THE ROLE OF AIR & FUEL PROPERTIES IN MEAN DROP SIZE CORRELATIONS FOR AIRBLAST ATOMIZED GAS TURBINE SPRAYS

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ABSTRACT

Current status of spray mean drop-size correlations for the gas turbine airblast atomizers of the pre-filming and plain-jet type is outlined in this paper. Methodology for their development for the low-shear, pre-filming and plain-jet airblast atomizers is presented in detail, thus helping to eliminate the long-standing confusion with regard to the precise role of air density in SMD correlations pertaining to the operation of such atomizers on both low and high viscosity fuels. This study also highlights a critical need for exhaustive research on the high-shear, pre-filming airblast atomizer encompassing a wide range of operational and design variables from the drop size performance correlation standpoint. This will help to extend our knowledge database concerning their behaviour relative to that of the low-shear designs.

INTRODUCTION

The gas turbine airblast fuel injector has been the subject of intensive, on-going research and development over the last thirty or so years in order to satisfy the continuously evolving requirements of combustion performance, fuel consumption and flexibility, and pollutant emissions. The necessity for improved fuel injector designs was initially triggered by the problems of exhaust smoke, flame radiation and poor pattern factor as a direct consequence of the reduction in spray penetration and cone angle encountered by all types of pressure-swirl atomizers with increases in combustion chamber operating pressures. The pioneering work of Lefebvre led to the development of a novel type of fuel atomizer in which the bulk liquid was first pre-filmed and spread into a low velocity, thin annular sheet that was subsequently exposed to the shearing action of high velocity air steams on both sides. This new concept, referred to as the airblast atomizer, delivered a fine, well-mixed spray of airborne droplets thus yielding significantly superior combustion – emissions performance [1-4]. This basic pre-filming atomizer design philosophy has seen the most widespread acceptance in the modern, high-pressure ratio gas turbine engine to date. An alternative but simpler form of airblast atomizer concept featuring the deployment of multiple, discrete liquid jets and referred to as the ‘plain-jet’ design has also been explored in some depth [5, 6]. This simpler concept has been incorporated into some large industrial gas turbines and is also being explored for use in modern, low-emission research configurations. These early research and development efforts were centred on ‘pre-filming’ and ‘plain-jet’ airblast atomizer configurations featuring comparatively low levels of shear through the deployment of swirl-free (or low-swirl intensity) airstreams. From around 1980 onwards however, airblast atomizer designs increasingly began to utilise high-swirl intensity airstreams. This promoted higher levels of shear and mixing between the two fluid streams as an integral part of the fuel spray formation process, to achieve further improvements in combustion and emissions performance. In high-shear designs the liquid sheet is subjected to an intense, turbulent flow-field that results in its rapid disintegration into a well-atomized spray with improved mixing and dispersion characteristics. Despite the prolonged period of time over which fuel sprays have undergone extensive investigations, our knowledge concerning the underlying processes of primary liquid break-up and spray formation is far from satisfactory to enable the prediction of droplet sizes purely from theoretical considerations. This inability to predict atomization quality *a priori* presents a serious difficulty to the practising engineer faced with the objective of trying to realise optimum combustion system performance for a given set of operating conditions. As a consequence, parametric experimental investigations exploring different nozzle design concepts, followed by a meticulous analysis of the resulting data to derive empirical spray mean drop size correlations, have been the norm in airblast atomization research over the last thirty or so years. This paper outlines some of the prevailing uncertainties within various pre-filming and plain-jet airblast atomizer correlations, including those pertaining to the rather challenging operating conditions of high air densities both with and without high fuel viscosity levels. Such conditions are of considerable relevance to both the aircraft and the industrial gas turbines as pressures to achieve significant improvements in the areas of emissions, fuel flexibility and consumption mount. It is anticipated that this paper will help to clarify and remove some of the confusion in this important and much valued area of fuel injector technology.

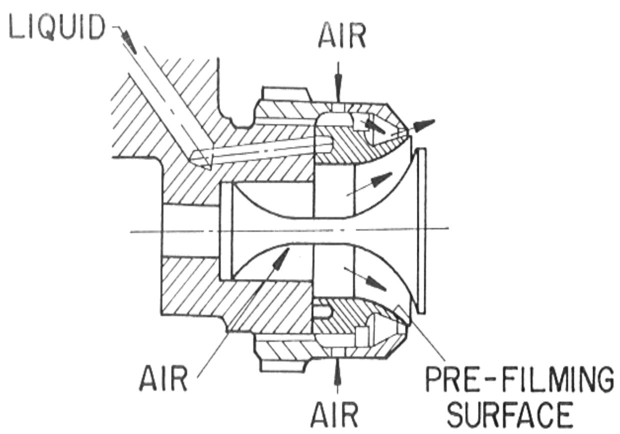

Fig. 1 Pre-filming Airblast, Low-Shear.

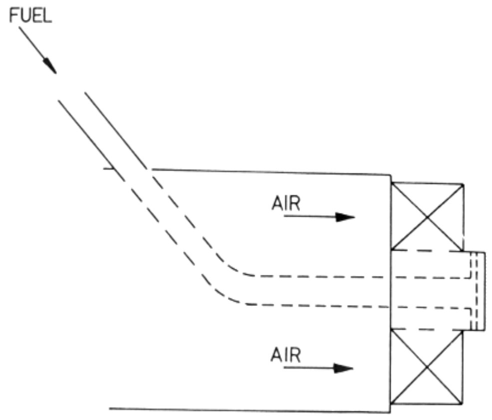

Fig. 3 Plain-Jet Airblast, Low-Shear.

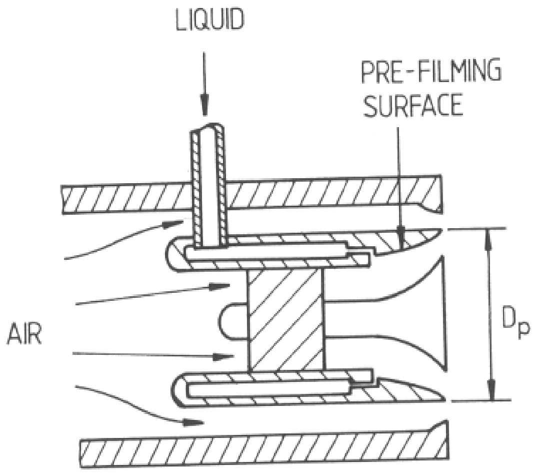

Fig. 2 Pre-filming Airblast, Low-Shear.

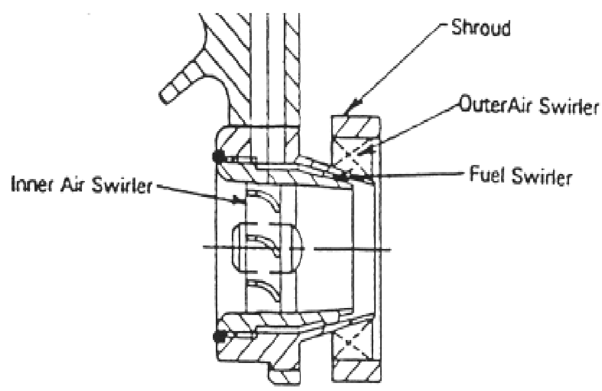

Fig. 4 Pre-filming Airblast, High-Shear

EXPERIMENTAL

A wide variety of airblast atomizers have been studied in specialist facilities at the Cranfield laboratories under varying air density conditions [2, 3, 6-9]. Schematic details of the present high-pressure spray facility can be found elsewhere [9]. The present pressure vessel is large enough to include all the major aerodynamic features of the combustor primary zone in addition to the engine standard fuel injector to ensure a representative measurement capability. It incorporates flexible optical access for a range of modern, non-intrusive diagnostics such as phase-Doppler interferometry and laser sheet imaging embracing both Mie scattering and laser induced fluorescence [9]. In contrast, circa 1980 research featured an in-house developed, laser light scattering technique [5-7]. Standard, calibrated laboratory procedures were employed to obtain measurements of variables such as air and fuel mass flow, pressure and temperature. Test fuels have ranged from highly refined aviation kerosine to a low grade of residual fuel oil, thus facilitating a wide variation in viscosity (μ_L *=0.0013 kg/ms @ 15^0 C to 0.086 kg/ms @ 75^{0}C,* ρ_L = 784 to 966 kg/m^3, and σ_L = 0.0277 to 0.0353 Kg/s^2) [3-8]. Standard tap water too has served as a spray media for a variety of test situations (μ_L *=0.0010 kg/ms at15^{0}C,* ρ_L = 1000 kg/m^3, and σ_L = 0.0735 Kg/s^2). The air temperature during the atmospheric through to high ambient air pressure research phases has been generally maintained around 300 to 325 K, thus implying negligible levels of droplet evaporation. Wide variations in atomizer air to fuel mass ratio, AFR, and atomizing air velocities, V_a, (i.e. atomizer air pressure drops) have been explored in general. A special feature of the author's work is the unparalleled variation in air density, in order to maintain a close similarity to the levels prevailing within the modern, high-pressure combustor [9]. Extensive droplet size measurements have been made on different airblast atomizers at ambient air pressures of up to and including 14 bar [6, 7, 9]. Most of these drop size measurements have been made at a downstream distance of 45 to 50 mm from the injector exit in order to ensure that near-nozzle regions, wherein combustion is initiated and sustained, are covered adequately.

Schematic details of the various airblast atomizers included in this study are illustrated in figures 1-4. This choice was governed by the twin considerations of ensuring compatibility with the gas turbine industry practice, and ease of availability of an in-depth droplet size database. Broadly speaking Figs. 1 [2, 5, 7] and 2 [3, 4] are conceptually similar except for some minor differences in respect of airflow passages – those of Fig. 2 being somewhat more streamlined than those of its predecessor. Both these designs are comparatively early ones incorporating a long, divergent pre-filming surface that generates an annular sheet of fuel which is subsequently 'sandwiched' between two high velocity, non-swirling airstreams. An injector based on this generic concept was utilised in some of the very early versions of the

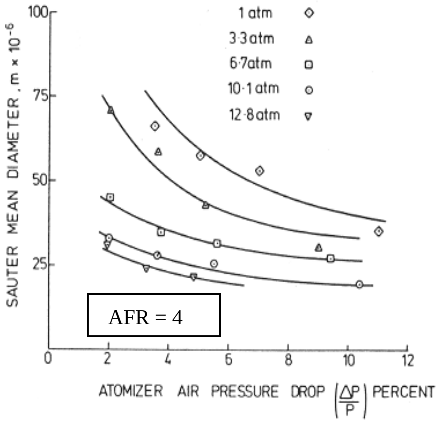

Fig. 5 SMD Performance of Fig. 1 Atomizer at various Ambient Air Pressures on Kerosine Fuel.

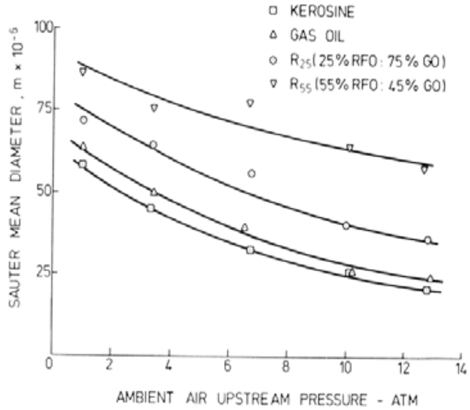

Fig. 6 SMD Performance of Fig. 1 Atomizer on Alternate Fuels at High Air Pressures (AFR=4, Air ΔP=5%).

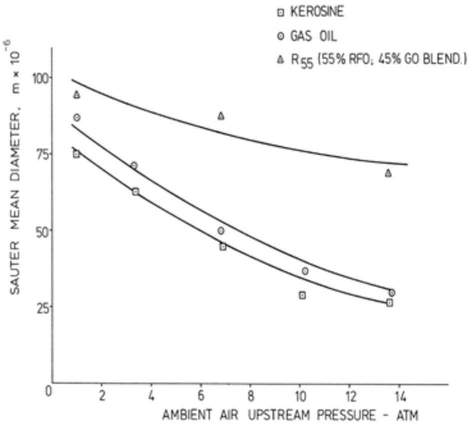

Fig. 7 SMD Performance of Fig. 3 Atomizer on Alternate Fuels at High Pressures (AFR=4, Air ΔP=3.5%)

RB211 engine. A basic requirement of this design concept is the provision of two, separate airflow passages within the injector body, thus adding to its complexity and cost. A plain-jet airblast atomizer of the type shown in Fig. 3 is, therefore, sometimes preferred due to its simpler and less expensive nature [5, 6]. In this design a single airstream flows through a conventional swirler, just downstream of which fuel issues out of plain circular holes in the form of discrete, multiple jets. These jets, numbering one per air annulus of the swirler, undergo in-flight disintegration without any prior preparation such as pre-filming. Another variant of the pre-filming family is shown in Fig. 4, featuring a short, convergent pre-filmer with contra-swirling inner and outer airstreams [9]. An injector of a similar design has been employed in some of the earlier versions of the RB211 engine. One of the major facets of injector design philosophy since the early 1980s has been the adoption of higher rates of shear, in marked contrast to the earlier designs. Pre-1980 designs exploit the classical, wavy break-up route to spray formation featuring low rates of shear due to weak aerodynamic interactions, whereas the post-1980 designs tend to invoke ‘instantaneous or prompt’ route to spray formation due to higher rates of shear that generate appreciably more intense and vigorous aerodynamic interactions.

BASIC SPRAY DROPSIZE TRENDS

Before discussing the development of mean drop size correlations, it is essential to realise that the bulk liquid is first prepared into a characteristic form prior to being subjected to the shearing action of the atomizing airstream(s). In the case of pre-filming airblast atomizers, the liquid is first spread into the form of a thin, annular sheet before being ‘sandwiched’ by airstreams that are either with or without swirl. In contrast, the liquid is converted into a plain, circular jet in the alternative airblast design before coming into contact with the atomizing airstream. Intuitively, the effect of liquid characteristic dimension such as a sheet thickness or jet diameter would seemingly be a maximum in situations of comparatively low-shear, and conversely a minimum in high-shear environments. The characteristic dimension for a liquid jet or sheet undergoing break-up relates to a diameter of the discharge orifice, d_o, or that of the discharge lip of the pre-filming surface, D_p, respectively for the two different types of atomizers covered in this study.

Figures 5 to 9 illustrate some drop size performance trends as a function of key variables of ambient air pressure (i.e. atomizing air density, ρ_A,), atomizing air pressure drop (i.e. atomizing air velocity, V_A,), and liquid viscosity, μ_L. Although not presented here, the effects of other important variables, namely atomizer air to fuel mass ratio, AFR, and liquid surface tension, σ_L, are discussed elsewhere for the various atomizer designs covered herein [3-9]. For the low-shear pre-filming and plain-jet designs they reveal that:

- Spray SMD reduces with increases in atomizing air velocity (or pressure drop) - Fig. 5.
- Spray SMD reduces with increases in atomizing air density (or pressure) - Figs. 5 to 7.
- Spray SMD increases with an increase in liquid viscosity – Figs. 6, 7.
- Spray SMD reduces with an increase in AFR – Refs. 3-8.
- Spray SMD increases with an increase in liquid surface tension – Refs. 3-4, 8.
- Low-shear pre-filming & plain-jet designs exhibit similar trends and broadly similar SMD levels on kerosene - Fig. 8.

In contrast, the rather limited amount of currently available database for the high-shear pre-filming atomizer provides a very restrictive insight into its behaviour in response to variations in operating parameters. Fig. 9 illustrates that the effect of an increase in atomizing air pressure/density manifests principally in the inner regions of the spray for the various characteristic drop diameters. Integrating point-wise drop size values across the spray radius, given that the majority of the fuel is contained in the outer regions, enables the determination of an area-weighted spray SMD. This in turn reveals the influence of air density on the overall spray SMD to be very small relative to that for the low-shear designs. Changes in atomizer AFR, on the other hand, have been observed to exhibit a similar effect as in the case of the low-shear design [9].

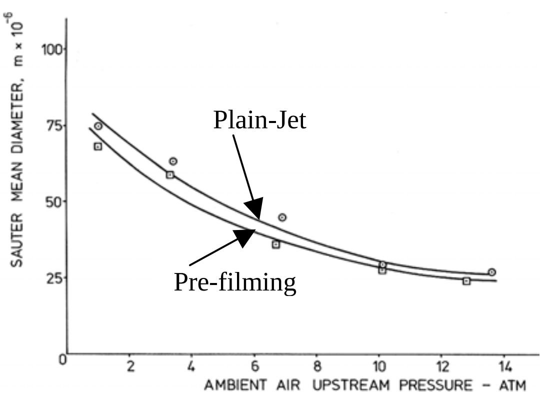

Fig. 8 Comparative SMD Performance of Fig. 1 & Fig. 3 Atomizers on Kerosine (AFR=4, Air ΔP=3.5%).

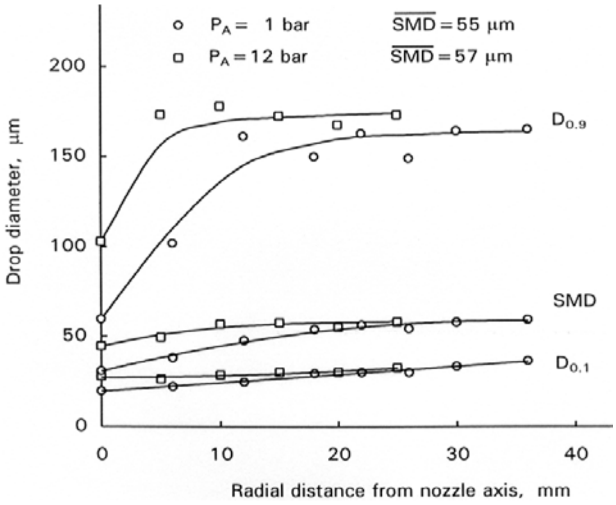

Fig. 9 Drop Size Performance of Fig. 4 Atomizer at Varying Air Pressures on Kerosine (AFR=4, Air ΔP=5%).

The trends established thus far for the high-shear, pre-filming airblast designs are as follows:

- Overall Spray SMD is largely insensitive to increases in atomizing air density (or pressure) – Fig. 9
- Overall Spray SMD reduces with an increase in AFR – Ref. 9.

MEAN DROPSIZE CORRELATIONS

Nukiyama and Tanasawa were the first researchers to come up with a drop size correlation based on their pioneering study on a geometrically simple plain-jet airblast atomizer back in 1939 [10]. Their work, as well as that of Lefebvre and co-workers [3, 4], suggested a summative form of correlation wherein the overall SMD was expressed as a sum of two terms, the first term being dominated by air properties, namely velocity and density, and the second term by liquid viscosity. Detailed and systematic air flow parameter-wise analysis of the author's extensive low-viscosity experimental data for the low-shear pre-filming designs revealed the following form of relationships

$$\begin{aligned} SMD &\propto (\rho_A)^{-0.45} \\ &\propto (V_A)^{-1.0} \\ &\propto (1 + AFR^{-1})^{0.5} \end{aligned}$$

Including the liquid surface tension effect, they lead to the following relationship

$$SMD \propto [(\sigma_L) / (\rho_A V_A^2)]^{0.45} (1 + AFR^{-1})^{0.5} \qquad (1)$$

Extending this analysis to high-viscosity data, following Nukiyama and Tanasawa [10], and Lefebvre et al [3] leads to

$$\begin{aligned} SMD - [\{(\sigma_L) / (\rho_A V_A^2)\}^{0.45} (1 + AFR^{-1})^{0.5}] &\propto \mu_L^{0.75} \\ &\propto (1 + AFR^{-1})^{0.8} \end{aligned}$$

This methodology follows the hitherto untested notion enunciated by previous researchers that fuel viscosity exercises an influence that is largely independent from that of air properties [3, 10]. Indeed the author's extensive, experimental data revealed little variation in the viscosity-dominated second term with air density alterations. Consolidating all the terms into a single correlation we have

$$SMD \propto [(\sigma_L) / (\rho_A V_A^2)]^{0.45} (1 + AFR^{-1})^{0.5} + [(\mu_L^2) / (\rho_L \sigma_L)]^{0.375} (1 + AFR^{-1})^{0.8} \qquad (2)$$

It should be noted that equation (2) above is not dimensionally consistent. However, introducing the pre-filmer lip diameter, D_P, overcomes this shortcoming to yield

$$SMD = A [(\sigma_L) / (\rho_A V_A^2)]^{0.45} (D_P)^{0.55} (1 + AFR^{-1})^{0.5} + B [(\mu_L^2) / (\rho_L \sigma_L)]^{0.375} (D_P)^{0.625} (1 + AFR^{-1})^{0.8} \qquad (3)$$

or in the dimensionless form as

$$SMD / D_P = A [(\sigma_L) / (\rho_A V_A^2 D_P)]^{0.45} (1 + AFR^{-1})^{0.5} + B [(\mu_L^2) / (\rho_L \sigma_L D_P)]^{0.375} (1 + AFR^{-1})^{0.8} \qquad (4)$$

where A and B are dimensionless constants whose values can be obtained from the author's own extensive experimental database [7]. The level of agreement realised between the predictions of Equation 3 and the experimentally measured SMD data is illustrated in Fig. 10 for A = 0.17 and B = 0.017, wherein the bulk of the measured values can be observed to fall within the ± 25% bands.

Comparison of this correlation with the previous work on the same pre-filming airblast atomizer family reveals some significant differences, especially in respect of the precise role of air density and liquid viscosity properties in spray mean drop performance. As can be seen in equation 3 above, the air density term, ρ_A, has an exponent, n, in the first term of –0.45 whereas the viscosity-dominated second term is completely independent of it. This is in marked contrast to the findings of the only two previous studies that merit a comparison, on account of having actually explored experimentally the effect of air density upon spray SMD [2-3]. Taking them chronologically, Bryan et al reported an air density exponent of –0.6 based on experiments conducted on low-viscosity fluids only [2]. Furthermore, they did not propose a comprehensive drop size correlation due to a restricted range of variables explored. Rizkalla and Lefebvre were the first to conduct a comprehensive pre-filming airblast atomization study featuring wide variations in air and liquid properties including air pressures up to 8.5 bar and liquid viscosity up to 0.044 *kg/ms* [3]. Their work was followed by the study undertaken by El-Shanawany, under Lefebvre's direction, to extend the work to embrace the effects of atomizer scale upon spray performance, but only under atmospheric pressure conditions [4]. Due to its more wide ranging nature, Rizkalla et al correlation [3] is deemed as more appropriate for comparison and is consequently reproduced here in its dimensionless form

$$SMD / t = A [(\sigma_L \rho_L / t)^{0.5} / (\rho_A V_A)^{-1}] (1 + AFR^{-1}) + B [(\mu_L^2) / (\rho_A \sigma_L t)]^{0.425} (1 + AFR^{-1})^2 \quad (5)$$

where A and B are dimensionless constants and, t, the initial liquid sheet thickness at the pre-filming lip which following Lefebvre is proportional to, D_P, the pre-filmer lip diameter [12]. Equation 5 reveals a ρ_A exponent of –1 and –0.425 respectively for the first and second terms; by comparison the author's work revealed corresponding values of -0.45 and 0 – see equation 3 above. The inclusion of air density in the viscosity-dominated second term by Rizkalla et al was principally on the grounds of dimensional consistency, as their investigation did not actually embrace the variation of air density on high viscosity liquids. To-date the only pre-filming airblast atomizer study that has experimentally explored the performance of these sprays for such a demanding combination of high viscosity fuels under high ambient air pressures is that reported by the author [7]. This was an important and necessary piece of work, in order to clarify whether it was an air or liquid density property that was appropriate for inclusion in the viscosity-dominated second term of the proposed correlating equations for the pre-filming airblast atomizer [11-12]. This uncertainty first arose during the mid 1970s, and confusion has seemingly prevailed ever since [3, 12]. Based on a wider range of ambient air pressures, the author's work also revealed the influence of air density to have been appreciably overstated in the air property based first term of the correlation. The earlier work featured an exponent of –0.6 to –1.0 [2-3], in contrast to a more realistic level proposed by the author of –0.45.

Equation 4 can be re-written using $W_{E,\,A}$, $W_{E,\,L}$ and $R_{E,\,L}$ which denote Weber number as applied to air and liquid properties, and the liquid Reynolds number respectively. The new correlating equation takes the form of

$$SMD / D_P \propto (1 / W_{E,\,A})^{0.45} (1 + AFR^{-1})^{0.5} + [(W_{E,\,L})^{0.5} / (R_{E,\,L})]^{0.375} (1 + AFR^{-1})^{0.8} \quad (6)$$

The nature of the $(1 + AFR^{-1})^n$ term is such that for typical pre-filming atomizer design AFR, the difference due to changing the exponent, n, from 0.5 to 0.8, as is the case in equation 6, is small enough to be ignored as a first approximation i.e. circa ± 5%. The current trend towards leaner primary zone to minimise NO_x emissions means that this difference will assume even lesser significance as the atomizer design AFR values rise. Eq. 6 simplifies to yield

$$SMD / D_P \propto (1 / W_{E,\,A})^{0.45} + (Z)^{0.375} \quad (7)$$

Where Z is the Ohnesorge number, Oh, simply collating the relevant fuel properties through a ratio of the liquid property-based Weber and Reynolds numbers, namely $[(W_{E,\,L})^{0.5} / (R_{E,\,L})]$. Thus the effect of air density is embedded within the air properties based Weber number, while that of fuel viscosity within the totally independent Ohnesorge number. The selection of liquid density instead of air density, as was the case before the author's findings, for inclusion in this second term makes it a liquid property only based group as opposed to the mixed liquid-air property based grouping used previously.

Repeating all the foregoing stages of correlation development methodology using an appropriate experimental database for the plain-jet airblast atomizer [6] and substituting, d_o, the orifice diameter as the characteristic dimension instead of, D_P, the pre-filmer lip diameter, one eventually arrives at the following correlation

$$SMD = 0.022 [(\sigma_L) / (\rho_A V_A^2)]^{0.45} (1 + AFR^{-1})^{0.5} + 0.00143 [(\mu_L^2) / (\rho_L \sigma_L)]^{0.4} (1 + AFR^{-1})^{0.8} \quad (8)$$

The above equation is not dimensionally consistent but can be made so through the inclusion of fuel orifice diameter, d_o, to yield

$$SMD / d_o = A [(\sigma_L) / (\rho_A V_A^2 d_o)]^{0.45} (1 + AFR^{-1})^{0.5} + B [(\mu_L^2) / (\rho_L \sigma_L d_o)]^{0.4} (1 + AFR^{-1})^{0.8} \quad (9)$$

which ultimately reduces to

$$SMD / d_o \propto (1 / W_{E,\,A})^{0.45} + (Z)^{0.4} \quad (10)$$

Correlating equation 10, which symbolises the performance of the plain-jet style of airblast atomizer, can be seen to differ only very slightly from equation 7 i.e. that of its pre-filming counterpart. The difference relates to the exponent for the fuel property based Ohnesorge number – that of 0.375 and 0.4 for the pre-filming and plain-jet types respectively. This suggests a slightly higher sensitivity of the plain-jet atomizer to liquid viscosity variations. Generally speaking, this corroborates the illustrative performance comparison depicted in Fig. 8 over a wide range of ambient air pressures.

Equations 7 and 10 also provide some rudimentary justification for the summative form of mean drop size correlations first proposed by Nukiyama and Tanasawa, and subsequently reinforced by Lefebvre and co-workers [10, 3]. The contribution of Oh number in these correlations changes from that of insignificance at low-viscosity levels to that of increasing significance at higher viscosity levels. This is particularly so at elevated air pressure level due to an appreciable increase in $W_{E,\,A}$. This serves to explain the different air density effects observed on low- and high-viscosity test liquids. It also reveals that the increasingly divergent character of the high-viscosity curve at higher ambient air pressures, as illustrated in Figures 6 and 7 for example, is a reflection of the interplay between two opposing effects. A rise in air density triggers a beneficial effect due to a corresponding increase in Weber number, and this is countered by the adverse effect resulting from a higher Ohnesorge number as liquid viscosity increases. In other words, it shows for the first time an incrementally diminishing level of benefit on higher viscosity fuels due to increases

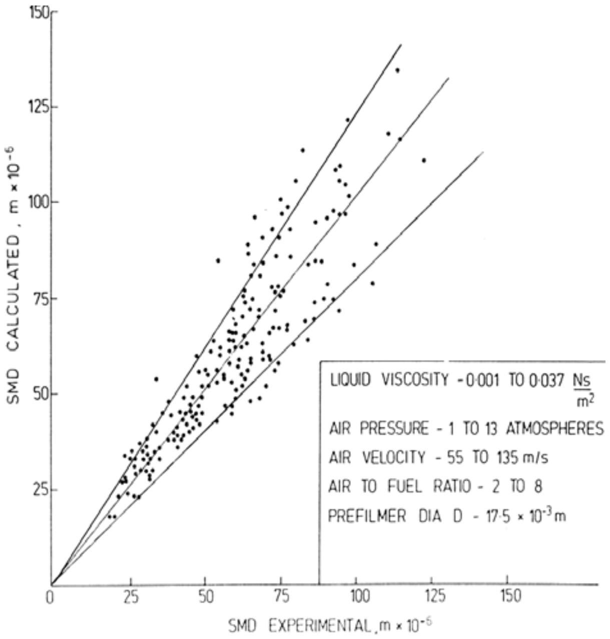

Fig. 10 SMD Correlation, Fig. 1(& ~ Fig. 3) Atomizer

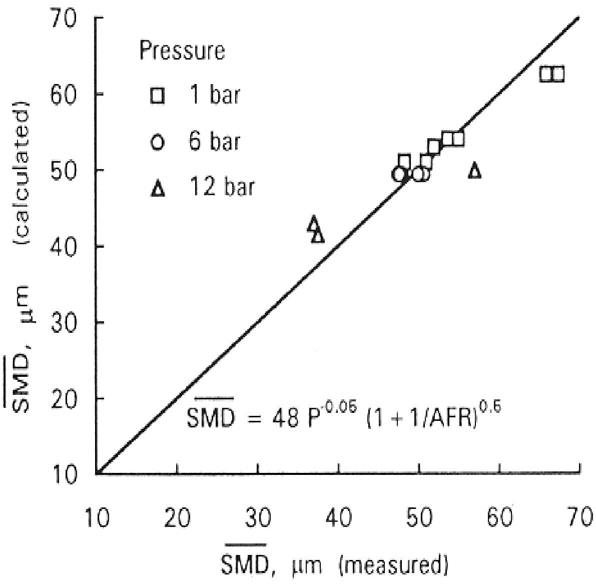

Fig. 11 SMD Correlation, Fig. 4 Atomizer

in air density relative to the low viscosity case. For these atomizer designs it also implies that the task of attaining good atomization performance on high viscosity fuels is likely to be rather difficult. Given their inferior volatility characteristics, achieving effective fuel preparation from the standpoint of adequate combustion and emissions performance could therefore be somewhat challenging.

The foregoing sections have featured a mean drop size equation development methodology that is relevant to pre-1980 airblast atomizer designs employing low-shear rates in transforming the bulk liquid into a spray of droplets. Post-1980 practical, pre-filming airblast atomizer designs, on the other hand, utilise high-shear rates to generate the droplet spray as stated already. Unfortunately these high-shear injectors have received only very limited attention thus far over a comparatively narrow range of operational and design geometry variables. For example, the liquid properties of viscosity and surface tension, atomizing air velocity, and nozzle geometry features have not been explored systematically with a view to developing a mean drop size correlation of a quality comparable to that of the low-shear airblast atomizer family. Analysis of this limited low-viscosity experimental database, following the previously outlined methodology, yields the following relations

$$\mathrm{SMD} \propto (P_A)^{-0.05}$$
$$\propto (1 + \mathrm{AFR}^{-1})^{0.5}$$

where SMD is the weighted, line-of-sight overall spray mean diameter derived from point-wise mean drop size values and P_A the ambient air pressure [9]. They combine together to yield the following equation

$$\mathrm{SMD} = 48\,(P_A)^{-0.05}\;(1 + \mathrm{AFR}^{-1})^{0.5} \tag{11}$$

where SMD is in microns and P_A in bar. The level of agreement between the measured and calculated SMD values when using equation 11 is illustrated in Fig. 11. A major drawback of this tentative equation is that it is dimensionally inconsistent, but it is anticipated that the availability of additional database will enable this shortcoming to be addressed in due course.

Regardless of its preliminary nature, equation 11 enables some illustrative comparisons to be made against the air properties only based equation 1. This provides an insight into the behavioural differences between the low- and high-shear pre-filming airblast injector design philosophies when operating on kerosine-type of low viscosity fuel. The exponents for the $(1 + \mathrm{AFR}^{-1})$ term are identical, whereas those for the air density (or pressure) term differ by almost an order of magnitude i.e. –0.45 and –0.05 for low- and high-shear designs respectively. Essentially injectors employing different shearing philosophies invoke different break-up mechanisms with their own distinctive nature and scale of fuel-air interactions, and in turn they display different levels of sensitivity to changes in air pressure. More efficient mechanisms will generate finer sprays, and that in turn would be expected to offer a smaller scope for further improvement vis-à-vis an increase in atomizing air density, for example. It should, however, be recognised that a high-shear design cannot always ensure high rates of shear. For example, air velocities during start-up and low power operation are not fully established and are comparatively low, as a consequence low-shear rates would prevail even on high-shear atomizer designs. This means that the break-up mechanism can change from one engine operating condition to another on a given injector design. The key parameter that determines which mode of atomization is going to exert the overriding influence at any given operational condition is the Weber number. Increases in rates of shear through higher relative velocities, and higher turbulence levels through a steeper angle of impact will both accelerate the break-up process vis-à-vis an increase in Weber number. Clearly the modern, high-shear injectors featuring multiple, strongly swirling airstreams merit further detailed and systematic study, embracing wide variations in all key operational and nozzle design variables including the high ambient air pressure work on high viscosity fuels.

CONCLUDING REMARKS

For the foreseeable future improvements in fuel-air mixture preparation are going to govern the ability of the combustion engineer to deliver solutions that comply with the evolving regulations in respect of NO_x and other pollutants. The fuel injector has occupied a pivotal role throughout the development of the combustor. The current level of knowledge relating to mean drop size correlations for some of the commonly used airblast atomizers is outlined in the foregoing sections. The detailed methodology presented above helps to clear up the long-standing confusion regarding the precise role of air density in SMD correlations pertaining to low-shear nozzle operation on both low- and high-viscosity fuels. This study also reveals a critical need for exhaustive research on the high-shear injector designs to cover a wider range of variables, including the current trend towards higher atomizer AFRs given the push for leaner primary zones. A word of warning here for the uninitiated is to stay strictly within the limits of applicability of the different variables for any given correlation. Equally, one needs to give due consideration to the question of geometric similarity in arriving at the correlation that is deemed to be appropriate and relevant to a given situation. This simply reflects the fact that no correlation is universally applicable and that there are carefully defined limits, usually by the original investigators, within which it can be relied upon.

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