale were set at 60mm. A vertical traverse was constructed in order to record radial plots with each atomiser configuration at various downstream distances (150, 300 mm, 500 mm and 700 mm).

To ensure precision, readings taken to the left of centre were given a minus (-) prefix, as shown in Figure 1 (a). Figure 1 (a) is a schematic diagram showing the radial positions used for measuring the velocity, SMD and liquid volume flux of the drops using PDA. Figure 1 (a) features a plan view of the mounting arrangement for the PDA optics, used to obtain the axial velocity for the flow.

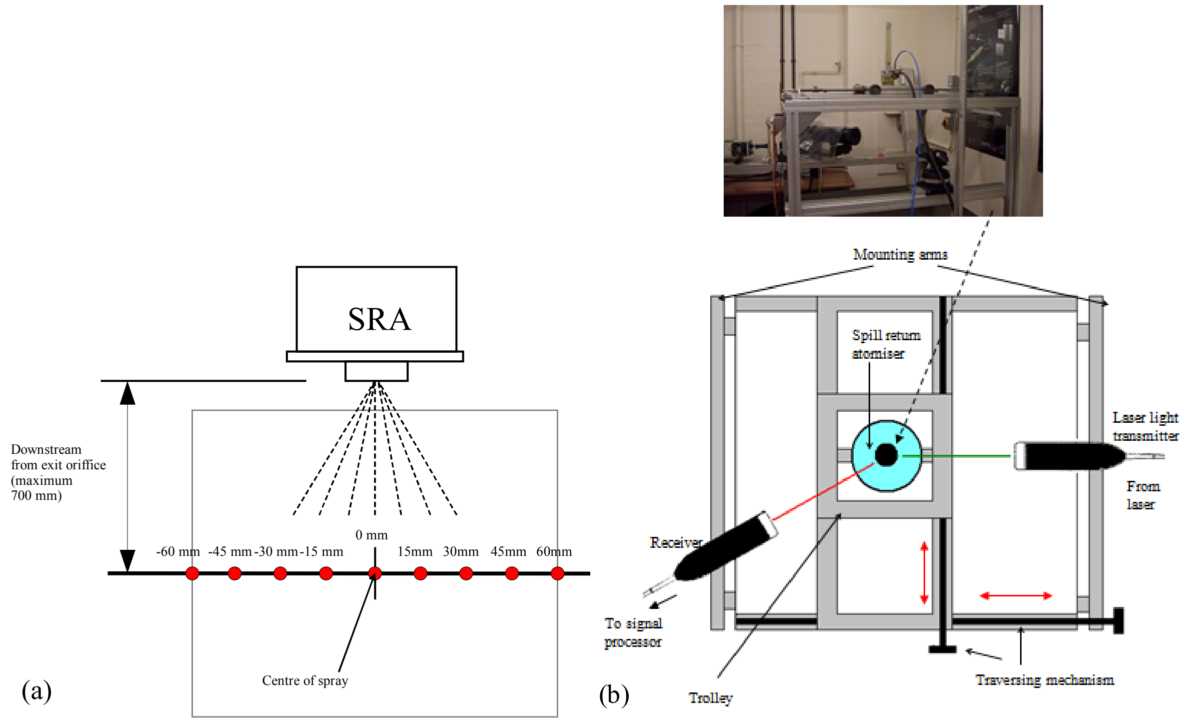


Figure 1. Schematic diagram of the radial positions used for measuring the velocity, SMD and liquid volume flux of the drops using PDA (a). Plan view of the mounting arrangement for the PDA optics (b)

During the experimental set-up both the transmitting and receiving optics were optimised for data acquisition. The only setting that can be adjusted on the transmitting optics is the power level of the laser. For duration of all the tests carried out, the maximum power setting was used which can have the effect of increasing the measuring volume.

The receiving optics were set to receive first order refraction from the particles, with the scattering angle being 72° which is the optimum forward refraction mode with reduced bias in the results due to the reflected light, thus ensuring good scattering light intensity levels (high signal to noise). In this mode the first order refraction has intensity levels twenty times greater than that due to reflected light, thus making it suitable for measuring small particles.

The focal length of the receiver was 310 mm. Decreasing the focal length of the receiver increases the sensitivity of the optics allowing the receiver to measure smaller particles. However there are trade-offs with reducing the focal length such as reducing the size of the measurement volume and reducing the maximum droplet diameter that can be measured. The set focal length of 310 mm was suitable for measuring the range of particles in the experiments.

Results and Discussion

Using the radial measurement positions presented in Figure 1(a), Microsoft Excel and 'D-Plot' software was used to produce 'radial plots' and 'Iso-contour plots' for the atomiser. Figures 2 - 4 show the corresponding 'radial plots', across a single plane. The radial plots are the direct measurements with no interpolation between positions which permit the variations of drop size, drop velocity and volume flux to be presented graphically at different downstream distances from the exit of the spill-return pressure swirl atomiser.

Figure 2 shows the distribution of mean drop velocity for different exit orifice and spill diameters, which coincidentally are reasonably axis-symmetric and this is a good confirmation of the validity of the PDA method for investigating patternation. The atomiser has its highest drop velocity near the centreline. There is also clear trend showing the reduction in the velocity of the drops as the downstream distance increases. This reinforces the comments made in a previous publication [4], on the characterisation of the spray with regards to high concentration of small drops and their deceleration downstream of the atomiser. Figure 3 also shows the PDA measurements of D_{32} (were D_{32} is the Sauter Mean Diameter, SMD) for the 0.3 exit orifice diameter, with 0.3 mm and 0.5 mm spill diameters at one value of supply pressure (9 MPa). The increase in drop diameter caused by increase in spill diameter can be seen in Figure 3. However the effect on the droplet diameter shown by the Malvern Mastersizer-X, in a related publication [4], is smaller than that found with the PDA. For sprays produced by the 0.3 mm exit orifice at 9 MPa, the PDA typically shows D_{32} values between 22 µm and 30 µm (for the 0.3 mm and 0.5 mm spill diameter) whereas the results acquired using the Malvern Mastersizer-X show that the drop diameters are between 18 µm and 20 µm at the same position (150 mm) from the exit of the orifice of the SRA.

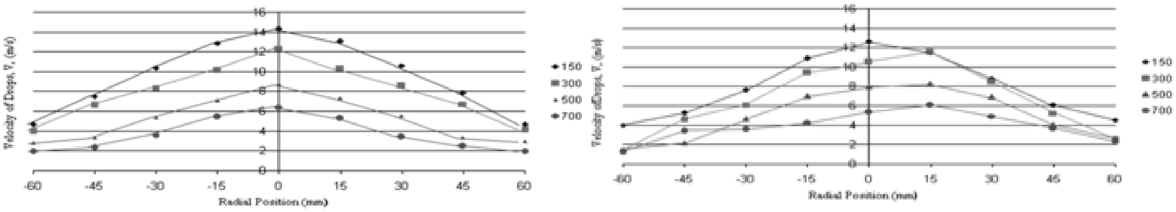
There are several effects that may contribute to this difference as the PDA tends to be biased towards measuring the larger drops (which effectively have a larger measurement volume than smaller drops) than the Malvern. Moreover, where smaller drops are moving with the gas velocity, but the larger drops penetrate more quickly and with "slip", the longer residence time of the smaller drops in the Malvern laser beam, causes a biasing towards these smaller drops. This is known as the "velocity bias effect". As one moves downstream, the distribution of D_{32} becomes somewhat homogenous across the spray, after an initial region where the smaller drops are concentrated towards the central region of the spray.

The error margins for were calculated as 0.32 % for velocity data and 0.51 % for the SMD (D_{32}) data. Thus, the clarity and accuracy of the data collected using the Dantec Particle Analyser is reasonably acceptable.

Figure 3 shows the variation of SMD, D_{32}, (µm). Drop size is quite homogeneous across the spray with smaller drops appearing to be at 150 mm downstream distance from the atomiser exit and with the larger drops to be present as at larger downstream distances (i.e. 700 mm). This is due to deceleration of smaller drops, coalescences and vaproisation. Compared to the data obtained by Malvern Mastersizer-X at downstream distance of 70 mm to 250 mm, the drop sizes lie within the 12 µm to 25 µm whereas with PDA the values are approximately 22 µm to 26 µm for the same exit orifice and spill diameter sizes (i.e. exit orifice 0.3 mm and spill 0.5 mm), as shown in Figure 3. Again, this is acceptable since Malvern Mastersizer –X is the rapid measurement of the global characteristics of the spray whereas the PDA simultaneously measures the drop size, velocity, mass flux and concentration of the drops volumetrically in the spray, and averages them out within that volume. Moreover, there are a number of difficulties in taking PDA measurements in dense spray, which becomes particularly apparent as the measurement taken at different downstream distances. There are regions that a number of droplets may occupy the measuring volume at the same time, leading to unprocessable overlapping, resulting in low validation rates. To reduce the occurrence of "multiple occupancy" and increase the light intensity, the size of the measuring volume can be reduced. However with this there are associated problems. By decreasing the control volume this will also reduce the number of fringes, therefore the amount of light scattered by each droplet will be smaller, resulting in a weaker burst signal which may cause the equipment to have difficulty in processing the signal to determine the Doppler frequency.

Even with a small control volume, "multiple occupancy" could still occur, for example having a large and small droplet in the control volume simultaneously. The signal from the larger one will be dominant and may be the only one successfully measured. Thus larger drops are obtained here too, using PDA compared to the Malvern Mastersizer-X as shown in a previous publication [4].

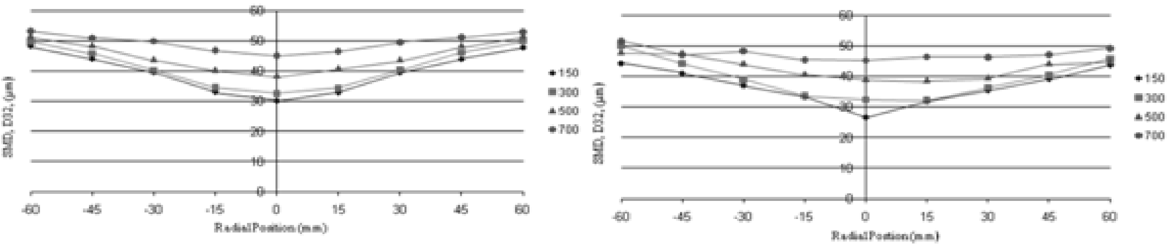
Figure 4 shows the drop volume flux at different radial positions across the sprays and various downstream distances. The liquid volume flux is axis-symmetric at the centre of the spray for different exit orifice and spill diameters. As can be seen from Figure 4, except for the exit orifice of 0.3 mm with spill of 0.5 mm and 0.3 mm diameters, at maximum downstream distance of 700 mm at the periphery of the spray the corresponding flux tends to be in negative region which is predominantly due to the gas recirculation. This is shown more clearly on the 'iso-contour plots' and on the various spray images which are illustrated in the following paragraph.



Diameters: exit orifice 0.3mm and spill 0.5mm

Diameters: exit orifice 0.5mm and spill 0.3mm

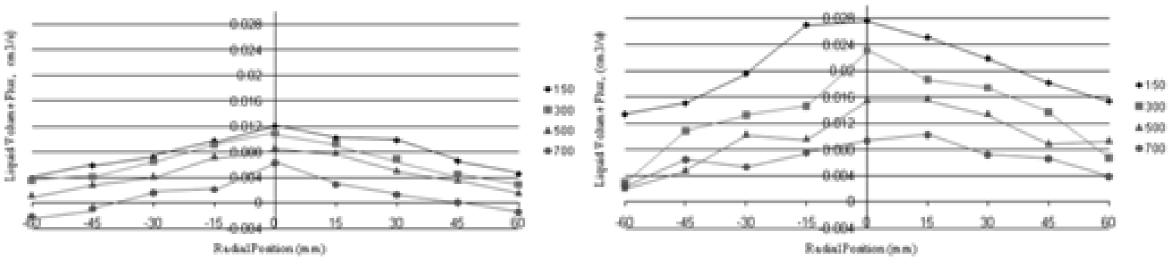
Figure 2. Variation of mean drop velocity at different radial positions for various sizes of the exit orifice and spill diameters, supply pressure 9 MPa



Diameters: exit orifice 0.3mm and spill 0.5mm

Diameters: exit orifice 0.5mm, spill 0.3mm

Figure 3. Variation of SMD at various radial positions for varied exit orifice and spill diameters, supply pressure 9 MPa



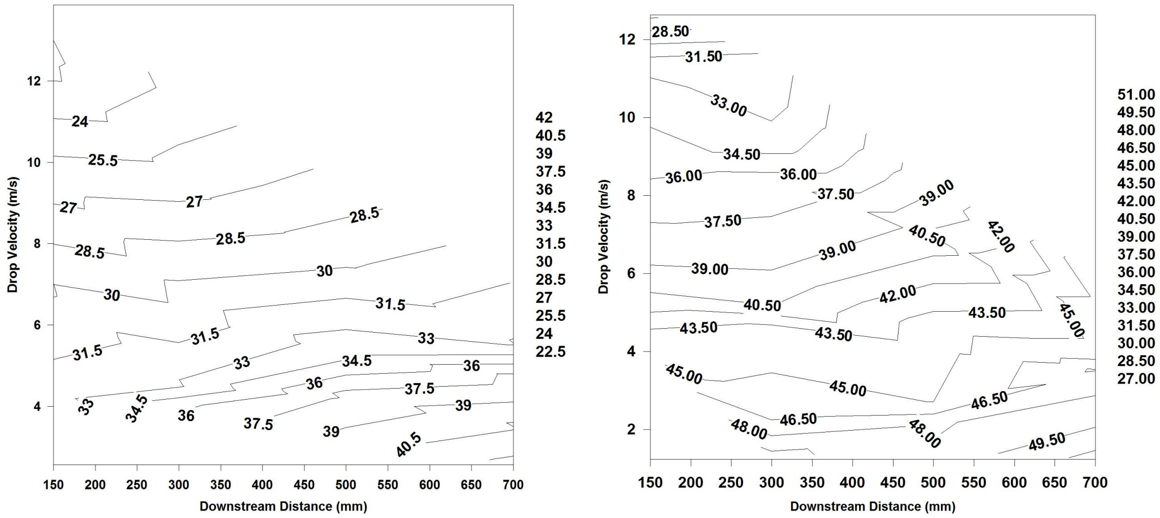
Diameters: exit orifice 0.3mm, spill 0.5mm

Diameters: exit orifice 0.5mm, spill 0.3mm

Figure 4. Variation of liquid mass flux at various radial positions for different exit orifice and spill sizes, supply pressure 9 MPa

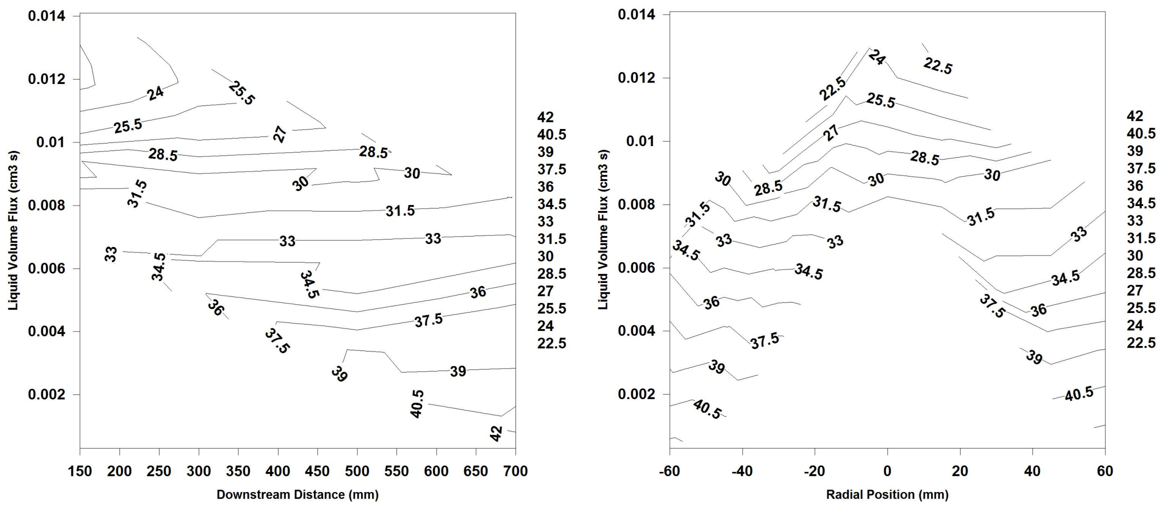
It is interesting to convert the data shown in Figures 2 - 4 to give "iso-value" contour plots, therefore "D-plot" interpolating software has been used for this purpose.

Figures 5 and 6 show the iso-drop velocity and iso-drop volume flux contours respectively, for the drops in the sprays from the 0.3 orifice at 90 bar, and with the 0.3 mm and 0.5 mm diameter spill orifices. The contours are shown in the plane of the measurements, i.e. a vertical plane through the axis of each spray. The symmetry of each spray is evident (see Figure 6). It is interesting that, although the volume flux reduces more rapidly moving away from the atomiser, for the larger (0.5 mm) spill orifice case, the drop velocity field is relatively insensitive to the spill diameter. It is emphasised that the drop velocity presented here is the average velocity for all drops detected by the PDA, in a period of typically 5-20 seconds. Inevitably there are always many more small (i.e. sub-10 µm) than larger (say above 20 µm) drops, even though the latter contribute as much to the total volume flux of drops. Thus this average drop velocity is heavily biased towards the smallest drops and is thus likely to be very representative of the local mean gas velocity, except in the first few centimetres of spray where "slip" exists, even for those small drops.

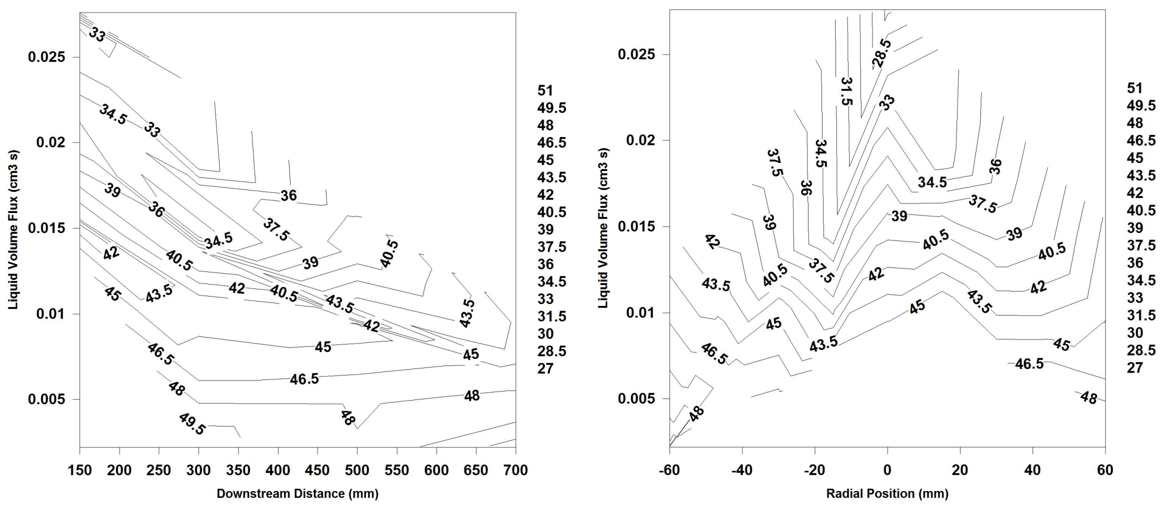


Diameters: exit orifice 0.3 mm, Spill 0.5 mm
Diameters: exit orifice 0.5mm, Spill 0.3 mm

Figure 5. Iso-contour plots of drop velocity, downstream distance and SMD, supply pressure 9 MPa



Diameters: exit orifice 0.3 mm, spill 0.5 mm



Diameters: exit orifice 0.5 mm, spill 0.3 mm

Figure 6. 'Iso-contour plot' of liquid volume flux and SMD at different downstream distances and radial positions across the sprays. Supply pressure 9 MPa

By combining radial graphs with iso-contour plots, a clear and comprehensive impression of a full radial analysis of the spray is attained.

Conclusions and Future Work

The processing of the PDA data from radial positions across the spray and at different downstream distances, provided basic understanding with regards to main spray properties (i.e. drop velocity, SMD and drop liquid volume flux) and thus the spray patternation across a single radial plane. The examination of the experimental findings together with the iso-contours, show that the structure of the spray is closely axis-symmetric and there is relative uniformity across the spray, with regard to velocity and SMD, although drop volume flux across the sprays does vary for different geometrical design such as exit orifice diameter and the spill sizes. The atomiser has a maximum velocity along the centreline and as expected this is the region of lowest SMD.

Future work will include further measurements at different radial positions and downstream distances, together with vertical and diagonal locations across the sprays. This would create a fully comprehensive view of the spray and its characteristics at various given points within full-cone patternation produced by the SRA. Future work will also include the use of Computational Fluid Dynamics (CFD) to further validate the experimental results.

Nomenclature

v droplet velocity
D_{32} Sauter Mean Diameter

Acronyms
SMD Sauter Mean Diameter
CFD Computational Fluid Dynamics
PDA Phase Doppler Anemometry
HAI Hospital Acquired Infection
MRSA Methicillin Resistant Staphylococcus Aureus
VRSA Vancomycin Resistant Staphylococcus Aureus

References

[1] Nasr G.G., and Yule A.J., Spray device, Patent, WO 2008/075063 A1, 26 June 2008
[2] Nasr G.G., Yule A.J., Lloyd S.E., ‘The Characterisation of the Spray from a New Design of a Spill Return Swirl Atomiser’, ILASS-Europe 2007.
[3] www.hughes-safety-showers.co.uk (accessed Sept. 2009)
[4] Nasr G.G., Yule A.J., Stewart J.A., Whitehead A., Hughes T., A New fine spray spill-return swirl atomiser, Journal of Mechanical Engineering Science, Proceedings of Institution of Mechanical Engineers Part C, submitted Nov. 2009.
[5] Burby, M.L and Nasr, G.G. ‘Spray characterisation and performance tests for an ultrasonic atomizer in the decontamination process’, ICLASS, Kyoto, Japan, Aug.27-Sept.1, 2006.
[6] Stewart J.A., Nasr G.G., M.L.Burby, Fine Spray for Disinfection Purposes within Healthcare Environments , 11th Triennial International Annual Conference on Liquid Atomization and Spray Systems, ICLASS, Vail, Colorado, USA, July 2009