ICLASS-2006
Aug.27-Sept.1, 2006, Kyoto, Japan

Paper ID ICLASS06-287

BEHAVIOUR OF AERO-ENGINE AIRBLAST SPRAYS IN PRACTICAL ENVIRONMENTS

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ABSTRACT This study explores the comparative behaviour of modern, engine standard high-shear, pre-filming airblast nozzle against its traditional, low-shear counterpart under as realistic gas turbine operating conditions of atomizing air density and fuel flows as currently possible. Data covering kerosine flow rates of up to 95 g/s and air densities of up to 14.5 kg/m^3 at an ambient air temperature of 325K is discussed in this paper. Near-nozzle spray cone angle and trajectory behaviour of the high-shear nozzle is shown to exhibit significantly greater sensitivity to increases in ambient air pressure under conditions of constant atomizer air to fuel mass ratio and air pressure drop relative to that of the low-shear design. The corresponding effect of a similar increase in atomizing air pressure on overall spray Sauter mean diameter at a downstream distance of 45 mm is also significantly different for the low- and high-shear injector designs. These differences in spray performance are a reflection principally of the distinctive nature and scale of fuel-air interactions invoked by the different injector design philosophies.

Keywords: Gas Turbine Fuel Injection, Pre-filming Airblast Atomizer , Dense Fuel Sprays, High-Shear Rate Sprays.

1. INTRODUCTION

The fuel injector has been the focus of on-going research and development ever since the gas turbine engine was adopted as the prime mover for aircraft propulsion. Even as early as the late 1930’s, Whittle encountered formidable challenges in order to achieve satisfactory gas turbine combustion performance and eventually had to incorporate a re-designed fuel injector for his first, W1, flight engine [1]. The gas turbine engine experienced sustained increase in engine pressure ratios from circa 7 ~ 10 in the early 1950’s to around 20 in the late 1960’s. After adequately satisfying combustor performance requirements in lower pressure ratio engines during the 1960’s, the simplex, duplex and dual-orifice type of pressure-swirl atomizers became increasingly afflicted with problems of copious amounts of primary zone soot and exhaust smoke, reduced liner durability, and poor outlet temperature pattern factor at higher combustion pressures. Pioneering research undertaken by Lefebvre identified the problem as one of improper fuel placement within the primary combustion zone due to ‘spray cone collapse’, and not due to deficiencies in fuel chemistry at higher combustion pressures as was generally inferred at the time [2]. To overcome this problem of ‘cone-collapse’, the ‘pre-filming airblast atomizer’ was invented by Lefebvre in the mid 1960’s [3, 4]. This novel concept embraced pre-filming and spreading of bulk fuel into a low velocity, thin cylindrical sheet that was subsequently sheared into droplets by being ‘sandwiched’ between two, high velocity airstreams. The generation of fine, well dispersed droplet spray coupled with intimate mixing as an integral part of fuel-air mixture preparation process resulted in major improvements in primary zone soot and exhaust smoke, liner durability and pattern factor performance relative to that of pressure-swirl atomizers. Around the mid 1970’s, additional pressures in the form of fuel flexibility and consumption as a consequence of potential embargo on oil supplies from the Middle-East, and anticipated pollutant emissions legislation led to an appreciable intensification of the research effort to explore further improvements in fuel-air mixture preparation quality. The earlier research and development efforts were centred on pre-filming airblast atomizer configurations featuring low-shear rate, swirl-free airstreams that were broadly of a co-flowing, parallel nature relative to the direction of motion of the fuel stream [5-7]. From around 1980 onwards pre-filming atomizer designs increasingly began to utilise air swirlers to promote higher rates of shear and mixing between the liquid fuel and the two encompassing airstreams as an integral part of the spray formation process to achieve further improvements in combustion and emissions performance [8-9]. In the high-shear design the liquid sheet was subjected to an intense, turbulent flow-field resulting in its rapid disintegration into a well-atomized spray with improved mixing and dispersion characteristics. Pressure-swirl atomizers were still being used, sometimes in conjunction with airblast atomizers to act as a piloting device for better start-up and altitude relight capability, and as a means to widening stability limits at other operational levels of power. They were also featured in other applications, for example as a device to deliver fuel onto an inner, annular pre-filming surface of the combustor swirl cup configuration used in many modern General Electric engines to facilitate the formation of a thin sheet of liquid [10]. This fuel sheet flows into a region of high-shear prevailing at the interface of two contra-rotating, swirling and encompassing airstreams. For the foreseeable future the necessity for further improvements in fuel injection – mixture preparation is likely to be driven by the increasingly stringent, anticipated regulations governing the pollutant emissions performance of the future generation of gas turbine combustion systems.

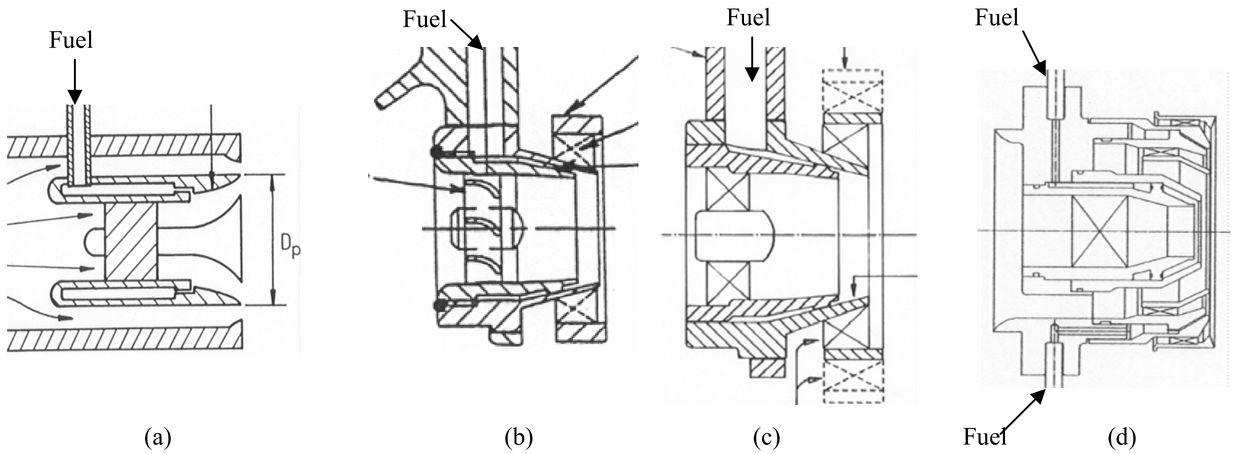


Fig. 1 Airblast atomizer schematics, (a) Low-shear; (b and c) High-shear, conventional; (d) High-shear, variable fuel placement.

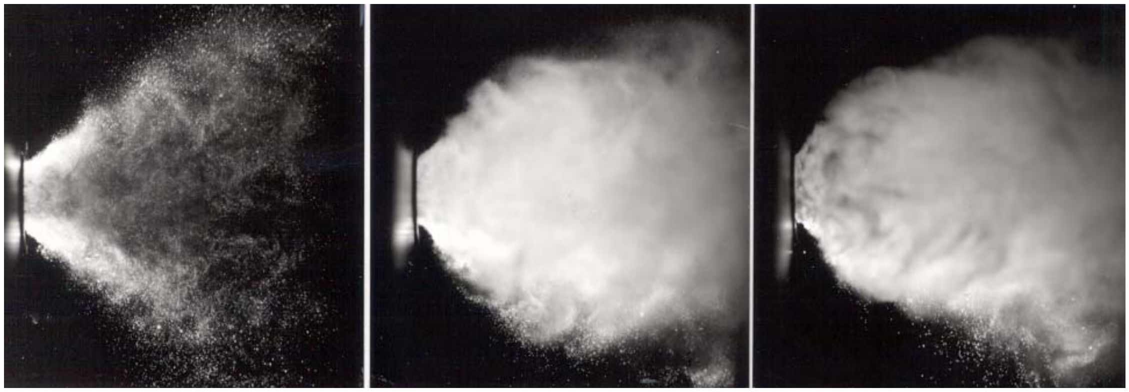
Much of our present knowledge of pre-filming airblast fuel injectors was gained during the 1970's and early 1980's on low-shear rate designs featuring non-swirling, co-flowing atomizing airstreams [5-7, 11,12]. Most of this work was conducted on laboratory-scale, research atomizers at conditions of low fuel and air mass flows. In recent years considerable advances have been made in the development of advanced laser diagnostics for spray characterization, notably phase Doppler interferometry. They offer the prospect of gaining detailed spray structure insights under conditions of practical relevance of high air mass flows and density, and high fuel flows. As a result many parallel efforts have been conducted to explore the spray flow-field produced by the so-called practical, engine-standard nozzles [13-16]. The existing knowledge database concerning the behaviour of engine-standard, high-shear rate fuel injectors has only relatively recently been extended to embrace the near-full power fuel and air throughput, and air density conditions in the research studies undertaken at Cranfield University [17-22]. Whilst studies carried out elsewhere have used engine-standard hardware, they have thus far not achieved as close a similarity to the practical environment prevailing within the modern engine combustors at conditions of near-full power operation as that of the author. This paper brings together some of the important findings from the earlier low-shear and the more recent engine-scale, high-shear injector studies to outline significant behavioural differences in response to changes in air and fuel operating conditions.

2. EXPERIMENTAL DETAILS

Most of the recent high ambient air pressure spray research undertaken at Cranfield has been conducted in the same test facility and it is described elsewhere [18, 22]. Briefly it features a large cylindrical vessel conforming to British Standards specification 5500 and incorporates appropriate optical access for a range of non-intrusive diagnostics including phase-Doppler interferometry and laser sheet imaging / particle image velocimetry. The facility also features a multi-point, air purge system to prevent contamination of the optical ports, along the line-of-sight, by fuel mist without perturbing the test spray.

Droplet sizes and velocities were measured using a single-velocity component phase Doppler system manufactured by Aerometrics, Inc. featuring a 4W Ar-I laser. 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 main axis of the conical spray. All the droplet data has been taken along radii perpendicular to the spray axis at a typical downstream distance from the atomizer exit plane of 45 mm. The technique of laser sheet imaging was also applied to capture global dispersion patterns in respect of dense, practical sprays at levels of resolution not achieved before. A high-energy, pulsed Nd:YAG laser was configured to deliver a 0.4 mm thick sheet and elastically-scattered images at 532 nm wavelength were acquired.

The schematics of the various atomizers covered in this paper are outlined in Fig. 1. The main differences between the configurations studied relate to fuel and air circuit design features. Configuration 1a is one of the comparatively early ones and exhibits a divergent, long pre-filming surface culminating in a sharp edged lip. This was to facilitate the development of a thin, continuous and uniform annular sheet of fuel that would detach readily from the final discharge lip in an attempt to generate a spray made up of fine drops with a homogeneous spatial distribution. In contrast, designs 1b – 1c feature a convergent shaped pre-filming surface of a comparatively short length along with the absence of a sharp edged discharge lip. Shown alongside is a more recent variant of the high-shear design that seemingly offers some interesting potential for improved NO_X emissions performance [23]. It features four, concentrically swirling air streams and two concentric, converging pre-filming surfaces incorporated within a single injector assembly. Here the aim is to generate two completely segregated re-circulation zones, an inboard main accompanied by an outboard pilot re-circulation zones. This is a fuel staging device attempting to improve combustion - emissions performance in a



1 bar 6 bar 12 bar

Fig. 2 Influence of ambient air pressure on spray structure at a constant AFR of 3.9, high-shear design (1b).

manner similar to the familiar double annular combustor configuration. These recent configurations clearly do not pay as much attention to the pre-filming process and the associated fuel sheet quality at the point of atomizer exit in comparison to the earlier concepts. The other key difference is in respect of the rates of shear invoked between the atomizing and the atomized fluid streams. Design 1a uses the classical approach wherein the liquid sheet is surrounded on both sides by non-swirling, co-flowing airstreams moving in the same general direction as the fuel. This is in marked contrast to the other geometries that feature a fuel sheet delivery into regions of intense shear created by the deployment of counter-rotating inner and outer swirling airstreams. The low-shear configuration 1a attempts to exploit the classical, wavy break-up route to spray formation while the higher-shear designs tend towards the deployment of the 'instantaneous' or 'prompt' break-up route to spray evolution. The initial characteristics of the liquid sheet are clearly going to become less relevant the higher the prevailing rates of shear in a given design. It is worth bearing in mind that not all injectors were designed for a common operational duty, therefore some scaling differences are inevitably going to arise in a study of this kind. However, from a generic viewpoint they are considered as being somewhat less important to the goal of this paper.

Typical maximum combustor operating air pressure and temperature values are currently around 40 bar and 900 K, yielding an air density of around 16kg/m^3. Maximum fuel flows, in general, lie around 100 to 150 g/s depending upon the number of fuel injectors in a given engine. A special feature of the author's work on engine standard fuel injectors has been to maintain a close similarity to the real operational air density and fuel flow levels. Spray imaging investigations have been carried out at up to ~14.5kg/m^3 air density and 95g/s kerosine flow rate [17]. Detailed droplet size and velocity measurements, on the other hand, have been obtained at maximum kerosine flow rate of 75g/s at an air density of 14.5kg/m^3 [20-22]. The droplet property data has been obtained at a distance of 27 to 45 mm from the injector exit and is of particular relevance to the near-nozzle zone where combustion is initiated and sustained. Appropriate levels of injector air pressure drop and atomizer air/fuel mass ratios were selected to ensure relevance to the gas turbine industry practice. Aviation kerosine (μ_L = 0.0013 kg/ms, ρ_L = 784 kg/m3, and σ_L = 0.0277 kg/s^2, all at 288 K) was used for all the data contained in this paper. The ambient air temperature was maintained constant at around 325 K implying negligible levels of droplet evaporation in near- nozzle measurement regions.

3. RESULTS & DISCUSSION

The focus of most of the research conducted since around 1990 has been to gain a better understanding of the spatial distribution of drop sizes and drop velocities in a given spray in order to facilitate improved combustion and emissions performance. Other properties such as cone angle, global dimensions and trajectory of the spray too are important in terms of optimising overall combustor performance and have received somewhat limited attention. In contrast, a vast majority of the mid 1970's through to circa mid 1980's research was directed principally at exploring the line-of-sight spray mean drop size behaviour of the test sprays, reflecting the step change that occurred in the diagnostics capability during the late 1980's.

Figure 2 shows some typical spray images obtained on injector 1b under conditions of varying ambient air pressure while the atomizer air/fuel mass ratio, AFR, was maintained constant at 3.9 using the pulsed laser sheet illumination technique. The atomizer air pressure drop was held constant at 5% for these tests. This figure shows how the physical structure of the spray is affected by a simultaneous increase in injector air and kerosine mass flow rates, following increases in ambient air pressure at a constant atomizer AFR. The comparatively hollow central regions of the spray under atmospheric pressure conditions seemingly become more-full as the ambient air pressure increases. In other words the spatial distribution of fuel droplets within the spray changes with increases in combustor operating pressure and fuel flow rates. Through

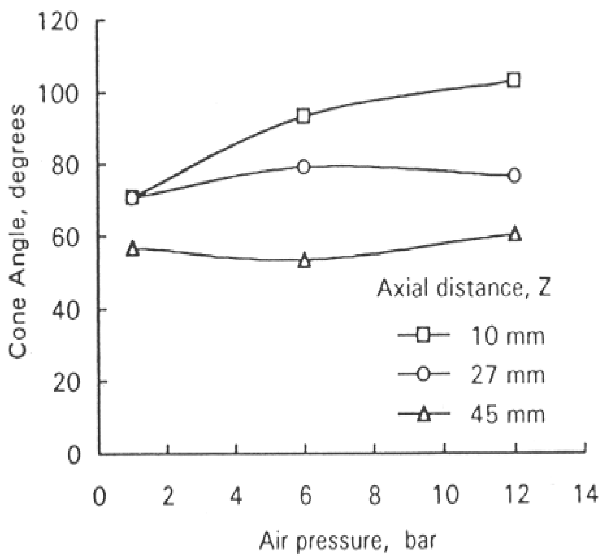


Fig. 3 Influence of air pressure on airblast spray cone angle for constant AFR of 3.9, high-shear design (1b).

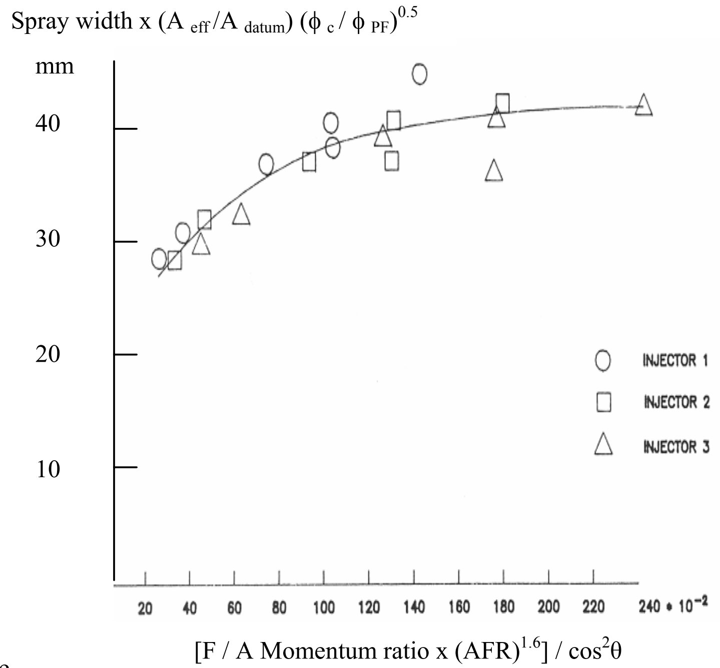


Fig. 4 Airblast spray width correlation covering high ambient air pressures and fuel flows, high-shear design (1c).

a process of super-positioning of a number of spray outer boundary profiles, derived from such high-speed images under nominally identical test conditions, an informative and reasonably accurate 'average' spray profile can be deduced. Such an 'average' image can then be used to obtain information concerning the overall diametral dimension of the evolving spray profile as it emerges from the nozzle and expands radially outwards along the main axis. Analysis of this type can provide useful insight into the changes that the spray cone angle undergoes as a function of downstream distance along its main axis for a range of ambient air pressures [22]. Figure 3 provides some illustrative results following this analysis for injector 1b. This reveals that the spray cone angle for the near-nozzle axial distance of 10 mm changes appreciably as the ambient air pressure is raised from 1 to 12 bar, namely from ~70 to 105 degrees. In contrast the changes for the 27 and 45 mm axially downstream positions are much less significant i.e. practically unchanged. It should be pointed out here that an increase in air pressure at a constant atomizer AFR (3.9) and a constant pressure drop (5%) results in an increase in fuel to air momentum ratio. This implies that increases in fuel momentum exercise an overriding influence on the resultant cone angle in the near-nozzle region for the design geometry that features a wider fuel-alone ('natural') spray cone angle relative to that of the atomizing air on its own.

Similar near-nozzle behaviour was also observed on injector 1c for a somewhat wider range of fuel flow conditions, a kerosene flow rate of up to 95 g/s against that of up to 75 g/s for injector 1b under comparable air density levels of 14.5 kg/m^3 [17]. Such a result is only to be expected since configurations 1b and 1c feature broadly similar air and fuel flow circuit designs. Interestingly however, this observation is contrary to conventional wisdom, based largely on the circa 1970's knowledge relating to injector geometries of the 1a type, that implied the spray trajectory to be solely dependent upon the prevailing aerodynamics [24]. There is however no comparable experimental high-speed imaging data for injector configuration of the 1a type under high ambient air pressure conditions to support such an assertion. An examination of injector configurations 1a and 1b/c suggests such a finding to be entirely consistent with the prevailing air and fuel circuit passage designs. The classical swirl-free air, low-shear injector design 1a features fuel and air passages configured to deliver the two fluid streams in broadly the same direction with their respective fuel- and air-alone cone angles of not too dissimilar nature. In contrast the modern high-shear, air swirler based configurations 1b and 1c feature 'fuel-alone' cone angle that is significantly wider than that of the 'air-alone' case. Moreover to reflect the higher operating air densities and fuelling levels prevailing in the current technology combustors, the recent engine-scale studies have featured significantly higher levels of fuel momentum than those appropriate to the circa 1970's technology levels. It is hardly surprising, therefore, that 1b/c nozzle designs exhibit dissimilar overall cone angle behaviour in the near-nozzle region relative to that of nozzle 1a. Further downstream though, i. e. approximately two pre-filmer diameters and beyond, the resultant cone angle would be expected to be less prone to fuel momentum influence due to progressively lower level intensity interactions between the spray efflux and the prevailing flow-field.

Large body of high-speed spray image data, acquired over a range of operating and design geometry variables on injector 1c, has also been studied for variations in spray dimensions (diameter or width) in near-nozzle region [17]. The usefulness and applicability of such information is, however, restricted to cone angle variations only, unless it enables the development of some quantitative trend. By bringing together the key geometrical variables of nozzle airflow effective area, (A_{eff}), pre-filming lip diameter,

(ϕ_{PF}), and average air swirl angle, (θ), with operational parameters of fuel to air momentum ratio, and atomizer air to fuel mass ratio, (AFR), all of the spray data can be made to converge into a single curve as depicted in figure 4. The two terms that are correlated here are

$$[(\text{fuel to air momentum ratio}) \times (AFR)^{1.6} / (\cos^2\theta)] \text{ and}$$
$$[(\text{spray width or diameter}) \times (A_{eff} / A_{datum}) \times (\phi_c / \phi_{PF})]$$

where the previously undefined symbols ϕ_c and A_{datum} are atomizer characteristic diameter and nozzle datum air flow area respectively. The correlation development methodology suggested the need for a separate AFR term in addition to fuel to air momentum ratio to fully account for its effect on the spray diameter. These tests featured variations in air density of up to 14.5 Kg/m^3, and kerosine flow rates to 95 g/s on engine standard fuel injectors that also embraced the dome swirler/combustor head assembly. In other words, all major aerodynamic features of the combustor primary zone were included to ensure that all significant contributors to the momentum-dominated, spray development and dispersion process were properly accounted for in the test programme. Furthermore, variations in nozzle airflow effective area were achieved through the incorporation of a convergent shroud cap in the outer swirling airflow passage at the nozzle exit plane.

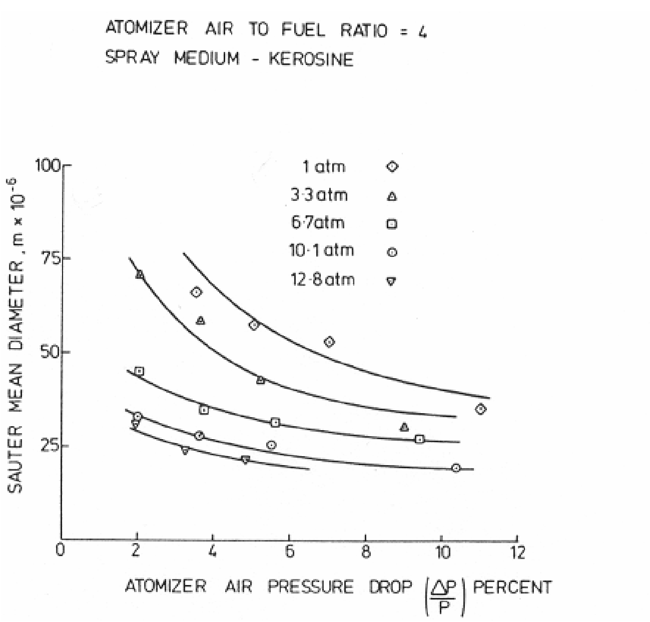


Fig. 5 Influence of ambient air pressure on Line-of-sight SMD, low-shear design (1a).

Figure 5 shows some spray mean drop size data for an injector of the 1a type under varying ambient air pressures on kerosine as the test fuel at an AFR of 4 [12]. This illustrates a significant improvement in the spray quality as the atomizing air pressure is raised from 1 to nearly 13 atmospheres. These measurements were made with an in-house developed, laser light scattering technique at a downstream distance of some 50mm along the main spray axis from the injector exit. This study featured a wide variation in liquid viscosity, μ_L, (0.0113 to 0.035 kg/ms), atomizing air velocity, V_a, (55 to 135 m/s), atomizer air to fuel mass ratio, AFR, (2 to 8), and ambient air pressures (1 to 13 atmospheres). Systematic analysis of the experimental data led to the development of the following dimensionally consistent correlation for the pintle type of pre-filming airblast configuration 1a

$$SMD/D = 0.17[(\sigma_L) / (\rho_a V_a^2 D)]^{0.45} [1 + (1/AFR)]^{0.5} + 0.017[(\mu_L^2) / (\sigma_L \rho_L D)]^{0.375} [1 + (1/AFR)]^{0.8} \quad (1)$$

where the previously undefined terms σ_L and ρ_L denote liquid properties of surface tension and density respectively, ρ_a the air density, and D the pre-filmer lip diameter. A special feature of this study was the unparalleled simultaneous combination of high levels of liquid viscosity and high air densities. As no such experimental database existed at the time, there was a special need for it to identify precisely the nature and role of the liquid viscosity dominated second term in the above correlation [25]. The correlation was deemed to be accurate to ± 20 % as illustrated in Fig.6 for the entire data set covering a wide range of variations in some hitherto unexplored key parameters.

$SMD \propto (P_a)^{-0.45}$

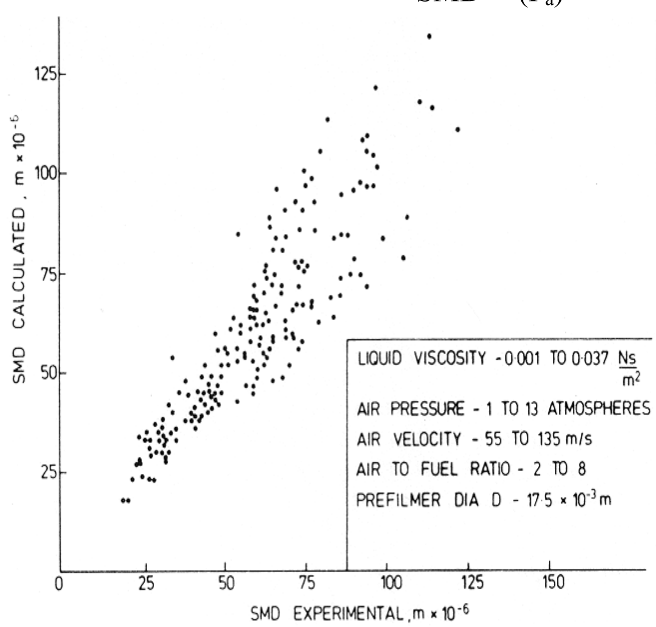


Fig. 6 Line-of-sight SMD correlation, low-shear design (1a).

One of the shortcomings of the above work, undertaken with the earlier generation of measurement techniques, was the absence of detailed droplet property data on a spatially resolved basis. Such data is essential to gaining a better grasp of the local fuel-air mixture characteristics in order to facilitate a better control over the emissions performance. This important aspect has been addressed recently in the studies conducted by the author on high-shear injector designs featuring detailed, point-wise droplet size and velocity distribution measurements over a wide range of ambient air pressures and fuel flow rates using phase-Doppler interferometry [18, 20, 22]. A high-shear, SNECMA designed, research injector was the subject of spatially resolved droplet property measurements at a maximum kerosine flow rate of 24.8 g/s at an ambient air pressure of 12 bar using a 10-mW He-Ne laser powered phase-Doppler system [18]. These measurements were made at an axial distance of 70 mm from the injector tip. For the same flow condition, droplet property data at shorter axial distances could not be procured due to higher spray densities resulting in excessive attenuation of both the incident and the scattered laser beams. This was deemed as being a useful initial outcome that provided new insights into the extent of point-wise homogeneity present in practical sprays at air densities of up to 14.5kg/m^3. However, there existed a pressing need to extend the knowledge database to embrace higher fuelling levels and nearer-nozzle regions to ensure relevance to the practical environment prevailing within the high-intensity, modern engine combustor. Using a 4W Argon-Ion laser powered phase-Doppler analyser, experiments were conducted on injector 1b to explore the spray structure under more representative test conditions than possible in the earlier study [20, 22]. Most of the airblast atomizers now in service on modern aircraft engines are generally similar to this type of high-shear design.

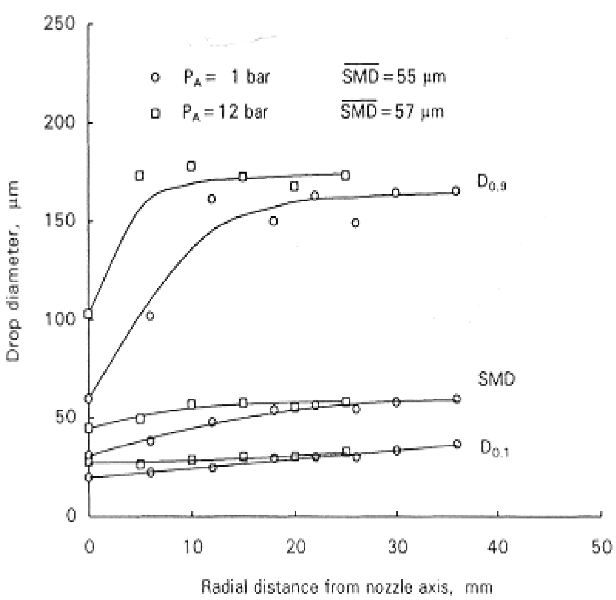


Fig. 7 Influence of ambient air pressure on radial distribution of drop diameters, high-shear design (1b).

Figure 7 shows the influence of increasing ambient air pressure from 1 to 12 bar on point-wise, radial distribution of $D_{0.1}$, SMD, and $D_{0.9}$ characteristic drop diameters. $D_{0.1}$ and $D_{0.9}$ are the drop diameters corresponding to the 10% and 90% points respectively on the cumulative liquid volume versus drop diameter distribution curve. For these tests the atomizer AFR and air pressure drop were held constant at 3.9 and 5% respectively. This corresponds to a kerosine flow rate of 75 g/s at an air density of 14.5 kg/m^3. Drop sizes were measured at an axial distance of 45 mm from the nozzle tip. This figure shows that the effect of ambient pressure change on drop diameter manifests mainly in the inner regions of the spray whereas the outer regions are largely unaffected. Since most of the fuel is contained in the outer spray regions, the overall effect on the weighted, line-of-sight mean diameter, $\overline{SMD}$, is comparatively small. This is borne out by the weighted, line-of-sight mean drop diameters of 55 and 57 microns for the 1 and 12 bar point-wise, SMD data curves respectively in Fig. 7 [20]. $D_{0.1}$ and $D_{0.9}$ diameters are affected in a similarly small way by the changes in air pressure.

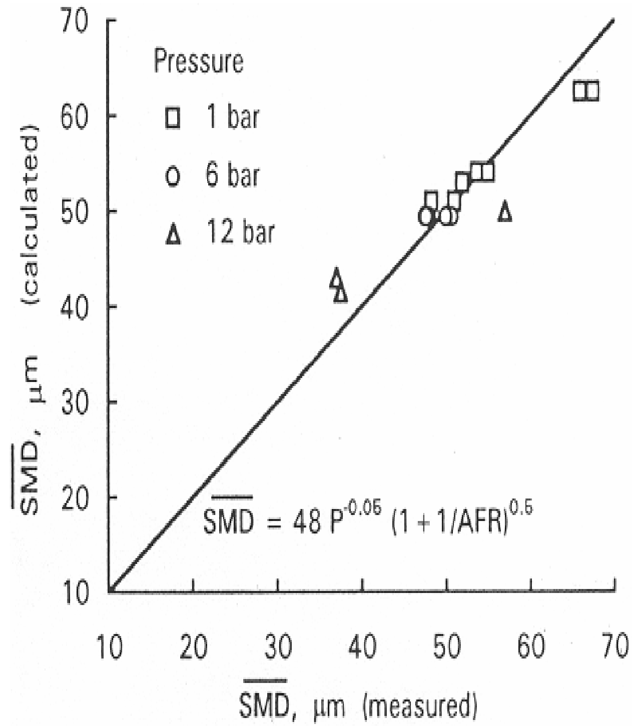


Fig. 8 $\overline{SMD}$ correlation, high-shear design (1b).

Analysis of all the experimental data acquired in this programme resulted in the following correlation

$$\overline{SMD} = 48\, P^{-0.05}\, [1 + (1/AFR)]^{0.5} \qquad (2)$$

where $\overline{SMD}$ is in microns and P is the ambient air pressure in bar [22]. The level of agreement realised by Eq. 2 is illustrated in Fig. 8. This equation is not dimensionally consistent and basically serves to illustrate in a simplistic way the effects of two main variables covered here. A major limitation of this correlation from a practical viewpoint is the absence of liquid properties of viscosity and surface tension, atomizing air velocity, and characteristic injector dimension(s). Nonetheless it serves to provide a simple basis for drawing some illustrative comparisons against the previously developed correlation for the low-shear design as typified by injector 1a. The exponent for 1+ (1/AFR) term can be seen to be identical for the low- and high-shear concepts when operating on low viscosity kerosine type of fuels. There is, however, a major difference in regard to the exponent for the air pressure (or density) term – an exponent of –0.05 for the high-shear design versus that of –0.45 for the low-shear configuration. Intuitively this seems to make sense in so far as the low-shear designs would be expected to present a greater scope for further spray quality improvement vis-à-vis an increase in atomizing air density for instance. This additional shear force thus appears to yield a greater level of effectiveness relative to that on a high-shear based system. Essentially low-shear designs exploit the slow, classical, wavy break-up route to spray development initiated by a low intensity, weak aerodynamic interaction between the fuel and air streams. High-shear designs, on the other hand, invoke 'instantaneous or prompt' disintegration of liquid sheet directly into droplets due to a vigorous and more intense aerodynamic interaction with a turbulent air flow-field. The comparatively high levels of shear and turbulence generated inhibit the growth of flow and surface instabilities [26]. This serves to clarify the noticeably different spray quality response of low- and high-shear injector design concepts to increases in ambient air pressure. Of course, a high-shear design does not necessarily guarantee high rates of shear always. For example, because air velocities are low during start-up and low power operation, low-shear rates prevail regardless of the atomizer design. This implies that under some engine conditions a low-shear mechanism could be dominant, while under other conditions a high shear mechanism could assume overriding importance.

It should be mentioned here that the low-shear, airblast atomizer correlation has been developed from extensive studies conducted by numerous different researchers over a prolonged period of time. In contrast the high-shear injectors have received only limited attention over a comparatively narrow range of design and operational variables. Clearly, this is an area that warrants a thorough and systematic investigation embracing all the key variables. Briefly, these comprise the liquid properties of density, surface tension and viscosity; air properties of atomizer air to fuel mass ratio, atomizing air stream velocity and ambient air pressure; and nozzle design features relating to the fuel and air passage circuits. The promising, variable fuel placement design shown in Fig. (1d) also merits detailed studies to explore its spray performance characteristics, relative to current designs, at realistically high air and fuel flows and high ambient air pressures.

4. CONCLUSIONS

A comparative spray performance evaluation of the pre-filming airblast injectors featuring low- and high-shear design philosophies over a wide range of ambient air densities (14.5 kg/m^3 max) and kerosine flow rates (95 g/s max) enables the following conclusions to be drawn:

1. Increase in ambient air pressure under conditions of constant injector air to fuel mass ratio and constant air pressure drop was observed to appreciably influence the spray trajectory and cone angle for up to two pre-filmer diameters from nozzle exit for the modern, high-shear designs. Measurements at a near-nozzle distance of ~10 mm from the injector exit revealed a cone angle widening from around 70^0 at 1 bar to 105^0 at 12 bar. Low-shear designs have not been tested for cone angle behaviour under comparable conditions but are generally believed not to exhibit such a spray trajectory – cone angle sensitivity in the near-nozzle regions to ambient pressure variations. The principal explanation for this different behaviour is to do with the different design philosophies. The low-shear design incorporates broadly similar 'fuel-alone' and 'air-alone' cone angles, consequently its combined cone angle behaviour is unlikely to exhibit much of a sensitivity to changes in operating conditions. High-shear designs feature a wider fuel-only cone angle, which dominates the near-nozzle behaviour under conditions of increasing injector fuel flows.
2. Cone angle – spray trajectory behaviour at distances larger than two pre-filmer diameters is practically unaffected by changes in operating air pressures at constant atomizer AFR and air pressure drop for both the low- and the high-shear designs.
3. The radial distribution of fuel within the spray cone has been observed to change with operating conditions for the high-shear designs. This is expected to be so for the low-shear design too, albeit to a lesser extent.
4. The effect of increases in atomizing air pressure upon overall (i. e. line-of-sight) spray Sauter mean diameter is significantly different for the low- and high-shear injector designs. In contrast, the atomizer air to fuel mass ratio effect on spray quality is much the same. These findings warrant further research on the modern, high-shear design to understand more fully the manner and the extent to which different variables govern the influence on spray performance.

5. ACKNOWLEDGEMENTS

Thanks are due to colleagues and students for their contributions to my research in the area of gas turbine fuel injection over the last twenty plus years. Special thanks are due to David Whittington for his painstaking support over the last 20 years in respect of the experimental facilities and other related matters. Major gas turbine sponsors for my research have comprised MoD (DERA, DRA, NGTE), Rolls-Royce plc, Commission of European Communities, Engineering and Physical Sciences Research Council, MoD-Overseas, Parker Hannifin Corporation etc. I would like to gratefully acknowledge them for their financial support and confidence in my research.

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