Behaviour of Dense, Industrial Sprays: A Comparative Assessment under High Air Density Conditions

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Abstract

This paper provides a comparative assessment of conical pressure-swirl, elliptical fan and pre-filming airblast atomizers under realistic, industrially relevant operational conditions, namely at liquid flow rates and ambient air pressures of up to ~75 g/s and 14 bar. Mie scattering based laser sheet imaging and phase Doppler interferometry were employed to facilitate the experimental data acquisition on water and kerosene test fluids. Elliptical fan sprays were observed to perform better than the conical pressure-swirl whilst being broadly comparable with the prefilming airblast from spray structure standpoint.

Introduction

Pivotal role of the fuel injector in attaining appropriate combustor performance goals throughout the development of the gas turbine engine is now widely recognised. Even Whittle encountered formidable challenges in order to attain satisfactory combustion performance as early as the late 1930's and eventually had to incorporate a re-designed fuel injector for his first, W1, flight engine. The combustion engineer has traditionally expected the fuel injector to deliver the necessary solutions when faced with new and sometimes daunting challenges vis-à-vis new or modified design concepts. Some of the key drivers underpinning fuel-air mixture preparation research currently are:

- Steady increases in combustor inlet air pressure / temperature and injector low to high fuel turndown capability.
- Compliance with progressively tightening regulations in respect of gas turbine generated pollutants including the climate change concern driven interest in carbon neutral bio- and other alternate fuels.
- Innovative nozzle designs with superior management of the increasingly hostile, thermal environment.
- Trend towards shorter and more cost-effective combustor-injector development cycle times.

The above characteristics demand an in-depth understanding of the design, performance and operational trade-offs that are available to the combustion engineer in order to facilitate an optimal, overall practical solution. This in turn often necessitates experimentation over the widest possible range of ambient air densities and other related operating conditions to understand the nature and scale of detailed changes that the fuel spray structure undergoes in an operational sense for a given atomizer design concept. Over the years a variety of behavioural studies along these lines have been conducted by the Cranfield group on pressure-swirl conical sprays, pressure atomized elliptical fan sprays and pre-filming airblast sprays of both the low- and high-shear types, see references 1-5 for example. The purpose of this paper is to bring together the relevant aspects of spray performance characteristics of the three different atomizer designs, namely the pre-filming airblast, conical pressure swirl and the elliptical fan spray with a view to exploring their comparative behaviour under high liquid throughput and high air density conditions. Both the pre-filming airblast and the pressure swirl, as an integral part of the well-known swirl cup configuration, are widely employed in the modern generation of gas turbine engines. The interest in fan-shaped, elliptical fuel sprays is due to the potential for better localised mixing with the prevailing airflow distribution within fully annular combustor geometries. Wider spatial dispersion of elliptical 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 [6]. Currently there is no such comparative spray behaviour study, particularly under the challenging and important, high air density conditions within the extensive liquid atomization and spray literature.

Experimental Details

Most of the recent high ambient air pressure spray research conducted by the author has deployed the test facility schematically presented in Fig. 1. Its main component is a large cylindrical vessel conforming to British Standards specification 5500 and it is supplied 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 good quality, degradation free measurements. Two separate and independent motorised traverse systems are provided to vary the longitudinal and rotary positions of the injector within the pressure vessel - thus allowing very precise and repeatable injector positioning relative to

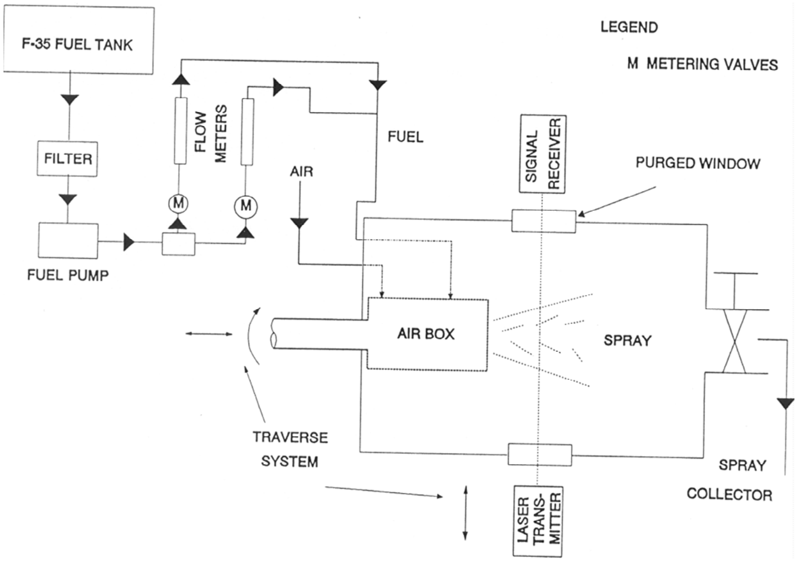


Fig. 1 Schematic of high ambient pressure spray facility

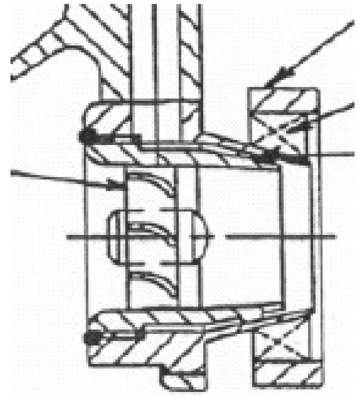
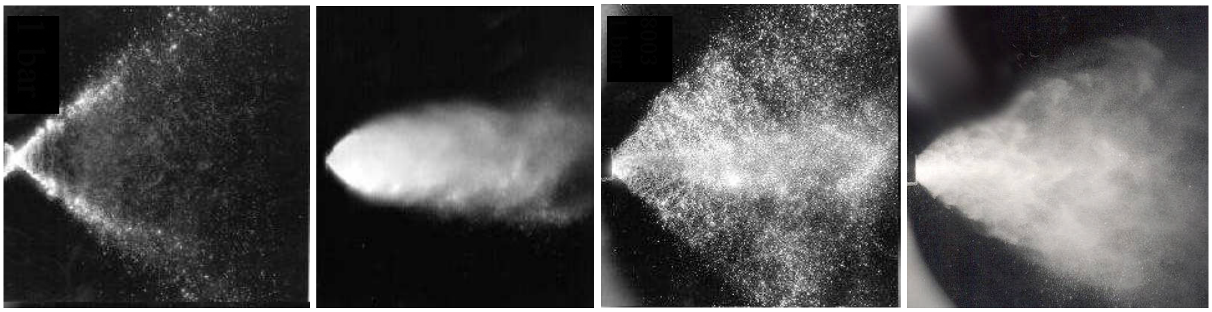


Fig. 2 Pre-filming airblast nozzle (courtesy of Parker Hannifin)

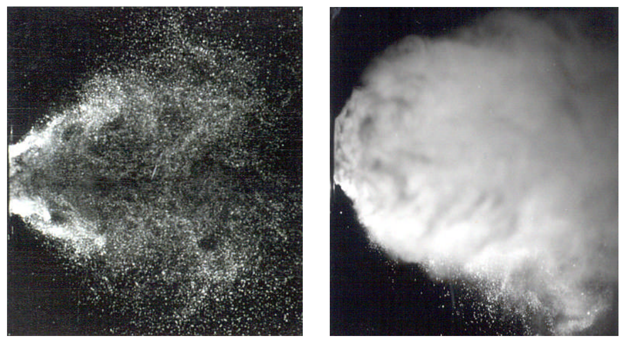
the optical diagnostics line-of-sight. The second traverse system, featuring three degrees of freedom, enables the laser diagnostics equipment to be mechanically adjusted as appropriate with a repeatability of position of 0.25 mm. This facilitates an in-depth, comprehensive spray structure mapping capability under conditions of high ambient air pressures and high liquid throughputs.

The simplex pressure swirl atomizer employed for experiments was supplied by Spraying Systems Limited and featured the orifice insert SIY48 and orifice SKY27 with a discharge hole diameter of 1.93 mm. According to the manufacturer, nominal cone angle of the developed spray under atmospheric air pressure conditions was 83^0. Flow number, FN, was calculated to be 0.124 $X10^{-3}$ m^3/hr/$Pa^{0.5}$ (22.75 pph/$psid^{0.5}$ units.) The nozzle was arranged to spray water into near quiescent air at 1, 8, and 12 bar air pressure levels. The pressure drop across the atomizer was held constant at 49 bars, regardless of variations in ambient air pressure, to provide a constant water flow rate of 75 g/s [4]. Fan spray experiments featured Spraying Systems nozzle (8004 TC) with elliptical orifices formed by the intersection of a 'V' groove with a hemispherical cavity. The nozzle flow number in m^2, equivalent orifice diameter in mm, and spray cone width in cm at 30 cm from exit as per the manufacturers catalogue are (1.508E-06); (1.3), and (48) respectively. Water flow rate of 77 g/s at a nozzle differential pressure of 30 bar was used for the 1 to 14 bar ambient air pressure tests reported here whereas more details are available elsewhere [5]. The pre-filming airblast atomizer used is depicted in Fig. 2 and has been studied extensively over a wide range of operating conditions [2-3]. All the airblast atomizer data relates to aviation kerosene as the test fuel with the extracted data set for this paper corresponding to the operating conditions of injector air pressure drop of 5 %, injector air to fuel mass ratio, AFR, of 3.9 which for an operating ambient air pressure of 12 bar corresponds to a maximum kerosene flow rate of 75 g/s. The key fluid properties of relevance from atomization performance standpoint for the two test fluids are those of liquid surface tension, σ, and viscosity, μ, and they are μ = 0.0013kg/ms, and σ = 0.0277 kg /s^2; and μ = 0.001kg/ms and σ = 0.073 kg / s^2 for kerosene and water respectively. Fluid pressure and mass flow metering etc equipment was the subject of appropriate calibration checks in each case.

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. The system featured a FFT based Doppler signal analyser for signal acquisition and processing for comparatively denser droplet 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 relatively expensive nature of the high ambient pressure measurement campaign. All the droplet data reported here has been taken along radii perpendicular to the main spray axis at a downstream distance from the atomizer exit plane of 45 ~ 50 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 orthogonal to the planar laser sheet. Some limited imaging 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.



(a) Pressure swirl – low & high power levels (b) Elliptical fan spray – low & high power levels



(c) Pre-filming airblast - low & high power levels

Fig.3 Effect of operating conditions on spray structure (Elliptical fan spray – major axis only data).

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 various sprays, and the manner and the extent to which they change with key operational variables of ambient air pressure and liquid flow rate through the nozzle. This was followed by point-wise drop size, velocity data acquisition employing the phase Doppler instrument over 1 to 14 bar ambient air pressure range for different nozzle types. Extensive data set was acquired but due to limitations of space only a small selection is presented in the ensuing sections.

Spray Imaging – Comparative Spray Structure

Figure 3 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, 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 simultaneous increases in ambient air density and liquid flow rate levels upon spray structure for the different nozzle designs under investigation herein. Such con-current increases are encountered in practice as the operating power level in a modern, large gas turbine engine changes from near idle to circa full-power. Broadly speaking the low power level corresponds to 5 ~ 10 g/s liquid flow rate at 1 bar ambient air pressure while the high power corresponds to 75 g/s liquid flow rate at 12 ~ 14 bar ambient air pressure. In this instance all the sprays appear to be broadly symmetrical; however the cone angle and the spatial distribution of the liquid appear to exhibit some notable differences. The pressure-swirl atomizer displays a dramatic reduction in cone angle at higher operating power conditions despite a significant increase in liquid momentum and this collapse is widely attributed to the creation of radially inflowing air currents due to the formation of a low pressure zone within the interior regions of the spray [4]. To the best of the author's knowledge this is the first documentary evidence in the open literature of cone collapse at such levels of ambient air pressures and liquid throughputs. Although both the fan and the airblast atomizers also show some changes in cone angle, they are however of a much smaller order. This reflects the presence of momentum driven interactions alone in the absence of a depression within the interior regions of these sprays. Previous pressure-swirl atomizer studies conducted by DeCorso & Kemeny [7], Neya & Sato[8], Parsons & Jasuja [9] et al have focussed on operating conditions that are significantly less representative of the modern, high-power gas turbine operation vis-à-vis ambient air pressures, liquid flow rates, choice of droplet property measurement location relative to the nozzle exit etc. (i.e. too close or too far). Moreover the curvilinear spray boundaries of the pressure-swirl atomizer standout relative to those of the elliptical fan and airblast atomizers. Also at higher power levels the central regions of the spray in each case appear to feature a larger proportion of the

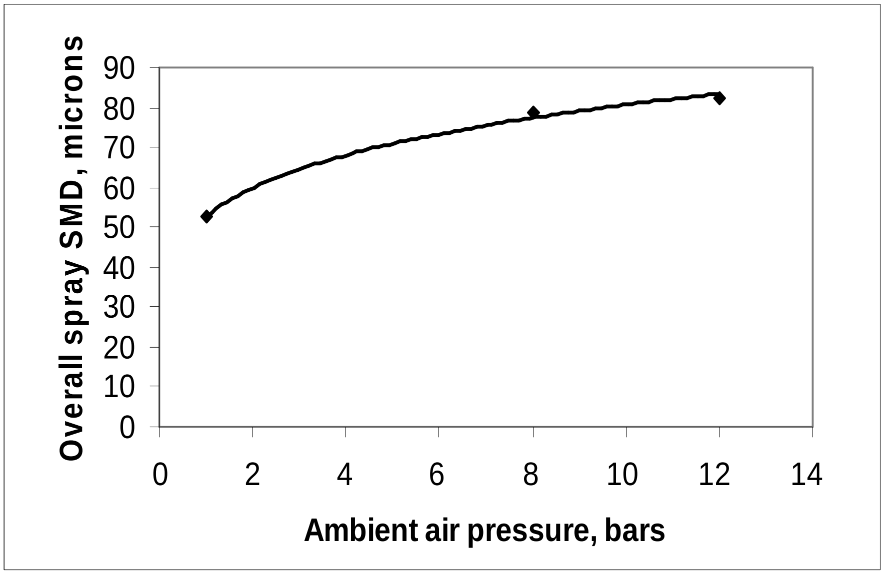


Fig. 4 Effect of ambient air pressure on overall spray SMD – pressure swirl atomizer (constant water flow rate of ~ 75 g/s, 50 mm from nozzle exit).

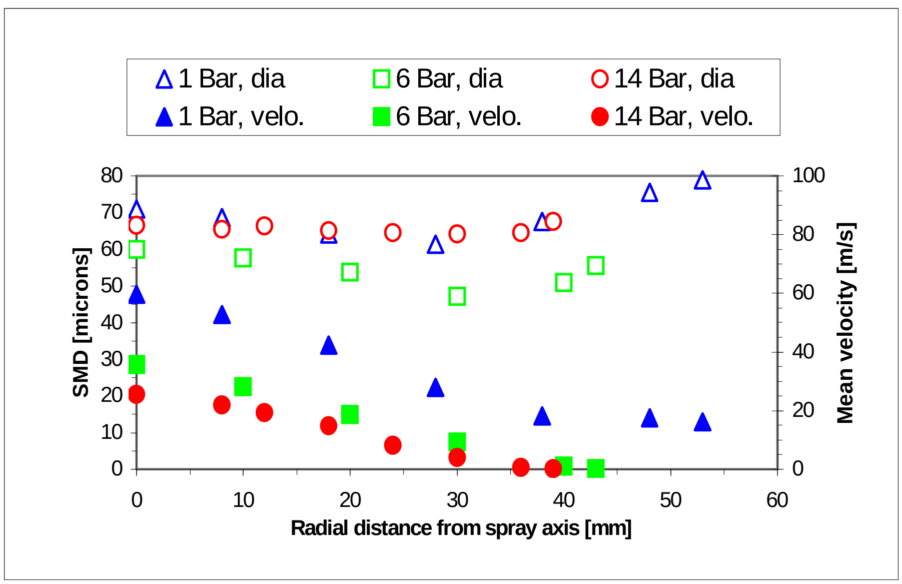


Fig. 5 Effect of ambient air pressure upon elliptical fan spray SMD and drop mean axial velocity(constant water flow rate of 77 g/s, measurements taken at 50 mm from nozzle exit).

liquid in comparison to the lower power counterparts in qualitative terms. An important aspect of this work is that it reveals the far-field, fan spray cone angle along the major axis orientation, to be only minimally affected by increases in ambient air pressure from 1 to 14 bars. Although not presented here, the cone angle in the minor axis orientation in fact encounters a small increase. A spray with broadly constant dispersion characteristics under varying engine operating conditions could be desirable from combustion and emissions standpoint vis-à-vis invariable fuel and air mixing quality.

Droplet Properties - Comparative Spray Performance

Figure 4 illustrates the effect of increases in ambient air pressure upon overall spray SMD which was obtained as the mean of all the point-wise measured local values of SMD after each local value had been corrected using appropriate area and velocity weighting factors to account for the larger flow areas in the outer regions of the spray and the non-uniformity of the radial velocity distribution. Here the overall spray SMD increases with an increase in ambient air pressure. This is a situation where competing adverse and beneficial spray processes are being triggered

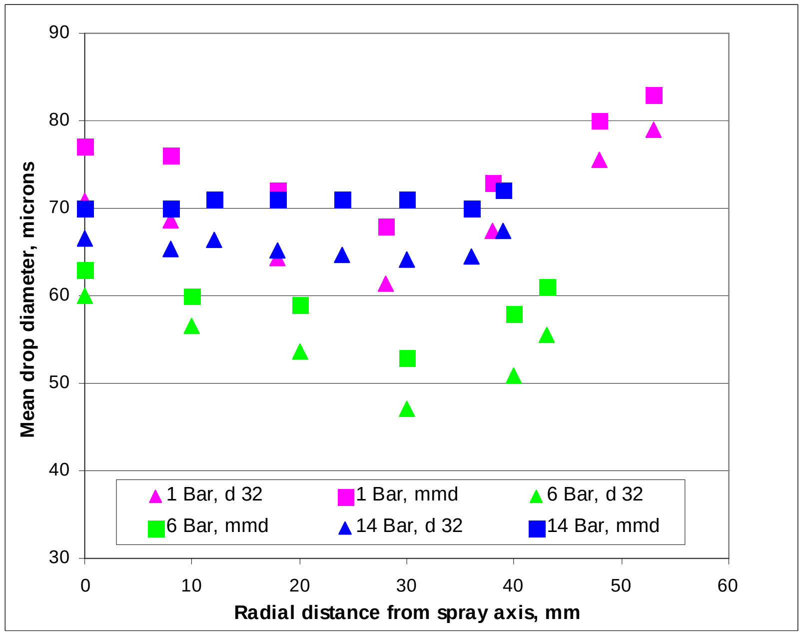


Fig. 6 Effect of ambient air pressure upon elliptical fan spray mean drop diameters (water flow rate = 77 g/s; 50 mm from nozzle exit)

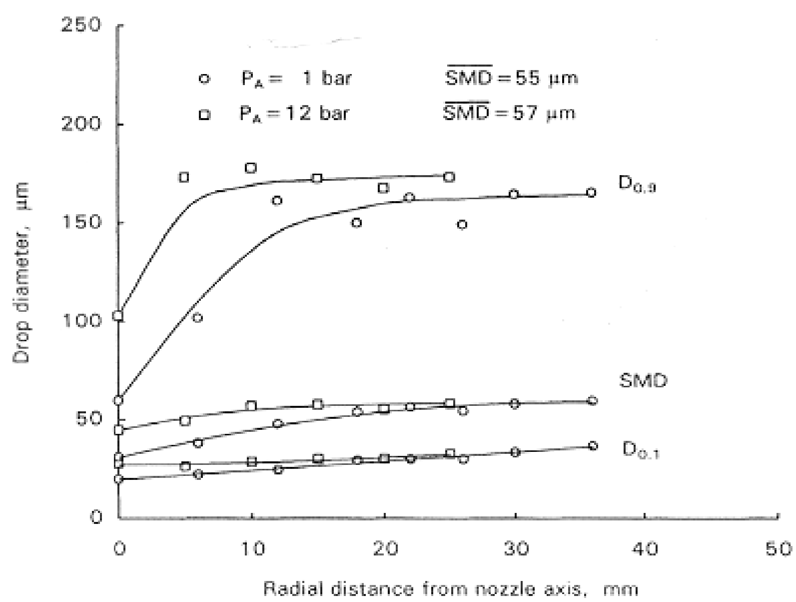


Fig. 7 Influence of ambient air pressure on pre-filming airblast atomizer drop sizes (injector AFR= 3..9, kerosine flow rate = 75 g/s - maximum, injector air Pressure drop = 5%, 45mm from nozzle exit)

con-currently by increases in ambient air pressure and the eventual outcome is governed by the balance between the more dominant ones [4]. The more notable ones to consider here are the increase in Weber number; the decrease in cone angle with potential agglomeration implications; and the acceleration of the liquid sheet breakup process that leads to upstream movement of the breakup point where the sheet is thicker due to a reduced degree of stretching. Fig. 5 shows the effect of ambient air pressure increase on size and velocity of drops present within elliptical fan sprays when explored along the major axis. Here the SMD decreases with an increase in ambient air pressure from 1 to 6 bar whereas further increase to 14 bar leads to an increase in SMD to a level that is not hugely different from that at 1 bar. Much like the pressure swirl atomizer, this behaviour suggests the con-current triggering of multiple droplet processes as a result of air density changes. However, as the reduction in cone angle at higher air pressures is noticeably diminished in the case of elliptical sprays, the extent of droplet coalescence would be expected to be much reduced too. The droplet velocity behaviour exhibits no surprises – decaying velocities due to the higher drag levels at elevated air pressures. Fig. 6 shows the relationship between SMD and MMD characteristic diameters over the 1 to 14 bar ambient air pressure range. Throughout the MMD is larger than SMD, the MMD / SMD ratio varies within a narrow range (i.e. 1.05 to 1.14). This is remarkably close to a value of 1.2 reported by Simmons based upon a large body of data covering various Parker Hannifin nozzles [10].

Both pressure-swirl conical and elliptical fan spray experiments featured water as the spray media. The pre-filming airblast atomizer study, however, was carried using aviation kerosene as the test fluid and figure 7 illustrates the effect of ambient air pressure on radial distribution of various droplet diameters including $D_{0.1}$ and $D_{0..9}$ which correspond to 10% and 90% diameter point on the cumulative volume versus droplet diameter curve. It can be seen from this figure that the local SMD values are not hugely different especially in the outer radial regions that contain the bulk of the fuel as ambient air pressure is increased from 1 to 12bar. This is further confirmed by determining the overall spray SMD values for this pre-filming airblast nozzle data set using the same methodology as employed for the pressure swirl conical spray data set presented in Fig. 4 earlier. This results in overall SMD values of 55 and 57 microns for 1 and 12 bar ambient air pressure levels. It should be pointed out here that these airblast nozzle experiments have been carried under conditions of constant atomizer air to fuel mass flow ratio which inevitably does not achieve constant liquid mass flow rate as the ambient air pressure is raised. For experiments featuring constant liquid flow rate at low and high ambient air pressures, the overall SMD at 1 bar ambient would be expected to be appreciably larger than that at 12 bar due primarily to the atomizing fluid stream energy considerations [2].

Closure

For the purposes of comparative assessment, it would be informative to extract some measured SMD values from the respective data sets discussed here for a typical high power condition that a modern gas turbine would be expected to operate at. A typical injector fuel flow of circa 75 g/s at around 12 to 14 bar ambient air pressure corresponds fairly closely to the prevailing air densities and fuel flow rates at near full power operation for the commercial aviation application, thus yieliding

airblast = 57µm SMD @ 12 bar, 75 g/s kerosene flow; pressure-swirl = ~ 80 µm SMD @ 12 bar, 75 g/s water flow; elliptical fan = ~ 67 µm SMD @ 14 bar, 77 g/s water flow.

It should be pointed out that measurements on water will, because of its higher surface tension relative to kerosine, inevitably yield larger drop sizes. Whilst one could attempt to use empirical correlations to make such adjustments, their reliability is somewhat questionable for the test conditions explored in this study. This clearly shows that the elliptical fan spray performance is close enough to that of the pre-filming airblast and merits further investigation from both spray atomization and combustion perspectives.

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