A NOVEL SPRAY CONFINEMENT TECHNIQUE FOR MEDICAL SPRAYS: DETAILED INVESTIGATIVE MEASUREMENTS OF SIX GEOMETRICAL CONFIGURATIONS

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Abstract
An axi-symmetric confinement chamber has been designed to control spray characteristics at the exit of a mouthpiece for new generation MDI devices. The design philosophy was to introduce the air in two stages, with variation in the two flow rates and some flexibility in geometry, such that the effect on the outlet spray could be assessed systematically. A twin fluid air blast micro-atomizer was used with detailed investigations of the sprays both under free spray conditions, and also within six mouthpiece configurations. In order to model realistic lung intake conditions pulsed sprays with a tidal breathing apparatus have been used. The Star-CD CFD code is used to assess it usefulness as a design tool for mouthpiece configurations.

Nomenclature

D_{32}	Sauter mean diameter
U	Streamwise component of the velocity

Introduction

Inhalation therapy has been used as a means of treating conditions of the upper lung passages. Asthma, for example, is typically treated either by using a spray of fine droplets of liquid medicine generated by a medical nebulizer or with a medicinal aerosol generated by a metered dose inhaler (pMDI). The spray or aerosol is inhaled by the patient causing quick deposition of the medication in the area of affliction; the upper airways of the lung. Other medications are used to treat deeper regions of the lung such as Pentamidine, which is used as a prophylactic treatment of the Pneumocystis Pneumonia often associated with AIDS. Symptomatic treatments of Chronic Obstructive Pulmonary Diseases are another common use of inhaled medications. Medical research into the use of a host of new inhaled medications has caused an increased interest in optimizing the performance of the devices used to deliver them, [1]. Indeed, in the future, inhaled aerosols are expected to be used for vaccinations, pain management and systemic treatment of illnesses that are currently treated by other methods, [2].

With explosive growth of inhaled pharmaceutical aerosols, comes the need for research and development, however this field is interdisciplinary requiring knowledge in a diverse range of subjects including aerosol mechanics, fluid mechanics, transport phenomena, interfacial science, pharmaceutics, physical chemistry, respiratory physiology and anatomy and indeed pulmonology. Not until recently has the research community witnessed a full collaboration between scientists and engineers in this field of research. The work reported here has been conducted to aid pharmaceutical delivery. It is however, approached from the point of view of engineers, meaning that it tackles fluid mechanical aspects of the flow. Its objective is to assess methods of controlling the quality of the spray exiting an MDI mouthpiece, including radial distribution of drop size, velocity and mass flux, by controlling the way in which air is introduced into a spray confinement chamber upstream of the mouthpiece.

Experimental apparatus, geometrical configurations and procedure

This confinement chamber, as shown in solid black in figure 1, has two-stages of induced air. All other parts of the apparatus shown in figure 1 are for control of inlet air and to permit measurement of the spray leaving the confinement chamber. The primary inlet air surrounds the spray at the chamber inlet, and the second stage is introduced at an annular inlet which was designed to set up a wall jet to help deflect the spray from wall impingement. The annulus gap could be controlled. The primary air flow can be controlled by using the two concentric tubes that act as a sleeve valve. These can be rotated to vary the relative positions of orifice arrays in

each tube wall. The atomizer used has been described by the authors [3], and uses 2300 mL/min air with water flow rate 2.2 mL/min. The different spray configurations used geometrical variations which also produced flow variations. These cases, as illustrated in Fig. 2, are as follows, where inlet area refers to the total open area of the holes of the primary air plenum, or the inlet area of the secondary inlet.

Case 1: Both inlets open but the effective inlet areas are not equal. Primary inlet orifices total area (A_1) is 1257mm^2. Secondary annular inlet area (A_2) is 251mm^2.

Case 2: As case 1 but secondary inlet closed. (A_1 =1257mm^2, A_2=0)

Case 3: As case 1 but primary inlet closed.

Case 4: As case 1 but inlet areas are equal. (A_1= A_2=1257mm^2)

Case 5: As case 1 but atomizer is moved 10mm downstream.

Case 6: As case 1 with a streamlined moulding constructed around the nozzle, Figure 2b.

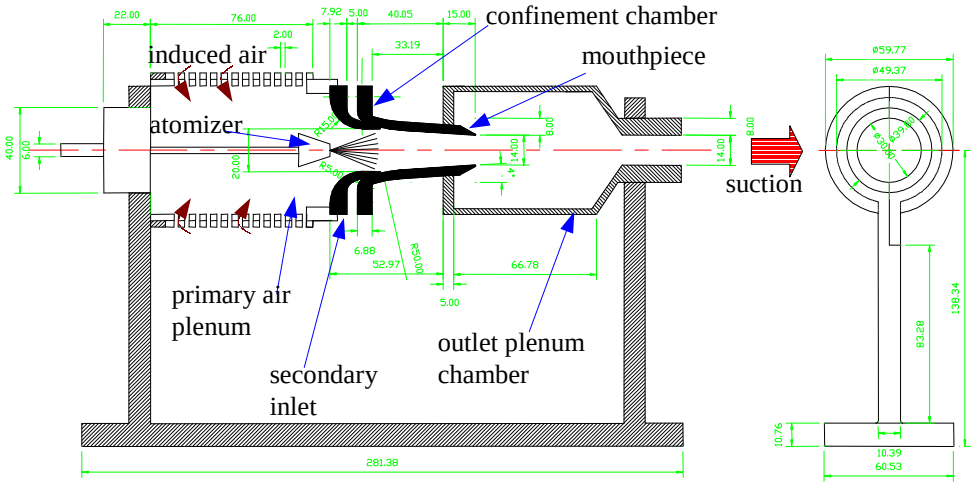

Figure 1. Cross section through the confinement chamber with primary inlet control and outlet chamber (plenum chamber for PDA measurements).

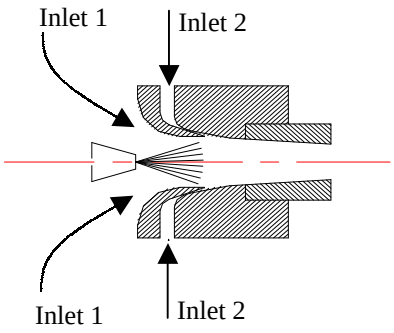

Figure 2a. Schematic diagram illustrating spray cases 1-5

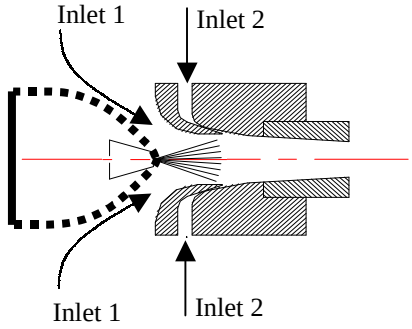

Figure 2b. Schematic diagram illustrating spray case 6

For realistic breath intake modelling, time varying suction was used. A vacuum pump operating at a constant speed was utilised. The air inlet to the pump can take either of two paths, one via the confinement chamber and the other via an orifice which is opened and closed by a slide valve. When this valve is closed, all of the air is pulled through the test piece but when it is fully open at least 95% of the air flow is pulled through this valve from ambient surroundings. The slide valve consists of a stationary slot orifice, with a triangular end, and a moving circular orifice. A variable speed stepper motor drives the valve slide. The system was set up to give a 2 sec air intake period, which had cosine-shaped flow rate versus time variation for opening and closing, each with duration 0.5 sec, and a one second constant flow period. There was a quiescent period of 12 sec between each air intake period. The water was supplied to the atomizer via an on/off valve, triggered using a photodetector system on the stepper motor. For the tests reported here, the water supply was switched on when each intake “breath” started. The atomizing air flow rate was not pulsed. Each of the six spray configurations

was investigated using three peak air intake flow rates; 30, 60 and 90 L/min. Thus codes such as "Case 1(60)" are used.

Results and Discussion

A Dantec PDA system was used to obtain radial traverses across the outlet of the mouthpiece, with the beams being introduced in to the outlet plenum (Fig. 1) and using 30^{o} collection angle. Examination of the PDA outlet data indicated that the use of a 2s data capture time, was insufficient as the end of the spray pulse was being clipped. The original 2s spray duration is stretched as the spray proceeds through the mouthpiece. This is shown in Figure 3, for Case 1 (60), in which a single spray pulse is injected, but a multiple series of inhalation breaths is used. Figure 3 shows the velocity data as a scatter plot, while figure 4 shows the drop size scatter for the same pulse. It is seen that the total outlet spray duration is several seconds. It can also be seen that there are some smaller droplets remaining in the chamber after the single spray pulse, and that these are marking the airflow velocity during the subsequent inhalation. The existence of a non-zero air velocity between the inhalation periods is caused by, (a) the method of controlling the airflow by using a bypass-inlet system, and (b) the use of a continuous atomizing air flow, (c) an inertia effect with a slight flow through the suction chamber continuing after suction was switched off. It was found that more than 90% of the droplets are detected during a 4s interval, and this, plus the time interval between 'switch on' and the spray pulse arrival, was used as the acquisition time in subsequent tests. Also, 4s was used as the averaging time for the data presented in subsequent figures, for the 30L/min, 60L/min and 90 L/min cases. Figure 4 shows that the droplets remaining in the plenum are few and are mainly of smaller diameters, indicating that they are caught up in recirculation of the flow in the chamber.

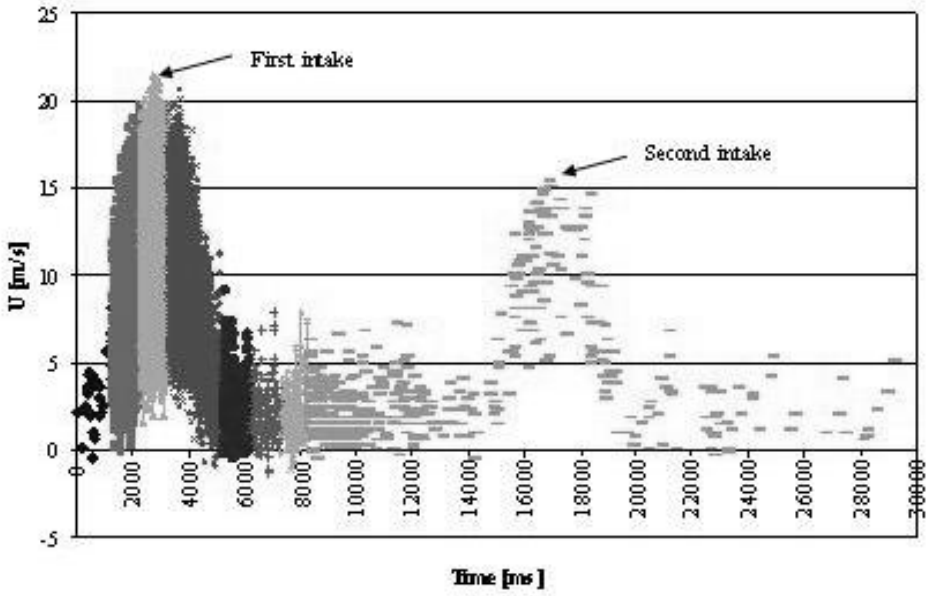

Figure 3. The behaviour of a single confined spray pulse (case 1 at 60 L/min) at the centreline and 5mm downstream of the mouthpiece outlet.

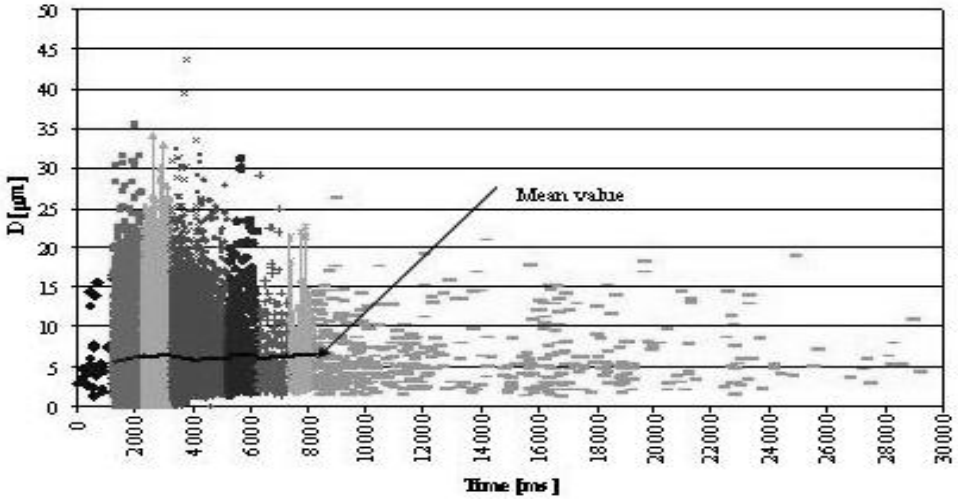

Figure 4. Droplet scatter for the same pulse shown in fig. 3, the first 7 seconds are shown in different colours.

Figures 5-6 show the time averaged mean droplet velocity and Sauter Mean Diameter (D_{32}) radial distributions, for the three inhalation flow rates, taken at 5mm downstream of the outlet. It can be seen that at first sight there are no dramatic differences between the cases. Velocity distributions for the different flow rates peak at the centre, but the peak tends to be flatter for lower suctions, this is true for all spray conditions, with one exception being spray 4. The closure of the primary inlet for case 3 caused a very high velocity jet to emanate from the secondary annular inlet. This caused the flow inside the chamber to become very chaotic and exit with a relatively low and flat velocity distribution but with dense mist like pattern. For case 6 velocities are somewhat lower and flatter than for the rest of the cases. The SMD distribution is more or less uniform for all spray cases. However, values are observed, for the 90 case, to drop at the edges of the mouthpiece. Negative velocities indicate recirculation of small drops in the outlet plenum.

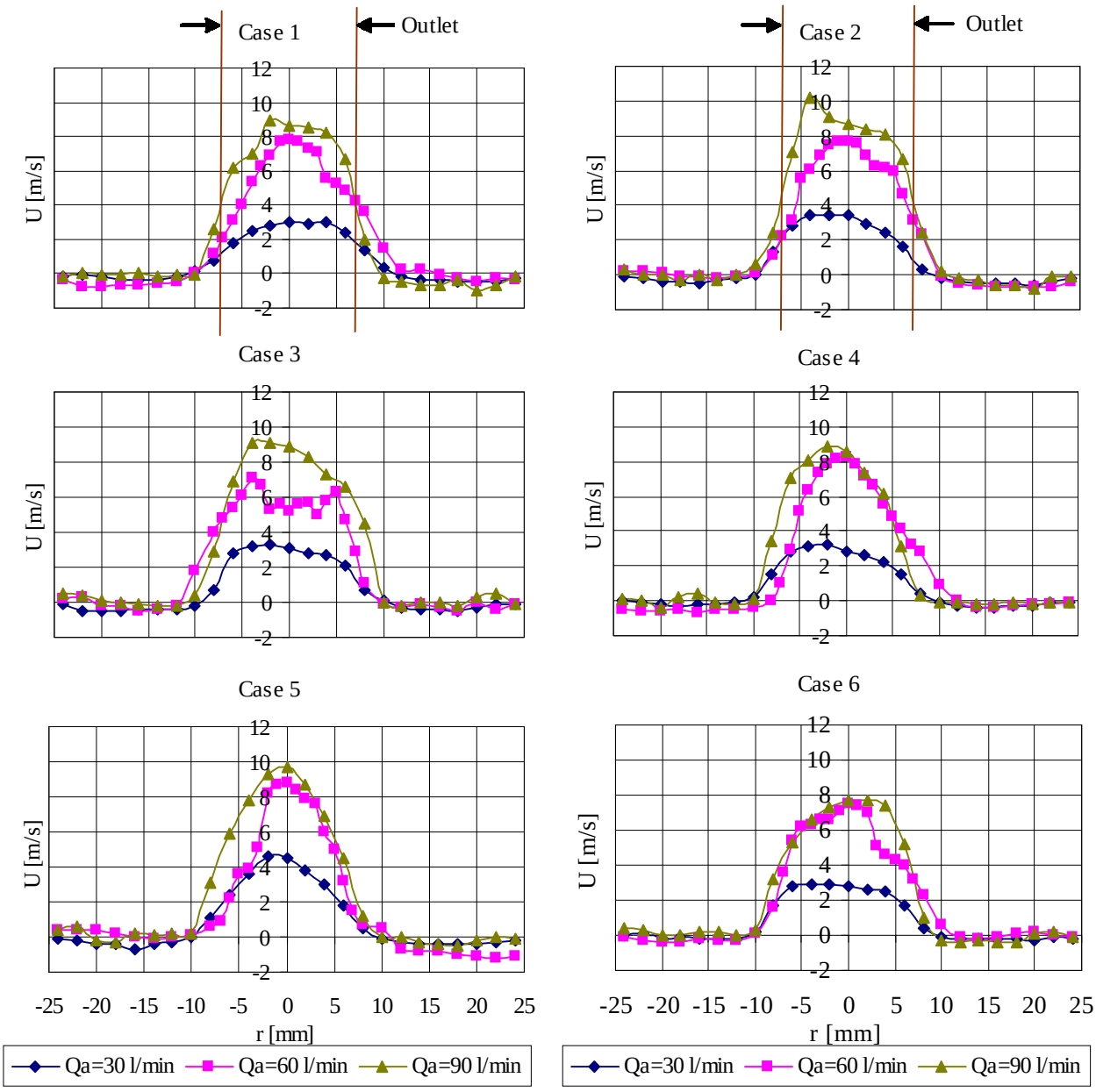

Figure 5. The profiles of the mean streamwise component of the velocity for the 3 suction cases (30,60,90 L/min)

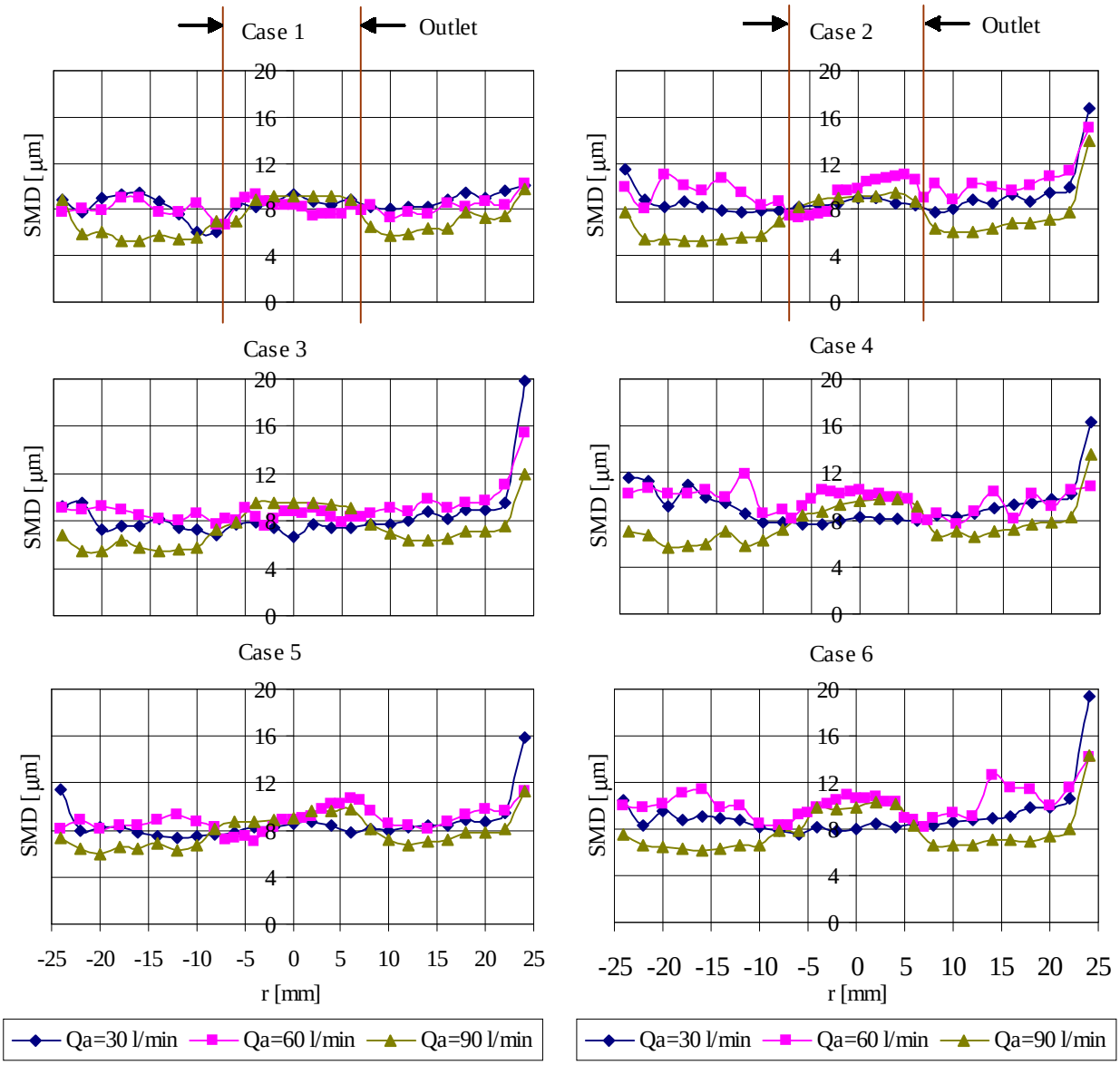

Figure 6. Profiles of the SMD for the 3 suction cases (30,60,90 L/min)

	Spray 1	Spray 2	Spray 3	Spray 4	Spray 5	Spray 6
Droplet percentage by volume leaving mouthpiece	45.7	44.9	40.7	43.1	47.6	42.4

Table 1. Droplet % leaving mouthpiece

Comparing the total volume of droplets collected by a Twin Impinger [4] with the liquid injected provided data shown in Table 1. It is seen that more than half the sprays are deposited inside the confinement chamber and mouthpiece, however the deposited droplets tend to be larger and non-inhalable. PDA measurements were also made across the chamber at 10mm downstream of the secondary inlet, and examples of the velocity profiles are shown in figure 7. These profiles peak at the centre of the chamber with much higher velocity than 50 mm downstream at the exit of the mouthpiece. There is an indication of reverse flow near the wall region, hence recirculation. There are no major differences between the three cases but one can observe that case 3 peaks with relatively lower velocity than the other two cases. To better aid understanding the nature of the flow inside the chamber the Star-CD CFD code was used to predict the first three spray cases. Figure 8 shows the velocity vector field inside the chamber near the atomizer region, of spray cases 1 and 3. The high recirculation region is quite evident near the atomizer and secondary inlet for case 3. This is responsible for the relative low efficiency of this spray case.

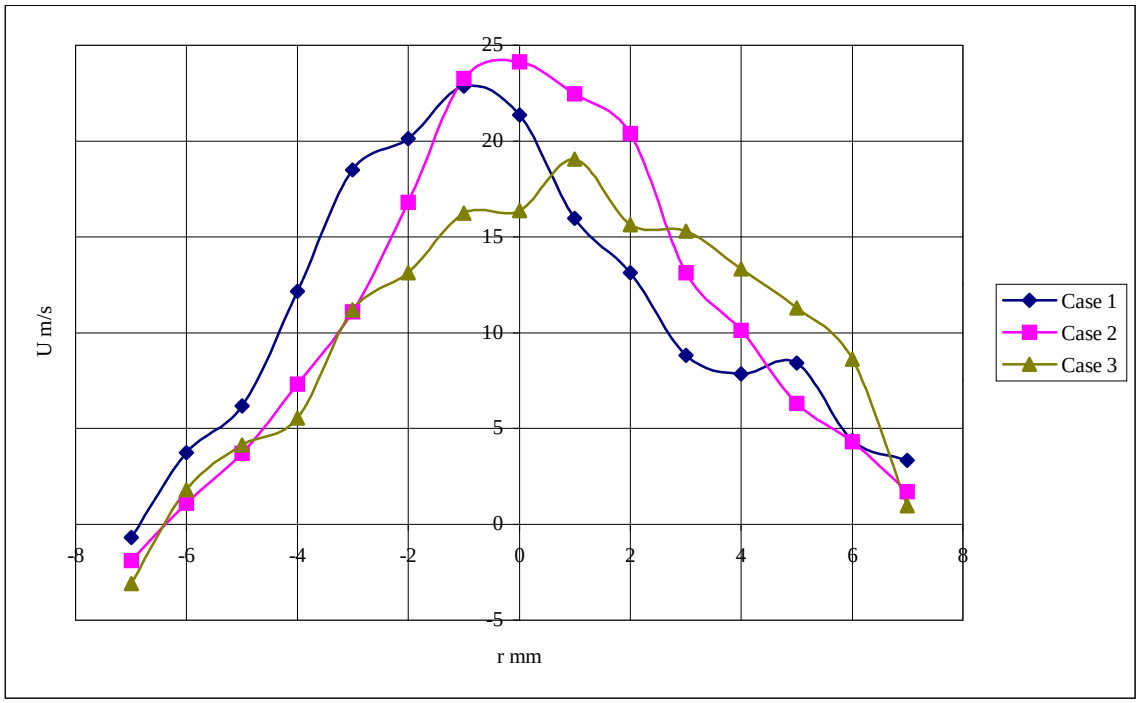

Figure 7. Time averaged axial velocity in chamber, 60 L/min, cases 1, 2 and 3.

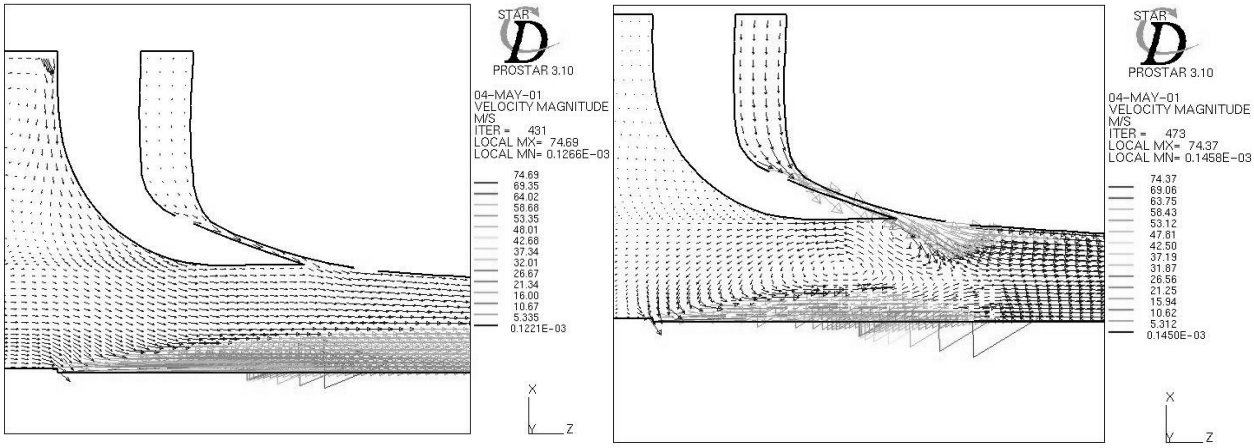

Figure 8. Near nozzle velocity vector prediction for spray case 1 (left) and case 3 (right), with atomizing air flow rate of 2.3 L/min and a suction flow of 60l/min

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The CFD predictions were made by Dr Simon Walmsley.

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