ILASS 2008
Sep. 8-10, Como Lake, Italy

Paper ID ILASS08-1-5

Structure of High Throughput, Dense Pressure Atomized Elliptical Sprays under High Ambient Air Pressure Conditions

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ABSTRACT

The findings of an experimental study undertaken over a range of ambient air pressures (1 to 14 bars), water flow rates (20 to 90 g/s maximum) and nozzle pressure drops (10 to 50 bar) are reported in this paper. Mie scattering based pulsed, laser sheet imaging technique was deployed to define changes in spray shape, cone angle and trajectories while detailed drop sizes and velocities were acquired using phase Doppler interferometry. This study, the first of its kind on fan jet atomizers operating under such a challenging combination of high liquid throughputs under high air density conditions, was aimed at acquiring key insights of fundamental importance regarding the detailed structure of elliptically shaped fan sprays. Cone angle of fan sprays is observed to be appreciably less sensitive to ambient air density changes relative to swirl atomized conical sprays i.e. the extent of cone angle reduction is much reduced. The mean drop sizes undergo an initial reduction with an increase in air density from 1 to 6 bars. However continuing increase in air density from 6 to 14 bars yields a subsequent increase in the mean drop sizes. Such behaviour suggests broad parallels in respect of the underlying mechanisms governing the disintegration of the liquid sheet at higher air densities for fan sprays and their swirl atomized conical counterparts.

INTRODUCTION

Pressure atomized sprays of the swirling, conical and elliptical, fan shape are used in many industrial and process applications. Amongst the large array of possible practical applications, arguably the most challenging ones relate to power generation and air transportation. This is because in these applications the air-fuel mixture preparation process is widely acknowledged to play a pivotal role in all efforts directed at achieving satisfactory combustion-emissions performance in order to eradicate (or at least minimise) the threats to our environment. The generation of finely atomized sprays with appropriately tailored spatial distribution to yield desired degree of local fuel-air mixing is now of paramount importance over the entire low-to-high ambient air pressure operational envelope of the power generation plant. Modern gas turbine engines feature fully annular combustion chamber design geometries. Whilst this yields appreciably superior combustor aerodynamics, nevertheless it presents a formidable challenge in respect of attaining improved local fuel-air mixing using traditional, circularly shaped liquid sprays. In principle elliptically shaped fuel sprays could offer better localised mixing with air together with wider spatial spread relative to their conically shaped spray counterparts. Wider spatial dispersion of fan sprays could also afford a potential reduction in the number of fuel injectors per engine set – thus providing a useful cost saving at the outset as well as during the engine's subsequent operational life through lower overhaul-maintenance effort. Intensive research and development effort is being devoted to tailoring the fuel injector technology to find solutions to the present and anticipated future challenges in general [1-5].

In general our understanding of the detailed structure of fan sprays is far from satisfactory. This is especially so from the standpoint of being able to ascertain their effectiveness in relation to the power generation application. The open literature mainly contains reports concerning their use in agricultural, spray painting and other industrial applications – all of them under atmospheric pressure conditions however [6-8]. The broad aim in some of the applications has been to generate a spray plume that enables the delivery and deposition of droplets to a target crop(s) or a surface to be spray painted with minimal loss and wastage of droplets through drift to adjoining areas. Often the droplet property measurements have been carried out at long distances away from the injector exit while for the modern, gas turbine power plant the data is required in the near-field nozzle regions wherein the combustion process is initiated and sustained. Moreover it also necessitates experimentation over a wide range of ambient air density conditions to understand the nature and scale of detailed changes that the spray structure undergoes in an operational sense. Over the years extensive behavioural studies along these lines have been conducted by the Cranfield group on conical, pressure-swirl and airblast atomizers, both on low- and high-shear types – see references 2-5 for example. The purpose of this paper is to extend this data base to embrace the elliptical, fan spray behaviour under comparable high air density conditions.

EXPERIMENTAL DETAILS

The schematic of the high ambient air pressure spray research facility is presented in Fig. 1 and it has been used extensively in a wide range of sponsored spray research projects [2-5]. Its main component is a large cylindrical vessel conforming to British Standards specification 5500 and it is fed

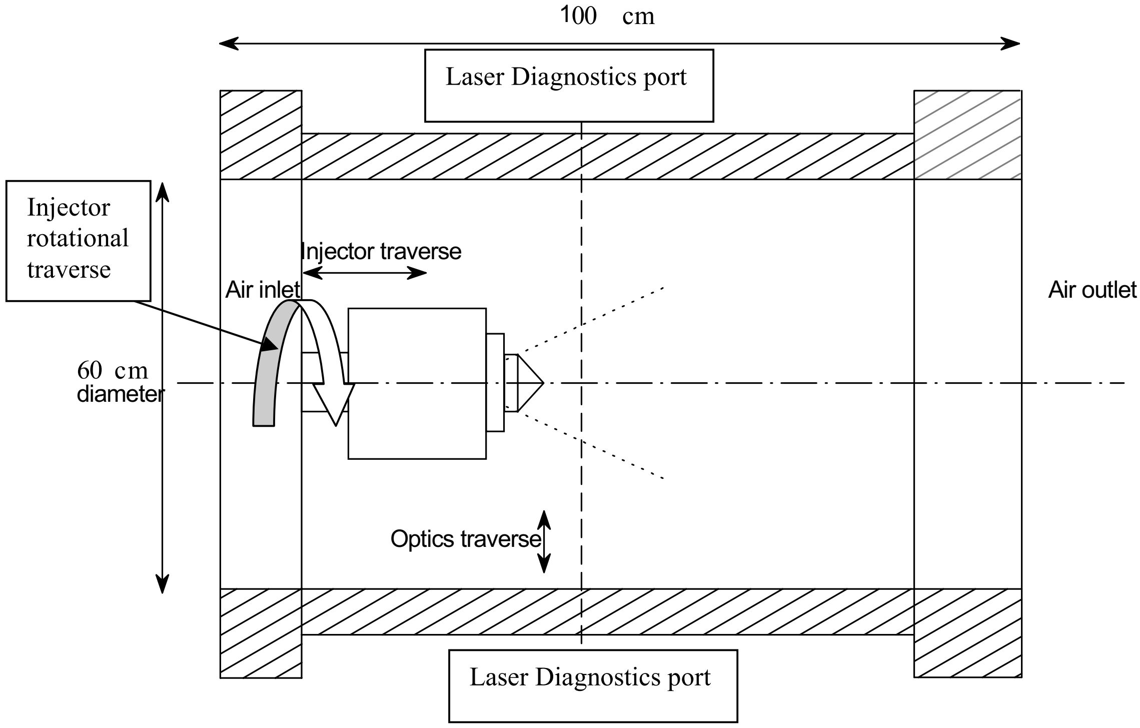

Fig. 1 Schematic of high ambient pressure spray research facility

with high-pressure air at near-ambient temperature to achieve the desired level of pressure. The compressor plant servicing the spray facility is capable of delivering a mass flow of 4 kilograms / second of air at pressures up to ~ 24 bars. This enables large scale research studies of practical – industrial relevance for a wide variety of spray application sectors to be accommodated with comparative ease. The atomizer is located at one end of the vessel and is arranged to spray horizontally along its major axis. Four large quartz windows provide necessary optical access for a range of non-intrusive diagnostics including phase-Doppler interferometry and laser sheet imaging. Each of these windows is provided with an effective purge feed of high velocity air to prevent fuel deposition without perturbing the test spray. The aim here is to achieve a clean, mist free test section in order to realise good quality, degradation free measurements.

Spraying Systems flat fan spray nozzles (8003 TC & 8004 TC) with elliptical orifices formed by the intersection of a 'V' groove with a hemispherical cavity were used for the experiments. The nozzle flow numbers in m^2, equivalent orifice diameters in mm, and spray cone widths in cm at 30 cm from exit as per the manufacturers catalogue are (1.131E-06 & 1.508E-06); (1.1 & 1.3), and (48 & 48) respectively. Water was used as the test fluid throughout all the experiments; the flow rate and nozzle differential pressures being varied over a wide range (20 to 90 g/s and 10 to 50 bar, respectively) whereas the ambient air pressure variation within the pressure vessel covered 1 to 14 bar range. Fluid pressure and mass flow metering etc equipment was the subject of appropriate calibration checks.

Spatially resolved droplet sizes and velocities were measured using a single-velocity component phase-Doppler system manufactured by Aerometrics, Inc. It featured a 4W Ar-I laser and all measurements are normally taken with the instrument operating in the forward scattering mode to ensure the highest levels of signal-to-noise ratios in difficult, dense practical sprays. The measured velocity component was arranged to coincide with the longitudinal axis of the cylindrical pressure vessel. Moreover, the system featured a FFT based Doppler signal analyser to enable reliable signal acquisition and processing in comparatively denser regions. The selected combination of optics and slit geometry resulted in a beam waist diameter of ~250 microns with fringe spacing of ~6.4 microns. A sample size of 5000 validated droplets was chosen given the comparatively expensive nature of the high ambient pressure measurement campaign. Droplet data has been taken along radii perpendicular to the main spray axis at a downstream distance from the atomizer exit plane of 50 and 80 mm. The technique of laser sheet imaging was also applied to visualise global, instantaneous dispersion patterns in respect of dense, practical sprays at high levels of resolution. A high-energy, pulsed Nd:YAG laser was configured to deliver a 0.4 mm thin sheet and elastically-scattered signals at 532 nm wavelength were captured on a conventional camera that was located orthogonal to the laser sheet. Some limited imaging

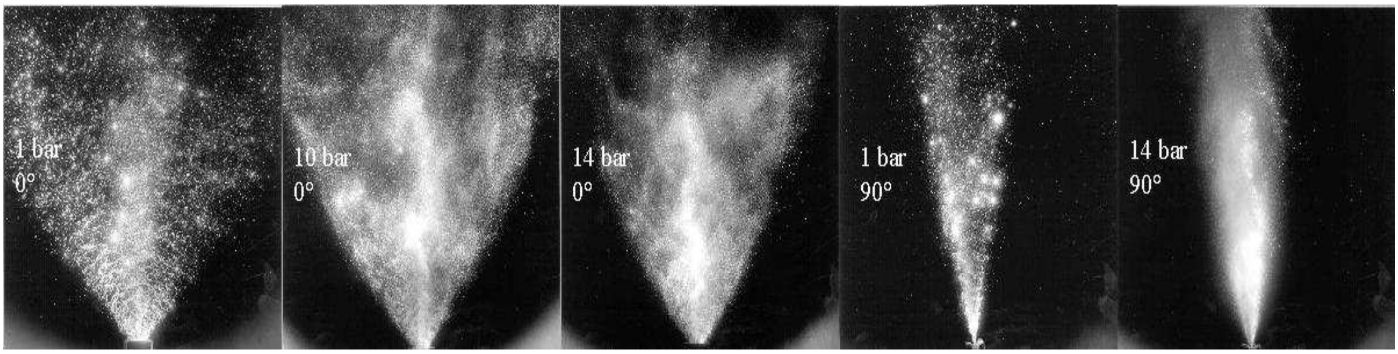

Fig. 2 Fan spray laser sheet imaging along major (0º) and minor (90º) planes under varying ambient air pressures.

was also undertaken with high primary magnifications, achieved using a long distance microscope (model K2, manufactured by Infinity Photo-Optical Co.) to access information concerning the underlying breakup mechanisms – interactions in the near-nozzle regions.

Two separate and independent traverse systems are provided to vary the position and orientation of the injector within the pressure vessel. The rotational and the longitudinal movement of the injector within the pressure vessel are both motorised and incorporated into a single composite traverse system. This allows very precise and repeatable injector positioning with two degrees of freedom relative to the optical diagnostics line-of-sight. The second traverse system, featuring three degrees of freedom, enables the laser diagnostics equipment to be mechanically adjusted as appropriate with a positional repeatability of 0.25 mm. Combination of the two traverse systems facilitates an in-depth, comprehensive spray structure mapping capability under conditions of high ambient air pressures and high throughputs.

RESULTS & DISCUSSION

The high speed laser imaging phase was performed first in order to gain insight into the physical shape and global structure of the spray, and the manner and the extent to which it changes with operational variables of ambient air pressure, liquid pressure drop across the nozzle and downstream distance from injector exit. This was followed by point-wise drop size, velocity data acquisition phase employing the phase Doppler instrument at ambient pressures of 1, 6 and 14 bar for a range of nozzle supply pressure drops and axially downstream measurement distances. A comprehensive set of data was acquired but due to limitations of space only a very small selection is presented in the ensuing sections.

Spray Imaging

Figure 2 presents a series of overview spray images capturing the liquid as it emerges from the atomizer orifice and spreads out spatially using comparatively low primary magnification optics. Images of this type, in general, reveal global features such as cone angle, overall dimensions, shape and symmetry etc characteristics of the spray. They provide useful guidance in determining the optimum locations within the spray for detailed drop size and velocity measurements. This figure shows the effect of ambient pressure variation on the spray structure for the 8003TC nozzle along both the major (0^0) and the minor (90^0) axis orientations. In this instance the spray appears to be broadly symmetrical with a measured cone angle that agrees reasonably (within ~ 5^0) with the manufacturer's specification under atmospheric pressure conditions. The spray boundaries are relatively straight here in contrast to the curved ones that are characteristic of pressure swirl and airblast atomization. Moreover the central regions of the spray, in qualitative terms, appear to contain a larger proportion of the liquid in comparison to radially outer locations. The above mentioned features are a reflection of a nozzle design that utilizes an intersection of a V-groove with a hemispheric cavity to form an elliptical discharge orifice. A very interesting aspect of this work is that it reveals, for the first time, the far-field spray cone angle along the 0^0 major axis orientation to be only minimally affected by increases in ambient air pressure from 1 to 14 bars in marked contrast to the conventional pressure swirl atomizer behaviour featuring a dramatic cone angle collapse. As a matter of fact the cone angle in the 90^0 minor axis orientation in fact encounters an increase. A spray with largely invariable dispersion characteristics under varying air density conditions could be desirable in many applications, for instance in gas turbines, power generation, chemical and process industry etc.

Although not presented here, some higher magnification spray imaging was also undertaken as a part of this investigation to complement the earlier work reported by the Cranfield group on low throughput fan sprays [9]. Imaging of high-throughput, dense sprays is a difficult challenge, especially if the aim is to gather detailed insights into the mechanism of sheet break-up and the subsequent droplet processes. The development of, air-friction induced, wavy disturbances on the emerging liquid sheet in the near-nozzle regions was visualized clearly despite the difficult operating conditions. Such studies are generally more productive when restricted to low throughput, dilute spray environments.

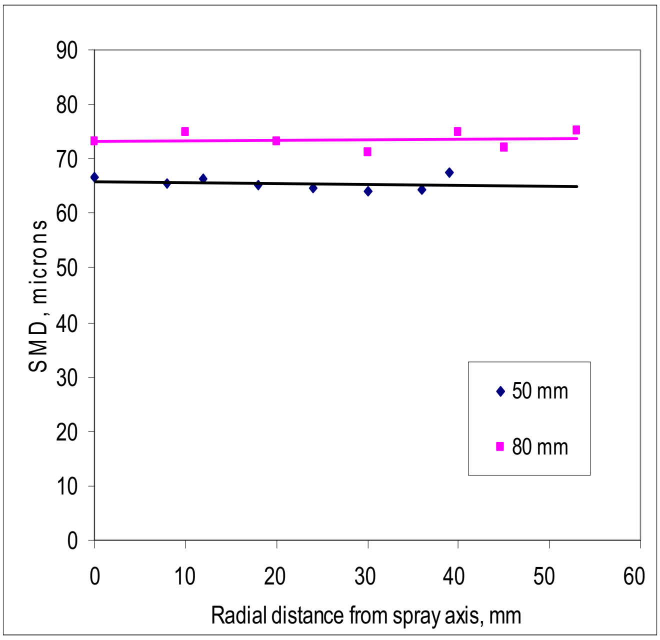

Fig. 3 Effect of measurement location distance on spray SMD. (ambient air pressure = 14 bar, nozzle pressure = 30 bar diff.)

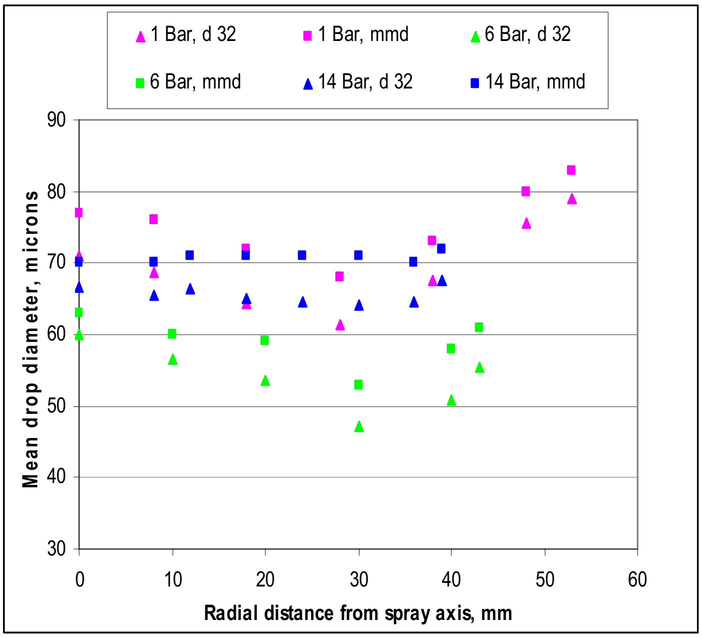

Fig. 4 Effect of ambient air pressure upon spray SMD & MMD behaviour (50 mm downstream location, 30 bar nozzle pressure differential.)

Phase Doppler Measurements

Before embarking with the detailed and extensive characterization campaign featuring key variables of ambient air pressure, nozzle pressure drop, nozzle flow numbers etc it was deemed prudent to explore briefly the effect of the phase Doppler measurement probe volume distance from the nozzle exit upon spray mean drop size. Figure 3 compares the measured SMD values at 50 and 80 mm downstream locations along the major axis of the elliptical fan spray for the case featuring pressure vessel operating at 14 bar ambient air pressure with 30 bar nozzle liquid pressure drop. This comparison reveals a noticeable increase in spray SMD with increasing measurement station distance. Given that these experiments have been conducted under ambient air temperature conditions, evaporation is clearly unlikely to be a contributory factor here. Similarly, further break-up can be ruled out to be a feature too. Secondary processes of droplet collisions and coalescence are likely to be the main reason for the observed increase in SMD as droplet velocities decay to an increasing extent with downstream distance due to the prevailing high air density environment. This is likely to increase the prospect of droplet coalescence – collisions in the farther downstream regions of the spray, especially at higher ambient air pressure conditions. Given that the elliptical fan spray behaviour relative to its conical spray counterpart under increasing air density levels displays greater resistance to cone angle contraction, the extent of these secondary droplet processes of collisions and coalescence etc would be expected to be prevalent to an appreciably lesser degree.

Figure 4 shows the radial distribution of spray SMD and MMD with varying ambient air pressure levels for the 50 mm downstream location for 30 bar nozzle pressure difference. Both the characteristic diameters decrease as the ambient air pressure is increased from 1 bar to 6 bars. Further increase in ambient air pressure to 14 bars however results in an increase in both the point-wise drop diameter values to a level that is not hugely different from their original levels at 1 bar condition. This is an interesting outcome as it suggests that changes in air density are triggering multiple droplet processes concurrently, some of which are acting in opposition to each other. This behaviour is somewhat akin to that observed earlier during conventional, conical pressure swirl atomized spray studies [10]. As a consequence the overall outcome is governed by the dominant process at any given operating environment. In this case an increase in ambient air pressure results in an increase in air density that, in turn, leads to multiple concurrent effects, namely, 1) an increase in Weber number resulting in higher rates of shear acting on the fuel sheet and thereby yielding a general reduction in drop sizes; 2) the disintegration processes are accelerated and consequently the appearance of initial perforations on the liquid sheet and the subsequent break up moves closer to the nozzle exit where the sheet is thicker and consequently would be expected to result in larger drop sizes; 3) a reduction in cone angle of the spray as ambient air pressure increases and thereby an increase in propensity for droplets to collide and coalesce with each other with a consequent increase in resulting drop sizes etc. This line of reasoning would explain the findings of the study reported by Ford and Furmidge that concluded that the mean drop sizes produced by fan jet sprays were unaffected by air density variations [11]. A similar conclusion would have been likely in our study had we not made measurements at the intermediate ambient air pressure level of 6 bars since the difference between 1 & 14 bar data sets is not huge.

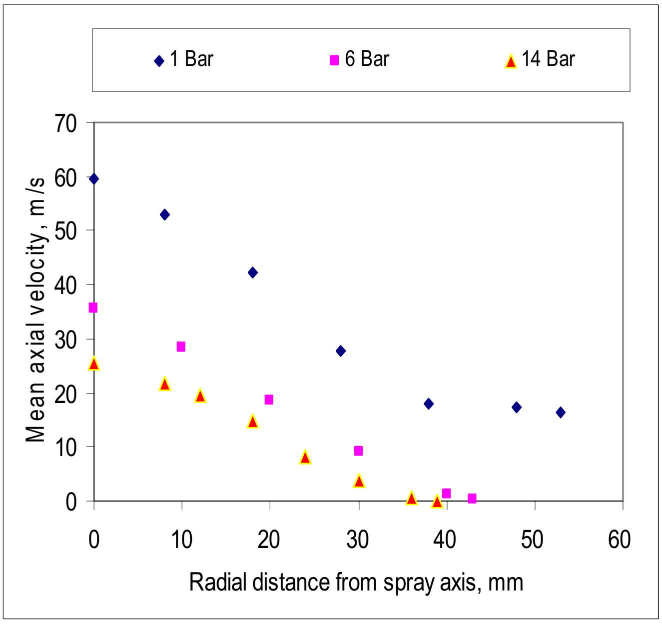

Fig. 5 Effect of ambient pressure on droplet mean axial velocities (50 mm from nozzle exit, 30 bar nozzle pressure differential)

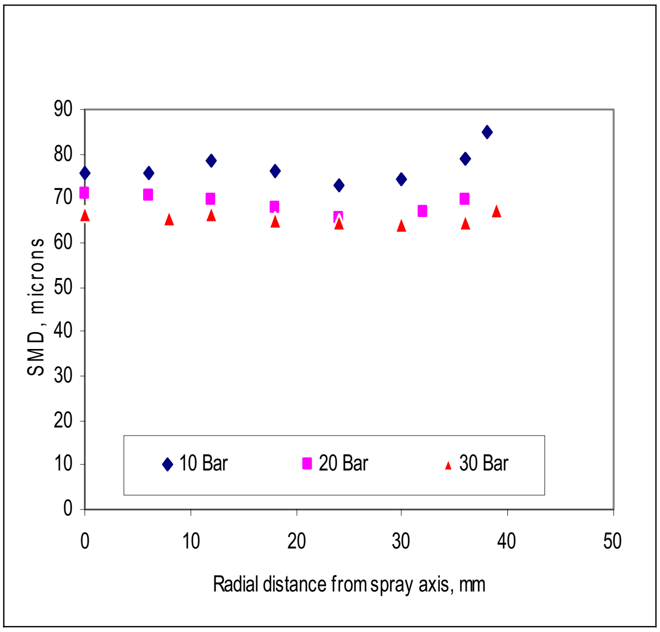

Fig. 6 Effect of nozzle pressure drop variation on spray performance (14 bar ambient pressure, 50 mm from nozzle exit).

This figure also shows the MMD to be always larger than the SMD - as a matter of fact the MMD / SMD ratio for the entire data depicted herein varies within a narrow range (i.e. 1.05 to 1.14). Averaging the point-wise values across the respective data sets yields a remarkable level of consistency – 1.087, 1.095 and 1.074 respectively at 1, 6 and 14 bar ambient air pressure levels. Simmons from Parker Hannifin conducted an analysis of a large body of spray data on various atomizers types and reported this ratio to be 1.2 [12]. It is noteworthy that Simmons work, despite having been undertaken in an era where the drop size determination was largely made using photographic / coated slide etc type of measurement techniques in marked contrast to the modern, non intrusive laser diagnostics of the phase Doppler, laser diffraction etc displays fairly good agreement with the findings of this exhaustive study incorporating large variations in air densities. Also evident in figure 4 is the increase in both the mean drop diameters towards the outer edges for the 1 bar operating pressure level. This has been observed before by the authors and is attributed to the increased liquid sheet thickness that is usually present at the outer edges in the case of nozzles employing elliptical discharge orifices.

Figure 5 depicts the effect of ambient air pressure variation over 1 to 14 bars on the point-wise radial distribution of the droplet mean axial velocity. Peak droplet velocities are observed along the spray centreline and they decline steadily as the radial distance from the centreline increases for all the three ambient pressure levels explored in this study. It is, however, interesting to note that the mean velocities are practically close to zero for both the 6 and 14 bar ambient pressure levels at the spray edges. In pressure atomization the initial velocity of all the droplets is the same but the rate at which the velocity decays is governed by the severity of the prevailing aerodynamic drag forces. This tends to at its maximum at the interface between the spray extremities and the surrounding quiescent air especially in the context of an elliptically shaped fan spray. It thus provides conditions that are conducive for droplet collisions and coalescence in these near stagnant sections of the spray at higher ambient air pressures. One would expect this tendency for coalescence etc to increase with increases in ambient air pressure.

Figure 6 shows the effect of nozzle pressure drop variation in the 10 to 30 bar range on the spray SMD for a constant ambient air pressure level of 14 bars. All the measurements have been carried out at the 50 mm axially downstream location from the nozzle exit. As is to be expected an increase in nozzle pressure drop can be seen to be having a beneficial effect upon the spray quality, vis a vis the reduction in SMD. In addition it appears as though the point-wise spread of drop sizes narrows with increasing nozzle pressure drop. In other words the spray is becoming spatially more homogeneous. This is a desirable attribute in power plant and other related applications where pollutants formation etc may be an important consideration. It also suggests that the extent of improvement with increasing nozzle supply pressure is somewhat decreasing. That is the increase from 10 to 20 bar nozzle pressure drop gives greater reduction in SMD relative to that realised by the increase from 20 to 30 bar i.e. a law of diminishing returns could be prevalent here. If so, this would limit the scope for further improvements in spray drop size improvements, although matters relating to penetration and dispersion could perhaps still be tailored as appropriate.

CONCLUSIONS

Systematic evaluation of the spray structure data acquired on pressure atomized, elliptical fan sprays covering water flow rates up to 90 g/s , nozzle pressure drops up to 50 bars over 1 to 14 bar ambient air pressure range using laser sheet imaging and phase Doppler interferometry enables the following conclusions to be drawn:

1. Increases in ambient air pressure yield only a small reduction in fan spray cone angle (along the major spray axis) relative to that encountered by the pressure – swirl atomizer of the conical type. The spray cone angle along the minor axis actually increases. Furthermore the spray boundaries of the fan atomizer remain relatively straight at higher ambient air pressures in marked contrast to the well documented, characteristically curved ones for the pressure swirl atomizer.

2. Drop size measurements at the farther downstream position of 80 mm for the 14 bar ambient air pressure level reveal the presence of secondary droplet processes of coalescence – collisions relative to those for the 50 mm location.

3. Increase in ambient air pressure from 1 to 6 bars results in an improvement in spray quality through a general reduction of spray mean drop sizes. Further ambient pressure increase from 6 to 14 bars yields a deterioration of spray quality. Broadly, the overall effect here appears to be that of a little change as the ambient air pressure is increased from 1 to 6 to14 bars.

4. An initial improvement followed by a subsequent deterioration in spray performance with continuing increases in ambient air pressure implies that changes in air density are triggering multiple droplet processes concurrently, some of which could be acting in opposition to each other. These effects can be explained through considerations of the influence of ambient air density variations upon the mechanism of liquid sheet disintegration.

5. Increases in nozzle pressure drop in the 10 to 30 bar range at a fixed ambient air pressure of 14 bar results in an improvement in spray quality.

ACKNOWLEDGEMENTS

The material presented in this paper was obtained during the course of a research project that was supported by RWE – npower (formerly Innogy plc). The author gratefully acknowledges this support and the opportunity to publish this research. The author also acknowledges various other sponsors who have, over the past twenty plus years, been involved in supporting the Cranfield high ambient pressure spray research activity. Special thanks are due to David Whittington for enthusiastic, diligent and proficient support in respect of the high pressure experimentation and equipment. Other Cranfield staff and students support is also gratefully acknowledged.

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