The Influence of Atomizer Geometry on Effervescent Atomization

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Abstract

After an extensive literature review of the current state of this technology, an adjustable geometry effervescent atomizer was designed, built and studied at the Cardiff School of Engineering. Water and air were used as the operating fluids. The sprays produced by the atomizer were characterized using a Phase Doppler Anemometry (PDA) system which allowed for simultaneous real-time droplet size and velocity data to be obtained. High quality data was achieved, with data rates over 10 kHz and validation rates over 90 % in 2-D PDA mode in the high density sprays. A PDA probe designed for dense spray applications was utilized. A number of important operating parameters identified during the literature review phase could be altered on the atomizer, and their effects on fuel spray quality investigated. The operating parameters investigated in this manner included a number of operating parameters, geometric parameters as well as fluid viscosity. This paper discusses and analyzes the influence of geometric parameters on the quality of atomization. Geometric parameters investigated include exit orifice diameter, nozzle length-to-diameter ratio, mixing chamber diameter, mixing length and air injection geometry. Comparisons are made with previous studies performed using earlier versions of the hardware or alternative sampling techniques. Ongoing work will assess and optimize the performance of the atomizer using simulated biofuels mixtures – these will be presented in future publications.

Introduction

Atomization – the break-up of large volumes of fluid into small droplets – is an important process employed in the chemical industry, agriculture, food processing, fuel injection and power generation. Of particular interest to the power generation sector is the atomization and injection of liquid fuels into combustors, incinerators and engines. Initial atomization of the liquid fuel is key to the fuel mixing and evaporation processes, which in turn impact the combustion efficiency and emissions. In combustion systems, reductions in mean droplet sizes result in higher volumetric heat release rates, easier light-up, wider burning ranges and lower exhaust concentrations of pollutant emissions [1]. Therefore in order for efficient combustion to be achieved in an economical manner, the use of a robust, well designed fuel atomizer is critical.

Fuel atomizers commonly used in industrial applications include rotary, pressure, air-assist and air-blast atomizers. Traditional combustion systems have been greatly optimized for their use over many decades. However, rather than traditional liquid hydrocarbons, combustion engineers are being increasingly forced to look into the use of alternative, biologically-derived hydrocarbon fuels. Such fuels often have very different fluid properties or display complex, non-linear behavior (e.g. non-Newtonian viscosity displayed by some Bio-Diesel blends) when compared to conventional fuels.

The acceptance to utilize such challenging liquid fuels is dictated by a combination of government directives, supply issues, fear of depletion of current stocks and increases in fuel prices (e.g. crude oil). For example a boycott by OPEC countries in 1973 led to a doubling or even tripling of crude oil prices in, amongst other countries, the USA [2].

Traditional combustion systems are not well suited to utilizing the new fuels, whether on their own (pure bio-diesels) or in combination with established fuel types (blends). Heavier fuels can potentially clog the fuel injector components and are problematic to atomize to acceptably small sizes. To achieve acceptable spray quality the heavy fuels often require pre-heating or treatment prior to use [3].

Nevertheless, bio-fuels are a promising fuel for the future because they are a comparatively cheap (especially with government subsidies), renewable source of energy that can be used on current combustion systems with relatively minor modifications. Finally, biofuels are considered "carbon neutral" sources of energy which can be an additional incentive to their implementation (although this depends on the type of biofuel and whether such factors as processing and transportation are considered when defining the term "carbon neutral").

They do, however, have disadvantages compared to conventional fuels. For example they tend to have lower heating values and therefore appear less economical to employ than standard fuels. Solid particulates present in the alternative fuels can also increase component wear and possess complicated fluid rheology. In addition, cost-

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intensive processing is required to allow fuel firing on current systems while inefficient combustion (due to the use of unusual fuels) leads to higher emissions of pollutants such as carbon monoxide, oxides of nitrogen (NOx) or partially combusted hydrocarbons.

At various times in the past decades high crude oil prices made research into new technologies for atomizing alternative fuel types seem more economically feasible. One promising new atomizer was developed in the 1980's by Lefebvre and co-workers, relying on a novel form of atomization now called Effervescent Atomization (EA).

This method, which differs fundamentally from traditional atomization techniques, relies on the creation of a pressurized "bubbly" two-phase flow upstream of the atomizer exit orifice. Upon discharge from the exit orifice the compressed gas-phase escapes the mixture, expanding rapidly and shattering the liquid fuel into ligaments and droplets (which can undergo further secondary atomization). It was found that this type of atomization was particularly advantageous for comparatively viscous fuels providing several advantages over conventional atomizers [4], such as:

- Large exit orifice diameters can be used on the atomizers helping to avoid nozzle blockage by high viscosity fluids and to reduce component wear.
- Fluid viscosity has a minimal impact (compared to impact on traditional atomizer types) on the resulting droplet sizes, allowing a single atomizer to be employed with a range of fluids.
- Equivalent droplet sizes were observed at injection pressures lower than those required by other atomizer designs (or comparable atomization at lower pressures thus reducing the pumping requirements and associated energy losses).
- The use of air as the atomizing gas was found to improve combustion efficiency, which leads to reduced soot formation and exhaust smoke [5].

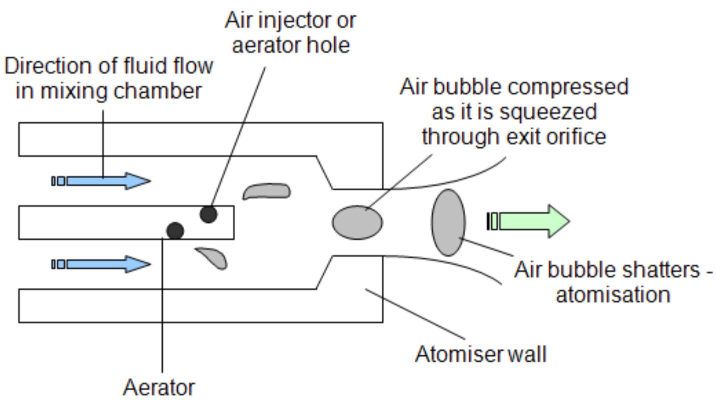
Thus the EA technique has been shown to have potential benefits in various industrial applications. With a view to this, an extensive literature review was performed to determine the primary operating parameters controlling EA [6].

The present paper investigates the influence of atomizer geometric parameters (discovered during the literature review) on EA. The optimization of geometric parameters is relevant to all effervescent atomizer applications. The current work discusses geometric parameters having an important influence on spray quality (exit orifice diameter, nozzle length-to-diameter ratio), as well as parameters very rarely mentioned in the literature (mixing length, mixing chamber diameter and air injector geometry). The present investigation therefore fills a gap in the current understanding of EA.

Experimental Methods

Experiments were performed at the Cardiff School of Engineering to characterize the effervescent atomizer developed, and to investigate the primary operating parameters controlling EA.

An adjustable "inside-out" type effervescent atomizer was designed based on the recommendations of Chin et al [7]. The atomizer was designed to perform at 2 MW equivalent power, though it should be noted that only air and water were used for the tests herein. Figure 1a shows a sketch of a typical inside-out type effervescent atomizer, and Figure 1b illustrates the parameters investigated in the present study. Figure 2 represents a schematic of the test rig used for the experiments.



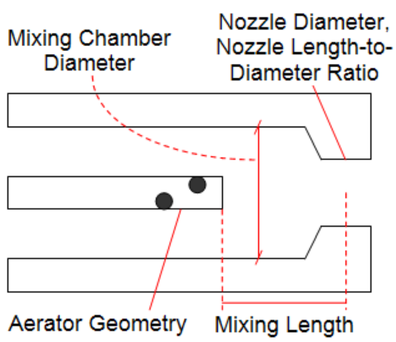


Figure 1a A sketch of an "inside-out" type effervescent atomizer. **Figure 1b** Geometric parameters investigated.

A rectangular water tank (WT) containing up to one cubic meter of water was used both to store the water and to capture the spray issuing from the atomizer (A). A Lowara SV 224 F30T 3-phase, vertical, multistage electric pump (WP) capable of delivering pressures over 10 barG was used to circulate the water. From the water tank the water was pumped through a calibrated Emerson Micromotion CMF 050 coriolis meter (CM1) before passing through a check valve (CV1) and being supplied to the atomizer mixing chamber. Water pressure and temperature were measured just prior to injection to the mixing chamber via a calibrated 0-10 barG Druck PTX 1400 pressure transmitter (P1) and a type K thermocouple (T1), respectively. The atomizer was located centrally over the water tank. Air was provided by the house air compressor (AC) at up to 7 barG. This was fed through a calibrated Emerson Micromotion CMF 025 coriolis meter (CM2), a check valve (CV2), a calibrated 0-10 barG Druck PTX 1400 pressure transmitter (P2) and type K thermocouple (T2) before being injected into the atomizer mixing chamber. The stability of the air compressor and the use of a gate valve (GV3) allowed the air pressure to be set accurately with minimal pressure drift or fluctuations. The pressure of the fluids in the mixing chamber were monitored using a calibrated 0-10 barG Druck PTX 1400 pressure transmitter (P3) mounted on the atomizer body.

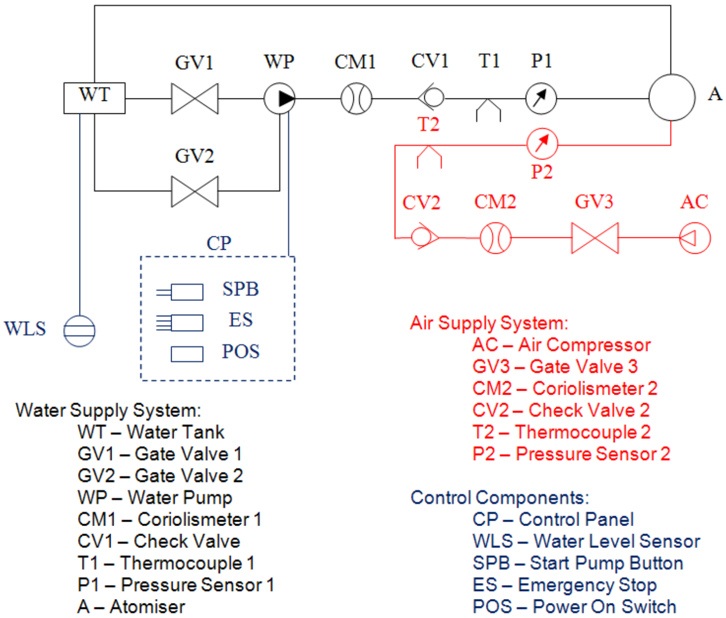


Figure 2 Schematic of fluid supply systems.

A 0-2 V input Delta T multi-channel data logger was used to record the pressures, flow rates and temperatures of both fluids at points of interest (pressure within the mixing chamber, pressure, temperature and flow rate just before injection to the atomizer). To achieve this the sensors P1, P2, P3, CM1, CM2, T1 and T2 were wired up to the data logger allowing real-time voltage readings to be viewed and recordings to be made. The sampling frequency of the data logger was set to 1 Hz for all tests performed.

Comparison with a National Instruments Compact RIO 9022 – NI CRIO 9022 – with NI 9205 analogue input card programmed using the FPGA sampling at 2 kHz indicated that sampling at 1 Hz produced an error of less than 1%, compared to sampling at 2 kHz.

The pressure transmitters were calibrated individually using a Druck DPI 601 Digital Pressure Indicator for pressures of 0-10 barG.

Phase Doppler Anemometry (PDA)

Droplet size measurements were performed using 2-D PDA. PDA is a non-intrusive optical laser diagnostic technique capable of simultaneously measuring the diameters, and up to three components of velocity of spherical particles (e.g. droplets). The measurements are performed on single particles and are applicable to both liquid droplets in a gas medium (e.g. a spray) and gas bubbles in a liquid medium (e.g. gas bubbles in two-phase flows). Since it is a technique based on absolute physical effects (e.g. light scattering, phase Doppler shift) and is unaffected by changes in physical parameters such as temperature and pressure, no in-situ calibration is required. With an appropriate choice of hardware, particle sizes from 0.1 µm to over 1 mm, and velocities up to supersonic can be measured. Maximal data rates of up to 250 kHz can be achieved [8]. However, throughout this study droplet sizes of 0.1 µm to 600 µm, and velocities up to 80 m/s were measured; maximum data rates of over 10,000 droplets per seconds were recorded.

A Multiline Coherent Innova 70-5 Series Argon-Ion Laser at an all-line power output set at 2W was used in this investigation. The laser light was split into three pairs of beams providing six in total – two green, two blue and two violet beams. One beam from each of the three pairs was shifted in frequency by 40MHz to overcome directional ambiguity inherent in the PDA technique.

All six beams could be sent to the transmitting optics via fiber optic cables. The dominant laser wavelengths of 514.5 nm (corresponding to green visible light) and 488 nm (corresponding to blue visible light) were used to perform velocity measurements in the nozzle axial and radial directions, respectively. The green and blue pairs together were used for droplet size measurements and validation checks.

The receiving optics were located at an angle of 70 degrees from forward scatter, a focal length of 600 mm was used and sampling was performed for 5 seconds at each point. Dantec Dynamics BSA Flow Software V4.50 was used for all PDA tests performed. Figure 3 shows the PDA system used in operation. Clearly visible are the transmitting and receiving optics, the downward flowing spray, and the control volume formed at the beam intersections.

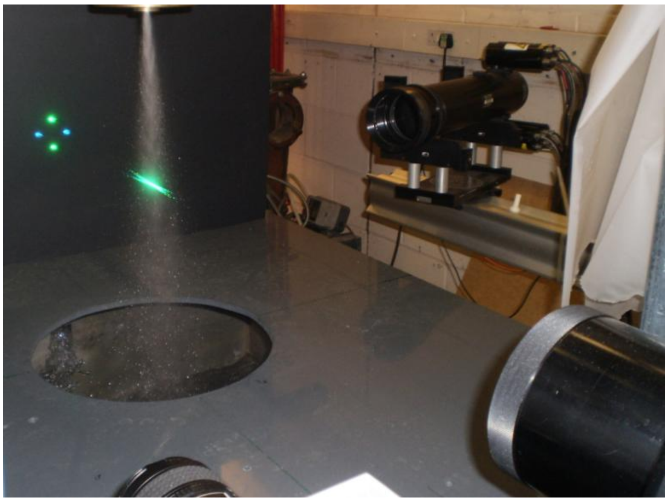


Figure 3 2-D PDA measurements being performed on an effervescent atomizer spray.

Spray Characterization

In order to isolate the influence of individual geometric parameters on spray quality, it was decided to investigate all geometric parameters (exit orifice diameter, nozzle length-to-diameter ratio, mixing chamber diameter, mixing length and air injection geometry) at the same operating conditions. Therefore all tests were performed at 5.7% ALR and 6.65 barG ΔP mixing chamber pressure, with an error of less than 2% and 1% respectively (ALR and ΔP were found to be the operating parameters controlling effervescent atomization). Each atomizer geometry was analyzed using PDA measurements at steady, stable operating conditions.

Preliminary experiments were performed to determine the dimensions of the sampling grid. As a result, the effervescent atomizer spray was deemed to be radially symmetric about the spray axis. Thus only a 2-D plane cutting through half of the spray needed to be sampled in order to characterize the entire spray. The radial spray edge at a given axial location was taken to be that radial location at which the validated data rates dropped to below 10% of the maximum validated data rates of any point at that axial location. This approach has been adopted by other researchers [9].

It was decided to sample at axial (downstream) locations of 25, 50, 100, 150, 200, 250, 300, 350 and 400 mm, with 1 mm radial spacings between data points. This would provide a much more complete view of the spray development than any other effervescent atomizer PDA investigation the authors are aware of.

The raw droplet data (from all measurement points) were compiled and analyzed in MATLAB, and global spray SMD (D_{32}) was calculated for each spray. The large number of data points (between 220 and 250 per spray) ensured highly representative global spray SMD values. Validation rates were high – over 90% at most sampled locations. Global spray SMD, representing spray quality for a given set of operating conditions (as well as geometric configurations and fluid properties), was calculated using the formula given by Equation 1.

$$SMD = \frac{\sum_{i=1}^{i=N} n_i D_i^3}{\sum_{i=1}^{i=N} n_i D_i^2} \quad (1)$$

Where D_i is the diameter of class size i, n_i is the number of droplets in each size class and N is the total number of droplets. The mass-under-size graphs for each spray investigated were plotted in MATLAB.

Results and Discussion

The results of the atomizer geometry tests conducted are presented and the results discussed in the present section. The results can be used to provide useful guidelines to the designers of practical, optimally-functioning “inside-out” type effervescent atomizers.

Nozzle Diameter

Nozzle diameter ranges of 2-2.8 mm were investigated by using detachable nozzles. The mass-under-size plots were obtained using droplet data from all the test points of a given spray, and are presented in Figure 4. The relationship between global spray SMD and nozzle diameter is shown in Figure 5. A second order polynomial line of best fit was added to Figure 5.

These graphs clearly illustrate the effect of nozzle diameter on spray quality. The mass-under-size plots show that the 2 mm nozzle produced the most finely atomized spray. As nozzle diameter was increased to 2.5 mm, spray behavior comparable to that of plain orifice atomizers was observed (i.e. larger nozzles leading to poorer atomization for equivalent operating conditions), as spray quality worsened with increasing D_O. Increasing nozzle diameter further to 2.8 mm resulted in a slight improvement in spray quality. This finding was unexpected.

Although one high-pressure effervescent atomization study found improved atomization with larger exit orifice diameters [10], most researchers consider D_O to have a minor or non-existent effect on SMD; where an effect is observed larger D_O tend to reduce spray quality [11-15].

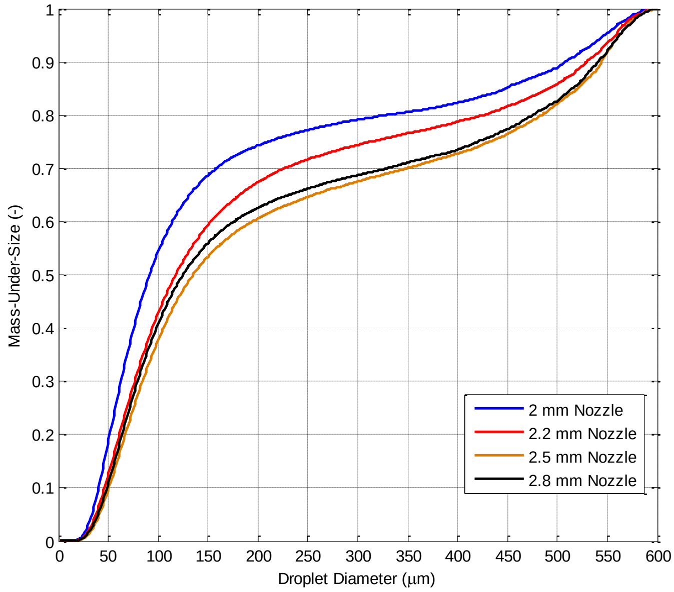


Figure 4 Mass-under-size plots for nozzle diameter sprays.

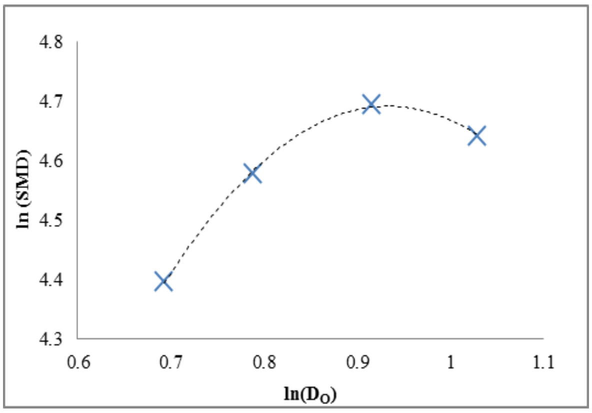


Figure 5 The relationship between global spray SMD and nozzle diameter.

In the present study, increasing D_O was found to lead to a clearly noticeable worsening in atomization quality. Nevertheless, the 2.8 mm spray was better atomized than the 2.5 mm spray. Clearly exit orifice diameter and SMD exhibit a complex, non-linear relationship for the conditions investigated. However the diameter range 2 mm < D_O < 2.5 mm appears to correlate linearly with SMD. Therefore it can be shown that for the geometries and conditions investigated (for 2 mm < D_O < 2.5 mm) the relationship between global spray SMD and exit orifice diameter is given by $SMD \propto D_O^{1.3138}$. A deterioration in atomizer performance is observed as D_O is increased to 2.8 mm. Further work is required to investigate the nature of the relationship between nozzle diameter and spray quality at orifice diameters larger than 2.8 mm.

Mixing Length

Fluid mixing lengths of 60-136 mm were investigated by winding in the aerator of the adjustable effervescent atomizer. The mass-under-size plots of these experiments are presented in Figure 6. This graph shows that mixing length had no influence on global spray SMD for the atomizer geometry and conditions tested.

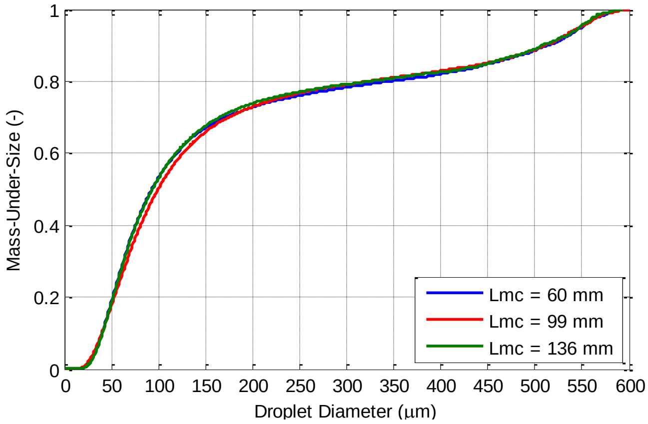


Figure 6 Mass-under-size plots for mixing length sprays.

Mixing Chamber Diameter

The influence of mixing chamber diameter on spray quality was investigated by fitting atomizer bodies of different internal diameters to the adjustable effervescent atomizer. Diameter ranges of 20-30 mm were investigated. Figure 7 displays the resultant mass-under-size plots; the relationship between global spray SMD and mixing chamber diameter is presented in Figure 8.

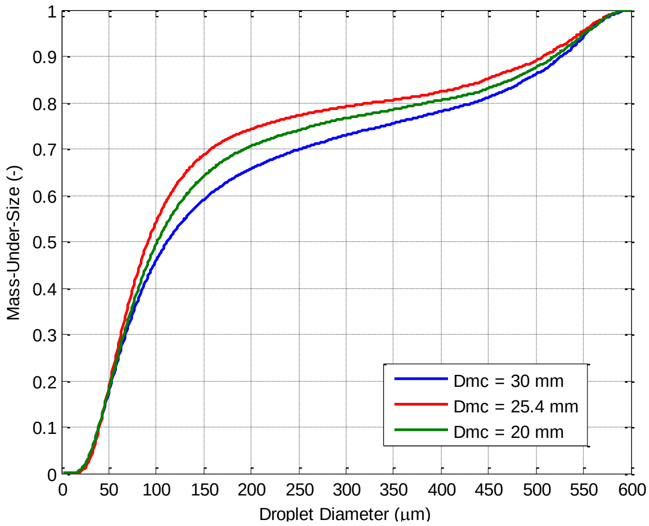


Figure 7 Mass-under-size plots for mixing chamber diameter sprays

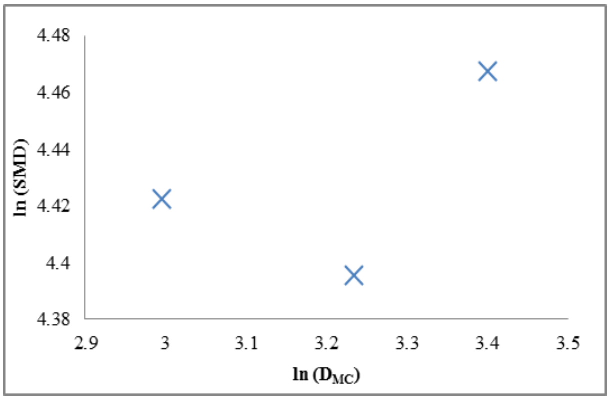


Figure 8 The relationship between global spray SMD and mixing chamber diameter.

The results displayed in Figure 7 and Figure 8 show that global spray SMD and D_{MC} exhibit a complex, non-linear relationship, with the 25.4 mm diameter mixing chamber providing the best atomization for the conditions and atomizer geometries investigated. These results clearly demonstrate that mixing chamber diameter has a noticeable (though relatively small) effect on spray quality. However the precise nature of the relationship between SMD and mixing chamber diameter requires further investigation using a larger range of D_{MC}.

Nozzle Length-to-Diameter Ratio

The use of detachable nozzles allowed the investigation of the parameter length-to-diameter ratio. Ratios of 0.5-2 were investigated. Ratios smaller than 0.5 were difficult to manufacture, those larger than 2 were not investigated as larger L_O/D_O were seen to provide increasingly undesirable reductions in spray quality. Figure 9 presents the mass-under-size plots obtained, while Figure 10 shows the relationship between global spray SMD and exit orifice length-to-diameter ratio. A second order polynomial line of best fit was added to Figure 10.

Previous researchers [7, 16], investigating the L_O/D_O range of 0.5-1.5 claimed improved atomisation at lower length-to-diameter ratios. One study found no clear effect on SMD, for the L_O/D_O range of 1-5 and for low flow rate minimal gas flow pharmaceutical applications [15].

The present investigation demonstrates a significant and non-linear relationship between L_O/D_O and global spray SMD at L_O/D_O ratios of 0.5-2, in contrast to the study by Petersen et al (although that study was conducted at very low flow rates, which may result in different flow behavior). The results of the current investigation show some agreement with the findings of Chen et al and Chin et al, as lower length-to-diameter ratios generally appear to improve atomisation. However, it was not the case that the lowest L_O/D_O ratios always provided the best atomization. In fact the best atomized spray was produced by the $L_O/D_O = 1$ nozzle. The superior atomization of the $L_O/D_O = 1$ nozzle is most clearly visible in Figure 10 where the differences in global spray SMD values for each spray are noticeable.

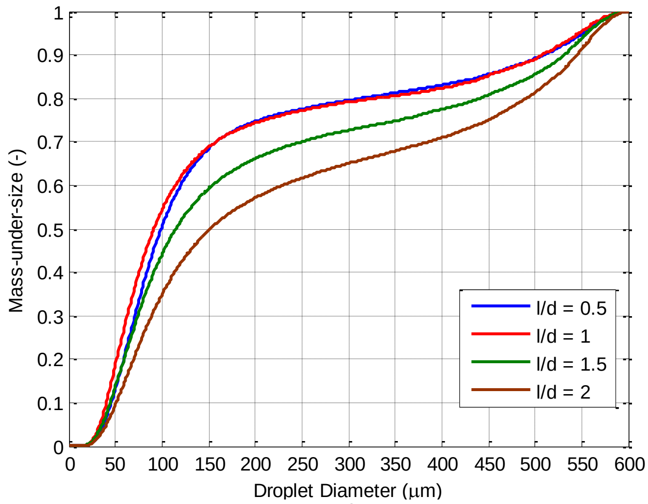


Figure 9 Mass-under-size plots for nozzle length-to-diameter ratio sprays.

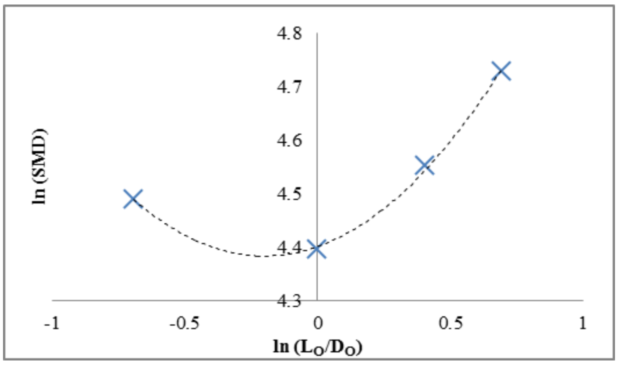


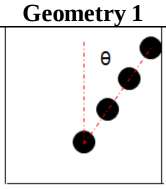
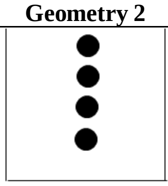
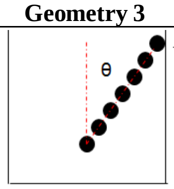
Figure 10 The relationship between global spray SMD and nozzle length-to-diameter ratio.

Although the relationship between SMD and L_O/D_O seems to be non-linear, the length-to-diameter ratio range $1 < L_O/D_O < 2$ appears linear. It can therefore be shown that for the geometries and conditions investigated (and for $1 < L_O/D_O < 2$) the relationship between global spray SMD and nozzle length-to-diameter ratio is given by SMD $\propto (L_O/D_O)^{0.4736}$. A reduction in L_O/D_O below 1 is seen to reduce spray quality. The reasons for this are not entirely clear. However further investigations of the L_O/D_O range of 0.5-1 would help improve understanding of the phenomenon observed.

Air Injector Geometry

These tests investigated the effects of two geometric features of the air injector on spray quality. These were the symmetry of the air hole injectors (as defined below) and the aerating hole diameter. Table 1 provides a graphical illustration of the geometric parameters investigated.

Table 1 Sketch of aerator geometries investigated showing location of air injector holes.

Aerator Geometry 1	**Aerator Geometry 2**	**Aerator Geometry 3**
		
6 x 2.5 mm diameter aerator holes; θ = 26.57˚ **Baseline aerator**	6 x 2.6 mm diameter aerator holes; θ = 0˚ Investigates influence of **air injector hole symmetry**	10 x 2 mm diameter aerator holes; θ = 26.57˚ Investigates influence of **aerating hole diameter**

The total air injector area and average mixing length (the distance from the axial midpoint of the air holes to the midpoint of the nozzle) were kept constant throughout these tests. Figure 11 shows the mass-under-size plot of each air injector geometry spray and Figure 12 shows the associated global spray SMD.

The results show that air injector hole symmetry has a significant influence on spray quality. Maximal air hole injector asymmetry (as in aerator geometry A2) is seen to provide a considerable improvement in atomization quality. Meanwhile air injector hole diameter had only a relatively small influence on spray quality. Over the air injector hole diameter ranges investigated, the 2 mm diameter arrangement provided the better atomizer performance.

Therefore it can be seen that air injector geometry can significantly influence spray quality. This contradicts previous researchers who reported little or no relation between air injection geometry and spray quality [11, 12].

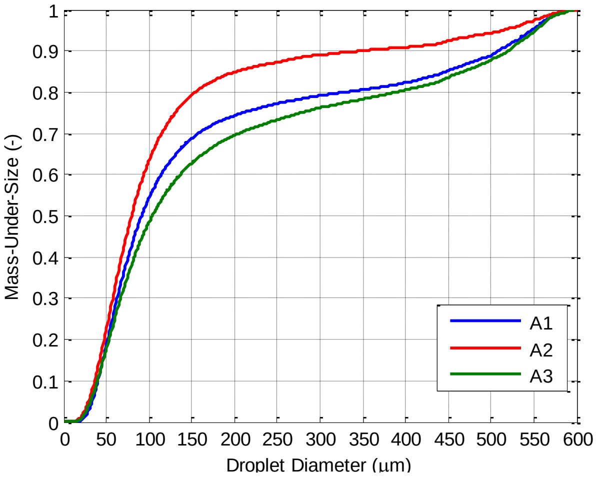


Figure 11 Mass-under-size plots for aerator geometry sprays

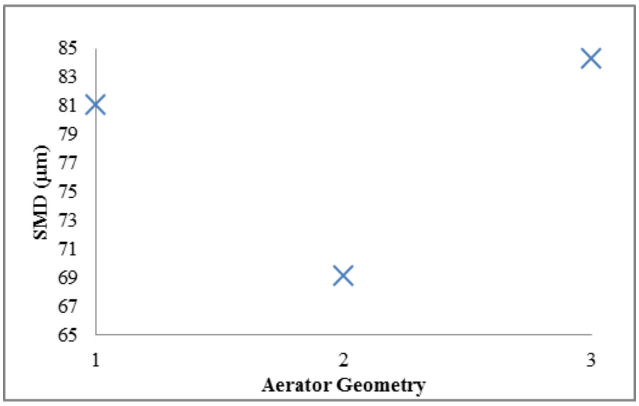


Figure 12 The influence of aerator geometry on global spray SMD.

Summary and Conclusions

A 2-D PDA analysis of 5 effervescent atomizer geometric parameters was performed using an "inside-out" type effervescent atomizer rated at 2MW equivalent power (using water as the operating fluid). Data rates over 10 kHz and validation rates over 90% were achieved using a PDA probe designed for dense spray applications. Between 220-250 data points were sampled for each spray ensuring high quality, representative data. Global spray SMD and mass-under-size plots were used to compare spray quality. The results revealed that:

- Effervescent atomizer nozzle diameter and global spray SMD displayed a complex, non-linear relationship over the diameter ranges (2-2.8 mm), geometric and operating conditions investigated.
- Global spray SMD $\propto D_O^{1.3138}$ for 2 mm < D_O < 2.5 mm with superior atomization using smaller D_O.
- Mixing length had no detectable influence on effervescent atomizer spray quality.
- Mixing chamber diameter had a relatively small but noticeable effect on global spray SMD; over the ranges investigated (20-30 mm) optimal atomization was achieved with D_{MC} = 25.4 mm.
- Effervescent atomizer nozzle length-to-diameter ratio displayed a strong influence on spray quality, with smaller L_O/D_O generally providing improved atomization; for the ranges $1 < L_O/D_O < 2$ it was found that SMD $\propto (L_O/D_O)^{0.4736}$.
- Although smaller length-to-diameter ratios seemed to offer improved performance, the best atomization performance was achieved using the $L_O/D_O = 1$ nozzle; the lower ratio of $L_O/D_O = 0.5$ provided comparatively poorer atomization.
- Air injector hole symmetry (as defined in the present study) had a large and important influence on spray quality; an asymmetric arrangement of air injector holes (as in air injector geometry A2) provided large improvements in spray quality.
- Air injector hole diameter had only a minor influence on spray quality; over the air injector hole diameter ranges investigated, the aerator geometry with the 2 mm diameter holes provided superior atomization performance.

Acknowledgements

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References

[1] Lefebvre, A.H., *Atomization and Sprays*. Combustion: An International Series, ed. N. Chigier 1989: Hemisphere Publishing Corporation. 421.
[2] Greene, D.L., D.W. Jones, and P.N. Leiby, The outlook for US oil dependence. Energy Policy, 1998. 26(1): p. 55-69.
[3] Sojka, P.E. and A.H. Lefebvre, A novel method of atomizing coal-water slurry fuels, 1990. p. Size: Pages: (116 p).
[4] Sovani, S.D., P.E. Sojka, and A.H. Lefebvre, Effervescent atomization. Progress in Energy and Combustion Science, 2001. 27(4): p. 483-521.
[5] Lefebvre, A.H., X.F. Wang, and C.A. Martin, Spray Characteristics of Aerated-Liquid Pressure Atomizers. Journal of Propulsion Power, 1988. 4(4): p. 293-298.

[6] Konstantinov, D., et al., Effervescent atomization for industrial energy - technology review. 2010. 20(6): p. 525-552.
[7] Chin, J.S. and A.H. Lefebvre, A Design Procedure for Effervescent Atomizers. Journal of Engineering for Gas Turbines and Power, 1995. 117(2): p. 266-271.
[8] Nasr, G.G., A.J. Yule, and L. Bendig, Industrial Sprays and Atomization2002.
[9] Crayford, A.P., et al., Comparison of Gas-Oil and Bio-Oil Spray Performance for Use in a Gas Turbine. ASME Conference Proceedings, 2010. 2010(43963): p. 659-667.
[10] Wade, R.A., et al., Effervescent atomization at injection pressures in the MPa range. Atomization and Sprays, 1999. 9(6): p. 651-667.
[11] Lefebvre, A.H., A novel method of atomization with potential gas turbine applications. Defence Science Journal, 1988. 38(4): p. 353-362.
[12] Wang, X., J.S. Chin, and A.H. Lefebvre, Influence of Gas Injector Geometry on Atomization Performance of Aerated Liquid Nozzles. International Journal of Turbo and Jet Engines, 1989. 6: p. 271-279.
[13] Lefebvre, A.H., Twin-fluid atomization: factors influencing mean drop size. Atomization and Sprays, 1992. 2(2): p. 101-119.
[14] Lefebvre, A.H., Some Recent Developments in Twin-Fluid Atomization. Particle and Particle Systems Characterization, 1996. 13(3): p. 205-216.
[15] Petersen, F.J., et al., Design and Atomization Properties for an Inside-Out Type Effervescent Atomizer. Drug Development and Industrial Pharmacy, 2004. 30(3): p. 319-326.
[16] Chen, S.K. and A.H. Lefebvre, Discharge Coefficients for Plain-Orifice Effervescent Atomizers. Atomization and Sprays, 1994. 4: p. 275-290.