Characterisation of a Spray Produced by Sharp-Edged Orifices in the Second-Wind Jet Breakup Regime

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Abstract

For hazard analyses of accidental releases of flammable or toxic fluid, often release pressures and apertures are outside the domain of previous atomisation studies [1,2], which are usually dominated by practical atomisation devices such as diesel injectors. The hazardous releases of interest here are in the second-wind jet breakup regime, where the influence of jet breakup length is highly influential. The influence of additional parameters, usually classed 'secondary', have been investigated in an extensive experimental programme through characterisation of sprays produced by a range of brass sharp edged orifices at various aspect ratios and downstream distances. A transition has been identified between the Sauter mean diameter (SMD) and the release pressure that effectively divides the data into a low- and medium-pressure region – in non-dimensional terms, a Reynolds/Weber number effect. Methods for correlating the data via appropriate dimensionless groups are discussed. It is proposed that as the aspect ratio influences the nozzle discharge coefficient in a highly non-linear manner, which in turn affects the jet velocity and thus the atomization quality.

1. Introduction

Flammable liquids are commonly found within process plant, often under conditions of low-medium pressure usually less than 12bar. Under suitable conditions, these liquids can be released to the atmosphere mixing with air, and hence giving rise to potentially explosive heterogeneous two-phase cloud. Recent fatal incidents in the transport sector (e.g. September 11th twin-towers terrorist attack (2001) and the Labroke Grove (London) train crash (1999)) have demonstrated that similar release conditions may be realised also through high-momentum impact and subsequent rupture of liquid fuel containment. The conditions for an explosion to occur are increased if the release generates sufficient quantity of fine mist. The flammability hazard posed by breakup of high-flashpoint liquid fuel jets under low pressure conditions is currently ill-defined.

Many parameters affect the atomization quality due to liquid fuel jet breakup. Previous studies [1] have reviewed the hazard posed in relatively idealised scenarios - 'simple' orifices, idealised impingement, *etc.* In reality there are many other 'secondary' parameters, which could have a significant influence on hazard quantification. Bowen and

Shirvill [1] categorised the hazard generally in terms of an 'unobstructed' scenario, and an 'obstructed' scenario.

Several correlations are suggested in the literature [2,3,4,5,6,7] to estimate the Sauter Mean Diameter of an unobstructed jet spray produced by plain orifices. Correlations usually relate the spray SMD directly to orifice size, jet velocity or pressure differential and sometimes, fluid properties. However most of these correlations are only validated under conditions of high-pressure and small orifices, typical of practical atomisation devices.

The aim of this paper is to study the influence of both primary and traditionally secondary parameters on the atomisation process in the relevant, second-wind jet breakup regime, and to appraise methods for providing practical predictive methodologies in this ill-defined yet practically important atomisation domain.

2. Experimental Facilities

2.1 Experimental Rig and Laser Diagnostic Techniques

The main features of the spray rig are represented in the schematic, Figure 1.

The DANTEC phase Doppler anemometer (PDA) system utilised includes a DANTEC 55X two-dimensional probe, in conjunction with a DANTEC beam expander, and a transmission lens focal length of 600 mm.

The green beams λ = 514.5 nm provide measurements of the vertical axial flow velocities and also the droplet size. The PDA was supplied by a water-cooled 5W Argon-Ion laser, and a collection angle of 72 degrees from forward scatter was utilised, consistent with the refractive index of water. The power source was used together with a DANTEC 60X40 transmitter box, which incorporates a Bragg cell, facilitating frequency shifting at 40MHz to avoid directional ambiguity.

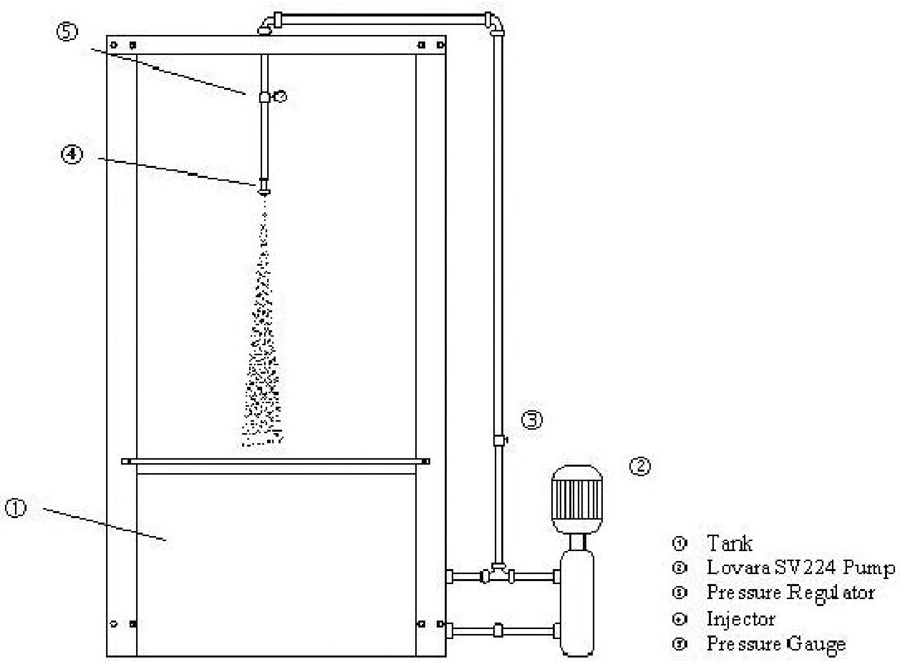


Figure 1: Spray Rig

Scattered light was collected via the DANTEC integrated receiving optics, and processed using a DANTEC co-variance particle analyser with the associated Sizeware software package. Both transmitting and receiving optics were mounted onto a computer-controlled transverse. All data collection and movements of the transverse were controlled via the software, and 15000 validated Doppler bursts were collected at each data point, unless 'timed out' after a period of 75 seconds.

2.2 Plain-orifice atomizer

Brass, sharp-edged, cylindrical orifices were used in these experiments, with orifice diameters of 0.75 mm, 1 mm and 2mm and orifice length of 3.4 and 7 mm respectively. These provide aspect ratios within the range $1.7 \leq L/d_{orf} \leq 9.33$. The orifices were manufactured by high speed drilling carried out from the exit of the orifice in order to avoid the formation of sharp edges on the nozzle inlet. Water was utilised as the atomisation medium throughout the experimental programme, and the injection pressure was varied between 4 and 24 bar, systematically increasing by 2 bar increments.

3. Results and Discussion

For each experiment, distributions of droplet size and axial velocity component were generated at radial positions for each downstream distance. The data has been reduced for the purposes of discussion here, so that only SMD values are presented, having been evaluated by averaging data across radial positions.

3.1 SMD/Pressure transition

The PDA data-set generated revealed a distinct transition in the characteristic trend-line relating droplet SMD and release pressure. The transition region is identifiable for all nozzles tested, and typically occurs when the release pressure is within the pressure region of 10 and 12 bar for the range of nozzles and the fluid used in this experimental programme. The SMD/pressure transition can be clearly observed in the representative non-dimensionalised plot of Figure 1. The data has been examined to assess if this transition is an artefact of distribution truncation due to the PDA optical configuration utilised. There does not appear to be data truncation, presuming a single-mode distribution.

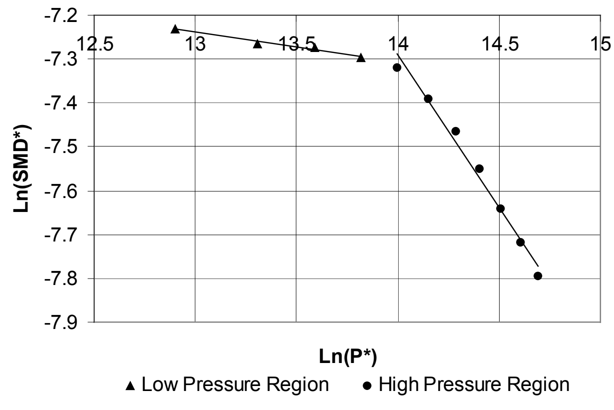


Figure 2: Transition of global droplet SMD with release pressure

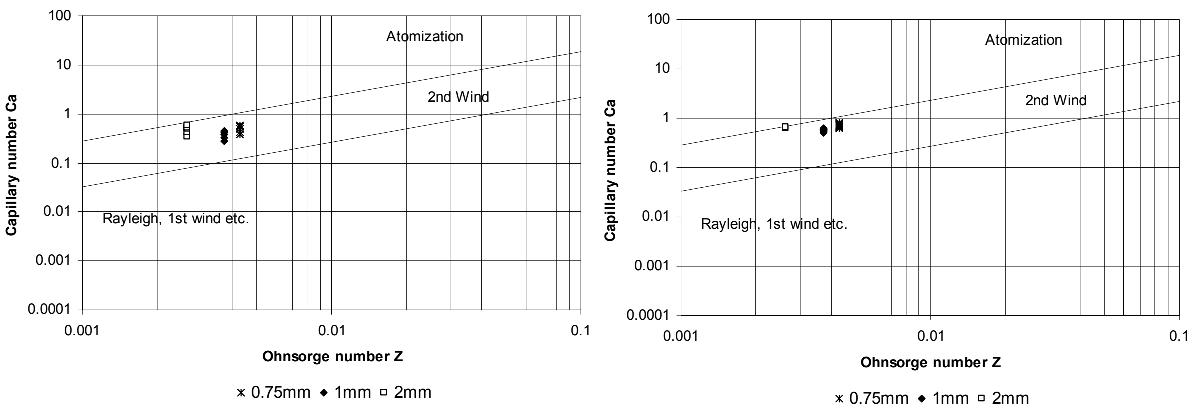
Both trend-lines indicate qualitatively plausible results, in that SMD reduces with increase in release pressure. Quantitively, note the gradual decrease in dimensionless SMD with dimensionless release pressure in the low-pressure region; for example, tripling the pressure by increasing from 4 bar to 12 bar only reduces the SMD by less than 7%. SMD reduces far more rapidly in the higher pressure region, presenting a correlation index more representative of those proposed previously for sprays in the 'atomisation' jet breakup regime. Here, for example, doubling the release pressure from 12 bar to 24 bar induces a 30% reduction in spray SMD.

3.2 Jet breakup Regimes

It was initially suggested that the transition discussed in the previous section may represent one of the traditional transition conditions. Hence, it is appropriate to analyse the data in light of previously published jet-breakup criteria.

The existence of a strong liquid core at the centre of the spray indicates a poor disintegration process, which translates to the jet break-up regime. Although a liquid core is now believed to exist even for very high-pressurise engine sprays [9], here the visual characteristics of the core indicates that the emerging liquid belongs to the 2nd Wind break-up regime. Supporting evidence of this conclusion is offered by the plot of Capillary against Ohnsorge number and by adopting the transition conditions quoted previously [1]. Figure 3 illustrates the Ca-Oh plots for all nozzles with length L=3.4mm, at every release pressure condition utilised in this experimental investigation.

For the low release pressure region (Figure 3a), the data lie almost at the centre of the '2nd Wind' breakup regime, whilst for the higher-pressure region (Figure 3b), the data lie almost at the boundary separating the '2nd Wind' and the 'atomization' regime. Hence, the SMD transition identified here does not coincide with the established jet breakup conditions, which suggests the possible existence of a sub-range within the traditional 2nd Wind breakup regime, or deviation from previous jet-breakup correlations.



(a) (b)

Figure 3: Breakup regime of the tested nozzles with length L=3.4mm at release pressure a) $4 \leq \Delta P \leq 10$bar and b) $12 \leq \Delta P \leq 24$ bar

3.3 Data Analysis and Correlations

The majority of the published correlations offer predictions of SMD in terms only on the so-called primary parameters such as the release or release pressure ΔP and the orifice diameter

d_{orf}. Other important parameters such as the nozzle's aspect ratio (L/d_{orf}) and the dimensionless downstream distance (z/d_{orf}) are invariably considered to be 'secondary' parameters, and as such have not been afforded as much attention as primary parameters. These assumptions are commonly adopted, but for the hazard application cited, secondary parameters can vary *significantly*, and so it becomes very important to quantify their effect.

By taking into account both 'primary' and 'secondary' parameters, the SMD can be expressed in a general form :

$$SMD = f(\rho, \sigma, \mu, z, L, d_{orf}, \Delta P) \tag{1}$$

All the experiments were conducted with water, and thus the influence of liquid characteristics in the above generalised SMD correlation have not been explicitly appraised in this programme. However, by applying dimensionless analysis, the equation 1 is commonly quoted in non-dimensional form in the following format:

$$\frac{\mathrm{SMD}}{\mathrm{d}_{\mathrm{orf}}} = \mathrm{C} \cdot \left(\frac{\mathrm{L}}{\mathrm{d}_{\mathrm{orf}}}\right)^{\mathrm{a}} \cdot \left(\frac{\mathrm{z}}{\mathrm{d}_{\mathrm{orf}}}\right)^{\mathrm{b}} \cdot \mathrm{Re}^{\mathrm{c}} \cdot \mathrm{We}^{\mathrm{d}} \tag{2}$$

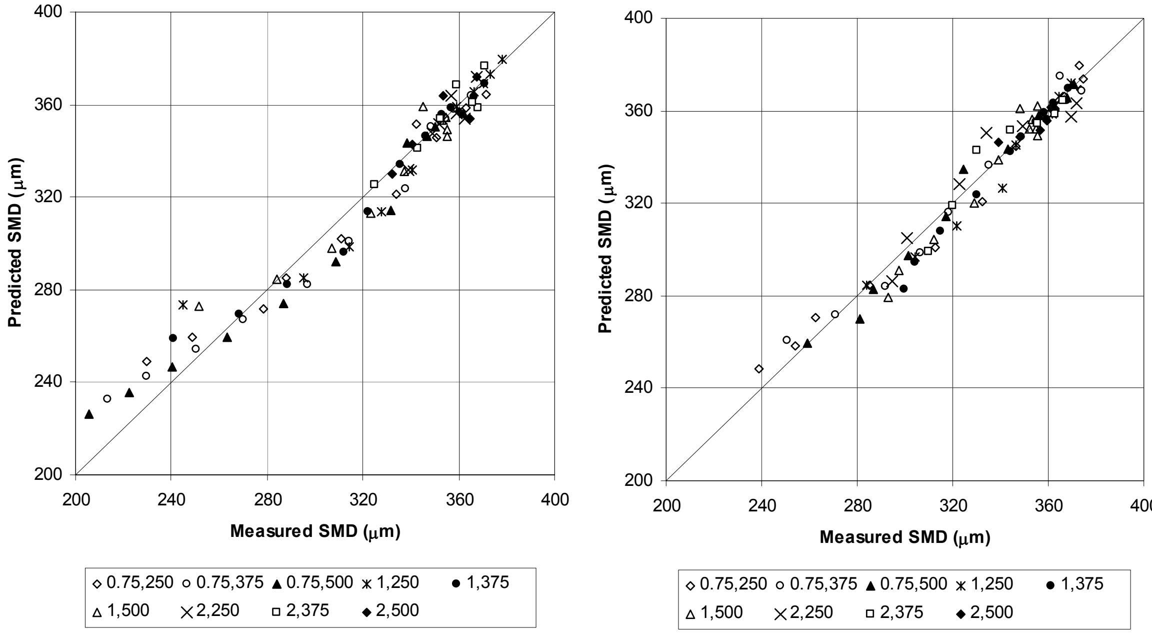
where *C* is presumed to be a constant, *a*, *b*, *c* and *d* are power indices are to be determined by the experimental data.

The transition described earlier strongly influences the effect of release pressure, hence the Reynolds and Weber numbers, on SMD in the correlation. Hence, the proposed correlation requires two discrete forms according to the pressure region.

The two constants C_1 and C_2 corresponding to the low and higher pressure regimes are to be derived from the experimental data. However, whilst undertaking the analytical data reduction, it became apparent that the correlation form specified in equation (2) did not readily lend itself to representation of this data-set. In particular, the influence of the secondary parameters L/d_{orf} and z/d_{orf} appeared more complex than can be represented accurately by equation (2) for the range of conditions studied.

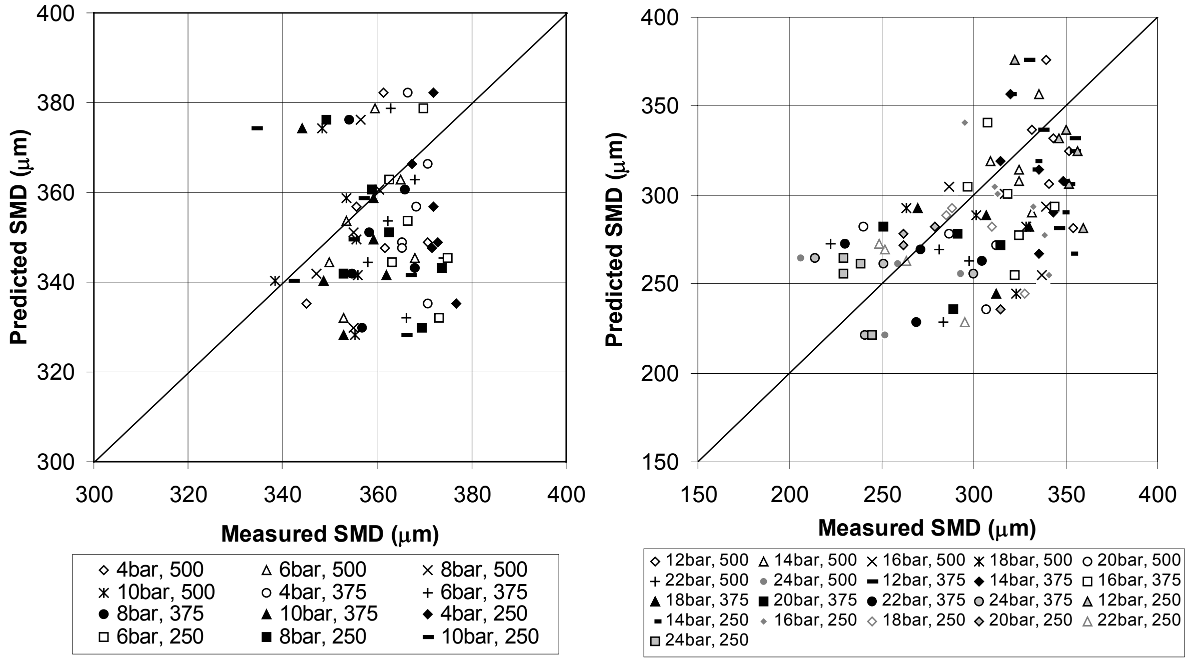
Hence, two options are presented: Using equation (2) to represent the data specifying a constant value for C incurs errors between data and correlation prediction; however, to obtain improved correlation representation of the data, then C must become dependent the secondary parameters rather than a constant value. Of course this loses the generality of the equation, and limits its value in interpolating or extrapolating trends for generalised modelling purpose. It is proposed that the reason for this added complexity is due to the effect of L/d_{orf} on internal nozzle flow structure, and in particular, the complex relationship between L/d_{orf} and discharge coefficient under these conditions. Preliminary studies utilising transparent nozzles and back-lit photography allowing visualisation of flow within the nozzles, have indicated some support of this hypothesis, indicating that the influence of processes such as cavitation may also be influential. However, further work is required to establish the link between the spray transition and the physics of the jet-breakup process.

A common approach for evaluating the accuracy of the proposed correlation is by plotting the experimental against the predicted SMD as illustrated in Figure 4 and Figure 5. The diagonal line indicates perfect agreement between the data and the proposed correlation. Any deviation from that line indicates the correlation error against the experimental data.



(a) (b)

Figure 4: Correlation with correlation coefficient as function against measured SMD's for all nozzles with a) L = 3.4mm and b) L = 7mm.



(a) (b)

Figure 5: Correlation against Measured SMD for (a) Low pressure and (b) Medium Pressure regimes imposing *constant* correlation coefficient

The overhead incurred by retaining the traditional correlation approach presented in equation (2) is immediately apparent by comparing the spread of data for the correlation utilising constant coefficients for the two pressure regimes (Figure 5), and that variable coefficients (Figure 4).

4. Conclusions

- A transition in the correlation between spray SMD and release pressure has been identified through spray characterisation using PDA, for relatively low pressure, large orifice liquid releases relevant to the problem of large-scale hazardous releases of sub-cooled liquid. In the lower pressure region ($4 \le \Delta P \le 10\,\text{bar}$), SMD decreases more slowly with increase in release pressure than in the higher-pressure region ($\Delta P \ge 12\,\text{bar}$). The higher-pressure region exhibits a pressure dependence consistent with that reported previously.
- Comparison of the current dataset with previous correlations for transition between jet breakup regimes, indicate that all experiments undertaken during this programme are classed as breaking up in the '2nd Wind' regime. Hence, this data-set either identifies a new transition sub-range within the '2nd Wind' regime, or the current data-set does not validate the previously published transition correlation utilised.
- It is proposed that the jet breakup regime and length are strongly associated with the nozzle's internal characteristics, and hence it is recommended that future studies attempting to correlate spray characteristics investigate internal flow within the nozzle.
- In developing spray correlations including the influence of secondary parameters such as L/d_{orf} for jets undergoing second-wind breakup, the highly non-linear interaction requires a compromise to be reached: Adoption of the traditional form of non-dimensionalised correlation with constant coefficient induces increased dispersion between correlation and data, whereas further dependence of the correlation coefficient on the underlying data reduces the general applicability for modelling purposes.

5. Nomenclature

Roman Characters

d_{orf}	Nozzle diameter
ΔP	Pressure drop (Pa)
Z	Downstream distance (m)
Greek Characters	
μ	Dynamic viscosity of the liquid (kg/ms)
ρ	Liquid Density (kg/m^3)
σ	Liquid surface tension (N/m)
Dimensionless	
Re	Reynolds number ($= U_{jet} \cdot d_{orf}\, \rho / \mu$)
We	Weber number ($= \rho_g \cdot U_{jet}^2 \cdot d_{orf} / \sigma$)
Z	Ohnsorge number $\left(= \mu / \sqrt{\rho_l \sigma d_{orf}}\right)$

Ca Capillarity number $\left(= \mathrm{We} / \mathrm{Re}\right)$

6. References

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