Jet Transition and Rainout from Large Superheated Spray Releases

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Abstract
This paper explores the capability of relatively simple photographic and liquid collection techniques for developing understanding and approaches for modelling the characteristics of large superheated jets, specifically the transitional superheat condition governing mode of jet breakup, and rainout characteristics. Superheated liquid jets have a broad range of applications, but in this context the scenario considered is the hazard posed by accidental rupture of a vessel containing superheated liquid. A simple method is proposed for identifying the transition superheat condition by identifying a critical point on an appropriate graph, generating a superheat limit condition similar to that reported elsewhere. The data from a simple rain-out collection method compares favourably with previous model and well-controlled data-set, showing anticipated rainout decrease with increase in superheat, differences in rainout from low superheat and fully flashing releases, and relative independence of orifice size in the fully flashing regime.

1. Introduction

When liquids initially contained under pressure are released into an environment of a lower pressure, superheat can potentially enhance the atomisation quality of the resultant jet or spray. This phenomena is relevant to a wide variety of industrial applications. For example, the storage of large quantities of toxic or flammable material under superheated conditions introduces potential hazards [1], which it is necessary to be able to quantify. Furthermore, superheated automotive fuel injection has also been afforded consideration in previous studies [2].

For atmospheric dispersion hazard modelling after an accidental release, it is critical to be able to predict superheated atomisation characteristics, and in particular, to have the capability of predicting the quantity of liquid which ‘rains out’, thereby contributing to pool formation in the near vicinity of the release [3]. It is envisaged that larger droplets are more likely to rain-out, whereas gravimetrically stable ‘fine-mist’ is more likely to remain as an airbourne hazard. Evaporation from the spreading liquid pool, and the subsequent reattachment of this material to the dispersing cloud, potentially more dangerously as vapour, is an additional necessary consideration in a scenario of this kind.

The problem involves predicting the atomisation characteristics of superheated releases as a function of the release conditions. The degree of superheat has been shown in several studies to significantly influence the atomisation characteristics, and rainout [4]. Moreover, additional parameters usually associated with atomisation control i.e. orifice characteristics, fluid properties, etc.. - are also likely to have an effect.

It has been proposed [2,5] that under conditions of 'low' superheat, break-up of the jet is dominated by mechanical mechanisms, i.e. aerodynamic interaction with surface wave instabilities [3]. A critical Weber number approach is often utilised to predict post-breakup spray characteristics. At higher values of superheat, the thermodynamics of the system tend to dominate such that catastrophic jet breakup occurs, associated with the development of two-phase flow either within or outside of the release orifice. Very fine mists have been reported to result from such conditions.

The aim of this programme of work is to appraise and develop simple, inexpensive methodologies for characterising transition between fully-flashing and non-flashing superheated jets, and the resultant liquid rainout associated with releases of this kind as a function of primary control parameters.

2. Experimental Facilities and Techniques

2.1. Superheated Atomiser and control

To undertake this study of large-scale flashing atomisation, releases were performed using a controlled superheating release system. Originally designed as a self-propelling extinguishant, its ability to store and heat a large quantity of water to temperatures approaching 190 ºC and subsequently release that water through a range of nozzle diameters renders it suitable for the investigation of the effect of superheat and orifice size on flash atomisation.

Figure 1. Superheated Atomiser

Fill/vent plugs are connected to internal level pipes which ensure that the required level of water fills the unit, with 'head' space to accommodate expansion. In order to fill the unit, both plugs are removed, with one connected to a tap/filling connection and the other one vented.

A helical-shaped incoloy electrical heating element, with a centrally located thermocouple running through it provides a controlled heating system. A simple heating control panel is used to pre-set the desired temperature, with a digital display indicating both the current and desired water stagnation temperature. The unit is vacuum-wall insulated against heat loss, which ensures that the units can remain active without power for long periods. The vessel is also protected against overpressure by a bursting disk.

On reaching the set temperature, the controller deactivates the power to the heating element. Thermostatic control then ensures that the heating process will automatically ensure stability around the desired set temperature.

The water is then discharged through the exit orifice via a manual release valve. An adaptable nozzle allows variation of the final exit orifice characteristics; for this study, simple orifices were utilised with varying orifice diameter. A pressure gauge and thermocouple positioned approximately 10mm from the exit orifice allows measurement of water temperature and pressure near the exit.

2.2. Spray Geometry Quantification

For a given combination of initial conditions, digital images of the jet are taken at regular intervals after the start of the release using a Sony MVC-FD87 Digital Still Camera. Jet width is derived through detailed image-by-image analysis using the software package ‘Corel Photo-Paint Version 8.433’, which facilitates various image measurement techniques. The ‘rulers’ function superimposes rulers of arbitrary spacing in the x and y planes at the edges of the image. Jet width is then calculated by the implementation of a scale factor determined from the analysis of a ruled grid containing 50x50mm squares, placed at a fixed distance behind the jet during each release.

For cases where the exact position of the jet boundary is difficult to identify, for example for low superheat releases where flowrates are low and the resultant plumes are subsequently less dense, this software package also facilitates image enhancement. The Colour Transform function offers two particularly useful techniques for this purpose, the ‘Bit Planes filter’ and the ‘Pyschedelic filter’, the former a powerful tool for analysing tonal gradients in images, whereas the latter changes the colours in the image to bright, electric colours. The combined effect on an image allows the unambiguous determination of the location of the jet boundary in almost all cases reported in this programme.

2.3. Rainout Quantification

A simple 6m x 4m steel frame aligned with the release direction and covered with two 5m x 4m tarpaulin sheets was found to be a simple and very repeatable method for quantifying water rainout. Repeatablity tests indicated that the technique produced results which varied by no more than 1.5% over three tests runs for a given set of initial conditions. The sheets were attached to the frame using plastic grips. As tests were conducted outdoors, care was taken to prevent weather conditions or collection material having an adverse affect on water measurements recorded. In this way steel deadweights were used to hold the tarpaulin in place, steel having been selected due to its non-absorbant properties.

As a precursor to any test, it is necessary to know the total volume of water contained within the rig, V_T. This is 32.8 litres for all cases.

Once the water in the rig was heated to the required temperature, the rig was left to discharge fully. The volume of water in the collection rig, V_R, was measured and recorded using a 3 gallon (13.64 litre) measuring drum, with surprisingly little liquid loss encountered, despite the crudeness of the technique adopted. The small amount of water, V_u, remaining in the rig after each release was measured using a measuring cylinder. The rainout fraction is then given by;

$$\eta_R = \frac{V_R}{32.8 - V_u} \tag{1}$$

3. Experimental Programme and Results

The experimental programme undertaken considered releases of varying stagnation temperature (130-180 °C) and orifice diameter (1mm, 2mm and 4mm) Release pressure varied only slightly through the releases, as discussed later.

Figure 2 presents thermodynamic control data for a representative selection of release conditions. Figure 2a) presents the variation of temperature over time at the nozzle exit for the range of nozzle diameters at a stagnation temperature of 170 °C. The release duration varies with orifice size due to the variation in mass flowrate associated with varying this parameter. Moreover, due to variation in heat transfer characteristics, the temperature at the nozzle varies significantly with the size of orifice employed. This is particularly noticeable for the 1mm orifice, and indicates that temperature at the orifice should be utilised to interpret the data, rather than stagnation temperature. This is also important for modelling practical release scenarios.

Figure 2a) also indicates that conditions at the exit orifice undergo an initial warm-up period during which time the temperature increases until it stabilises at a maximum. During this warm-up period the jet itself was observed to undergo a similar transitional process during which time the width of the jet increased until it too stabilised at a maximum. Preliminary tests were run in order to identify the time window during which this warm-up period endured over the full range of primary parameters. During this window images of the jet were then taken as detailed in section 2.2. Figure 2b) demonstrates the behaviour of the release pressure during this window over the range of stagnation temperatures for a nozzle diameter of 2mm. Only a gradual decay in pressure is encountered totalling less than 1bar in all cases

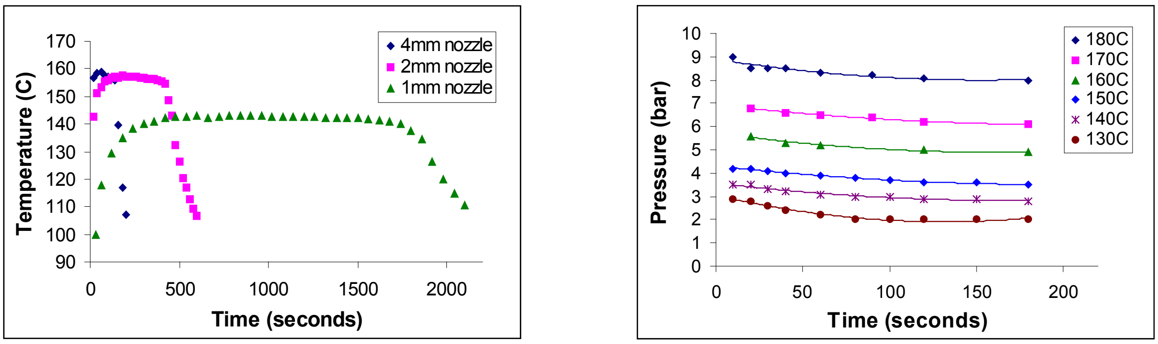

Figure 2. Transient Characteristics of Thermodynamic Nozzle Control Parameters During Releases (a) Temperature (b) Pressure

Figure 3 shows sequences of images taken during the initial transient development of a series of jets. The evolution of the jet width over the warm-up period is clearly visible for each sequence. Transition between jet break-up regimes is also in evidence as the stagnation temperature increases. Narrow-cone, sparsely-populated jets characterise the mechanical breakup mode, with wide-cone, dense jets characterising flashing releases. The core of the poorly atomised jet is visible throughout the sequence for the 140 °C stagnation temperature release. It was also noted during these experiments that the temperature decay along the jet length was rapid for flashing releases, such that it was possible to comfortably put ones hand into the spray a short distance downstream (approximately 0.1m).

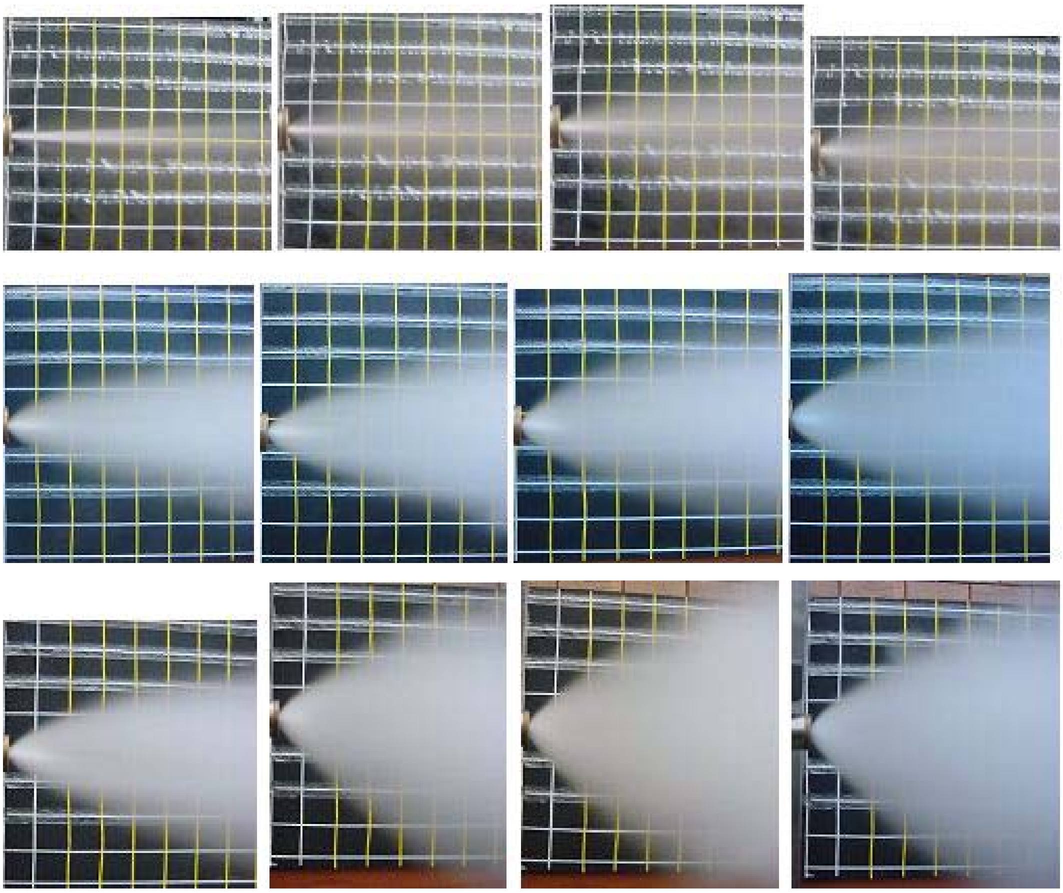

Figure 3. Jet Evolution from 3 Stagnation Temperatures : 140 °C, 160 °C, 180 °C

Figure 4 presents a sample of the dataset generated using the techniques discussed in section 2.2 for a nozzle diameter of 2mm, showing the variation of jet width with increase in degree of superheat. Such data were obtained for all 3 nozzle sizes, all stagnation temperatures and at 2 representative distances downstream from the nozzle orifice (0.05m and 0.1m). As to be expected, jet width increases both with downstream distance and degree of superheat.

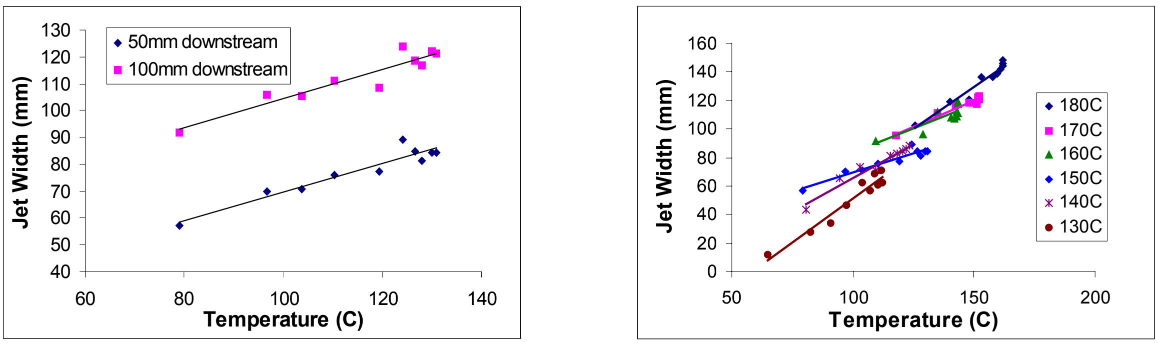

Figure 4. Jet-Width/Temperature as function of: a) downstream distance (stagnation temperature 150 °C) b) initial temperature

Figure 5 presents sample data generating using the simple methodology described in section 2.3. Figure 5a) shows the effect of increase in superheat on rainout – decreased rainout with increase in superheat as anticipated – for the 4mm orifice size. Figure 5b) shows the influence on rainout of changing orifice size whilst maintaining the same stagnation temperature, 160 °C in this instance.

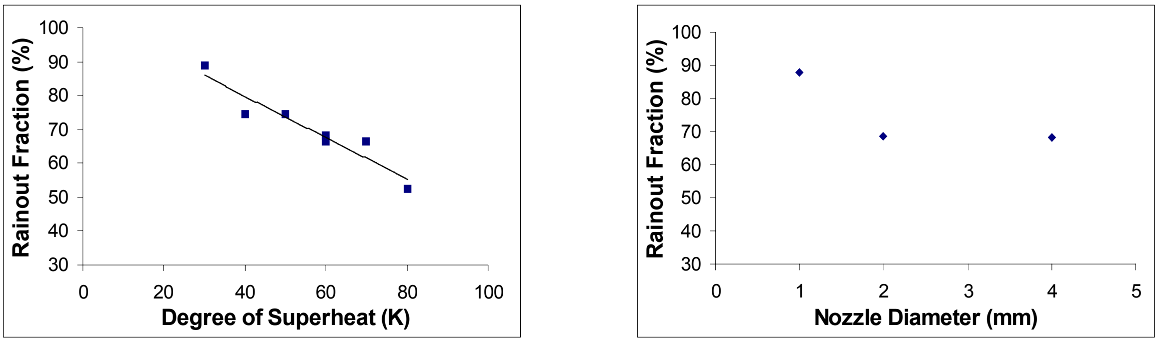

Figure 5. Rainout Fraction as function of (a) Superheat (b) Orifice Size

4. Analysis and Discussion

Figure 4 shows approximate linear relationships between jet temperature near the exit and jet width for each data set taken using a 2mm nozzle diameter, during warm-up towards steady conditions. However, this raises the apparent anomaly that for the same jet temperature, different jet widths exist. The reason for this is that the pressure at the orifice also varies, albeit gradually.

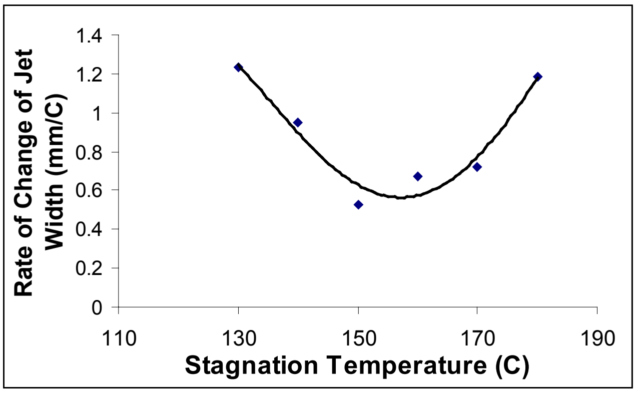

Figure 6. Jet Width Variation with Stagnation Temperature

This effect can be accommodated by analysing the gradients of the lines for the different stagnation temperatures represented in Figure 4b). Plotting the gradients against stagnation temperature identifies a minimum, which appears to identify the transition between the mechanical breakup atomisation mode, and that of flashing jet breakup, and is demonstrated in Figure 6. It is proposed that this minima offers a simple method for identifying the transition criterion. It must be noted at this stage however that the stagnation temperature at which the minimum occurs is not representative of the transition temperature. The peak jet temperature achieved during a release for a 2mm nozzle fell short of the initial stagnation temperature by approximately 15 °C. Since the temperature was also transient during the time window in which results were taken, no exact figure can be given for the temperature at which transition occurs. However, by taking the average temperature of the jet during each release to represent the data an approximation of the transition temperature can be achieved, demonstrated by Figure 7. It must be stated that this is an approximation and by no means an absolute value, however it compares favourably with a previous study conducted by Vanderwege *et al* [2] where it is suggested that a superheat of about 20 °C is required for flash boiling to be vigorous enough to noticeably change spray structure.

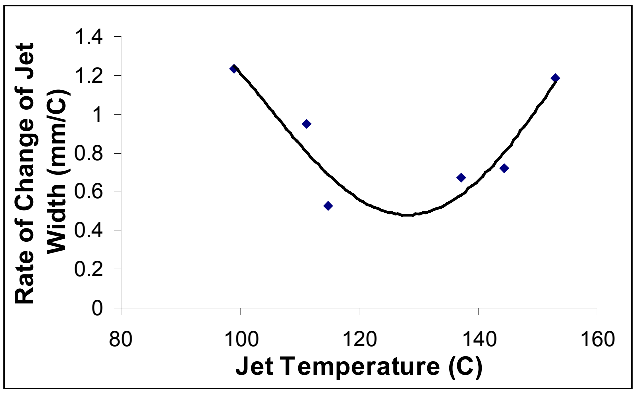

Figure 7. Jet Width Variation with Jet Temperature

The data in Figures 5 for rainout fraction show plausible trends. Certainly the monotonic decrease in rainout fraction is as expected. Moreover, there is an indication of the effect of transition between atomisation modes, with a sharp drop in rainout at the first two lower temperatures compared with the rest. For releases through the 1mm orifice, mechanical mechanisms were observed to dominate break-up, whereas flashing atomisation was dominant in releases through the 2 and 4mm nozzles. This transition is indicated in Figure 5b), which also implies that when in the flashing break-up regime, rainout is independent of orifice size. Figure 8 shows that the De Vaull and King correlation overpredicts this data-set, as it does the CCPS data-set [2]. Slight differences also exist between the CCPS dataset and the current one, though these are not considered significant considering differences in release conditions between the two datasets such as nozzle characteristics, release height, wind conditions. It should be noted that Figure 8 presents information in terms of jet temperature as opposed to stagnation temperature.

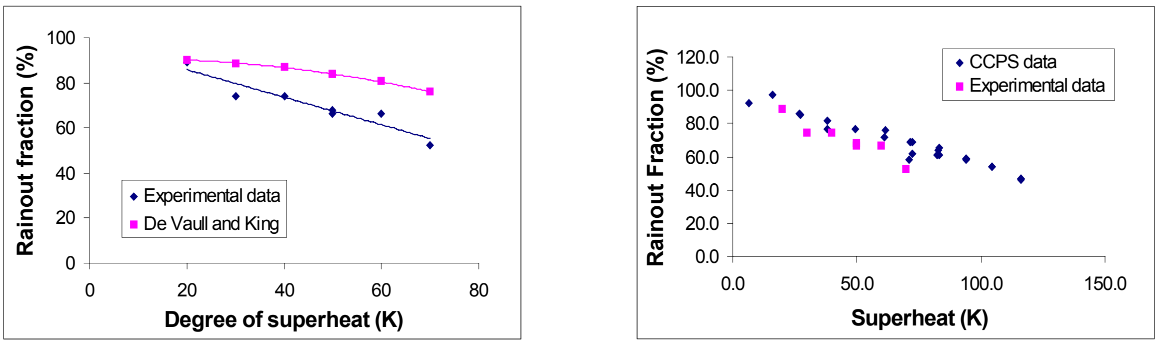

Figure 8. Comparison with Previous Predictions/Data (a) De Vaull and King Model (b) CCPS 'Release' Data for 3.2mm nozzle

5. Conclusions

- It is proposed that spray width or cone angle provides a simple diagnostic technique for characterising transition between flashing-jet breakup regimes
- It is proposed that a minimum on the corrected plot of jet width gradient /superheat provides a simple method of identifying the point of transition.
- For superheated water release through a 2mm orifice, the transition between apparent mechanical breakup and flashing jet breakup occurs at a superheat temperature of approximately 25 C.
- A simple method for quantifying rainout fraction of water proved reasonably robust and surprisingly repeatable, comparing favourably with a previous study undertaken in a more controlled environment.
- For conditions considered, rainout fraction varies inversely with degree of superheat, and is only weakly dependent upon orifice size in the 'flashing' mode. There is an indication of the effect of jet transition in the rainout dataset.
- Consistent with the previous data-set, the simple model of De Vaull and King overpredicts data under flashing jet conditions, whereas the opposite is true pre-transition, i.e. when mechanical breakup prevails. The difference between rainout prediction and measurement is generally less than 20%.

6. References

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