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High-Speed Internal Nozzle Flow Visualization of Flashing Jets

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Abstract

Flashing or thermodynamic breakup of a liquid jets occurs when a pressurized, subcooled or saturated liquid is released to a lower pressure, resulting in violent vapor nucleation, expansion, and breakup of the liquid phase. Flashing is known to produce very fine droplet atomization, often not possible by other means. Despite its usefulness as an atomization method, the fundamental processes involved in flashing remain poorly understood. This has limited its applicability due to a lack of control of spray characteristics. In a previous study, several new flashing modes emanating from long tube nozzles were discovered through high-speed imaging and depended on the level of superheat. Breakup mode and frequency appeared to be highly dependent on the state of two-phase internal flow within the nozzle.

In this study, a review of the state of knowledge of flashing sprays is presented along with motivation for continuing research. Ongoing work is also described in which internal flashing phenomena were observed using transparent glass tube nozzles. Water was used as the working fluid and was preheated and pressurized within a sample cylinder prior to release to the atmosphere. These nozzles allowed for imaging of the developing internal two-phase flow with a high-speed video camera set at 10000 fps. Internal flow phenomena were then related to observed external jet breakup.

Results revealed the bubble nucleation, migration, and coalescing processes occurring during flashing. Bubble nucleation near the nozzle wall could be observed near the tube entrance. At higher superheats, an annular flow pattern develops near the nozzle exit and corroborates previous conjectures to the internal flow pattern during flare flashing.

Introduction

Flashing occurs when a pressurized supercritical, subcooled or saturated fluid is released to a lower pressure, resulting in expansion, violent vapor nucleation, and break up of the liquid phase due to thermodynamic instability. Flashing of liquid jets has been studied since the early 1960's [1]. Early works were primarily qualitative visualization studies documenting the phenomenology of the flashing process [2-4]. Later, empirical and semi-theoretical correlations were developed to predict spray properties based on initial conditions, though applicable conditions for these relations were limited [5]. Modeling work of jet breakup and droplet dispersion has also been performed for limited situations [6-8]. Recently, due to advances in spray diagnostics, some quantitative spray characteristic measurements have been performed [9-11] though currently a lack of comprehensive measurements exists and more are needed to facilitate modeling.

Interest in thermodynamic atomization persists due to applications in a variety of areas. Because of the low temperatures possible from a flashing jet, it is being actively studied in the area of cryogenic spray cooling [12-14]. The use of low boiling point liquids such as refrigerants or cryogens in spray cooling is ideally suited in applications requiring very intense cooling or low temperatures, namely in dermatologic laser therapies and high power electronics. Advancement in this area requires better control of spray characteristics, and in turn, of cooling characteristics.

Fine droplet atomization is another attractive feature of flashing sprays. In fuel injection, flashing is being explored to improve fuel atomization in internal combustion engines [15, 16], especially for diesel or direct injection applications where atomization and, thus, combustion efficiency is poor. The fine droplet atomization also has potential in other process applications such as emulsification of immiscible liquids [17] and nanoparticle production by flame spray pyrolysis [18], though the application of flashing to the latter has not yet been explored.

Also, of great public concern is the risk of release of hazardous pressure liquefied gases (PLG's) during transportation or storage [19, 20]. In recent decades, a variety of highly destructive and deadly release scenarios have occurred (Seveso, Italy, 1976; Bhopal, India, 1984; Mexico City, 1984; Milwaukee, 2006) exposing the need for further risk assessment and safety measures. Past dispersion studies have avoided flashing atomization issues by assuming arbitrary initial release characteristics, making results questionable and of limited usefulness [20]. Scale-up of existing flashing research to the dimensions relevant to industrial releases is currently not possible due to a lack of fundamental understanding of the atomization and dispersions processes. More detailed study of the initial release processes would greatly improve the accuracy of subsequent dispersion predictions.

In the present study, a review of the current state of knowledge of flashing liquid jets is presented along with motivation for continuing research. The study will present a review of the topic on a fundamental level, as well as describe the ongoing work of the authors on high-speed imaging of internal flashing flow processes. Preliminary results and findings are discussed as well as ideas for future work.

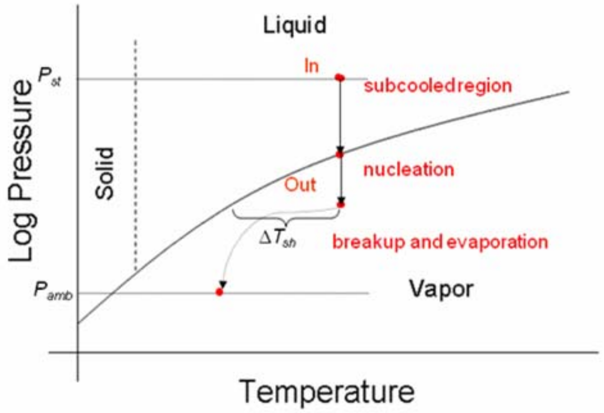

Figure 1. Phase diagram of the flashing process.

Thermodynamic Breakup Mechanisms

The basic mechanism behind thermodynamic or flashing breakup involves the transfer of energy from the expansion of vapor bubbles nucleated within the bulk liquid to the surface energy of droplets. This occurs when a pressurized supercritical, subcooled or saturated fluid is suddenly released to a lower, thermodynamically unstable pressure by way of a throttling process. Figure 1 illustrates this process with a *P* vs. *V* phase diagram. Obviously, if the pressure drop does not cross the liquid/vapor saturation line, flashing will not occur. Also, the intensity of flashing is dependent upon the superheat, ΔT_{sh}, with a certain minimum threshold superheat required for flashing to occur. Peter *et al.* [2] identified four breakup regimes, depending on the level of superheat. These are illustrated in Figure 2 and represent changes in flow characteristics with increasing superheat. Type 4 or “flare flashing,” represents a transition from external flashing to internal flashing in which most or all of the vaporization and liquid phase breakup takes place within the ejection orifice or nozzle. Flashing has also been found to be influenced by the nozzle diameter with larger diameters promoting more violent liquid breakup. This finding has been corroborated by many authors [2, 5, 21].

The energy exchange taking place was first conceptualized by Brown and York [1] by considering single bubble nucleation. Under adiabatic conditions, the latent heat of vaporization for bubble formation comes from the sensible heat of the bulk liquid. Equilibrium is reached when the residual liquid has cooled to the saturation temperature. A nucleated bubble is subject to three forces: the liquid pressure p_l, the vapor pressure inside the bubble p_g, and the pressure exerted by surface tension $2\sigma/r$. Bubble growth can only occur when the pressure acting outward exceeds the pressure acting inward:

$$p_g > p_l + \frac{2\sigma}{r} \tag{1}$$

An important property for the shattering effect of the nucleated bubble is the rate of bubble growth. It is believed that bubble growth initially occurs rapidly because of the relaxation of surface tension pressure and the slow decrease in temperature of the surrounding liquid. After the bubble is approximately ten times its initial size, heat conduction becomes the limiting mode for bubble growth. Sher and Elata [6] assumed that flashing would occur when nucleated bubbles formed a simple cubic array just touching each other, at which time they would burst (Figure 3). The fractional volumes occupied by vapor and liquid are π/6 and 1-π/6, respectively. In this way, the liquid mass of all n_d droplets may be determined.

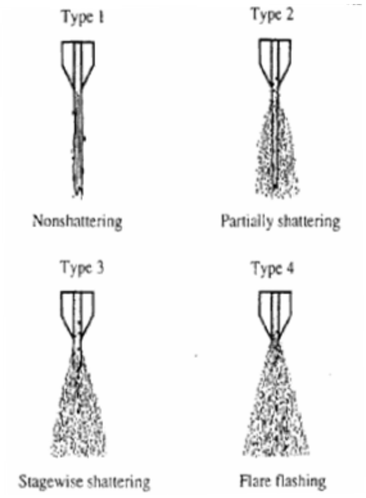

Figure 2. The four types of flashing breakup (taken from [14]).

More recent efforts by Zeng and Lee [8] and Chang and Lee [22] known as "blob models" examine the flashing mechanism occurring outside the nozzle while simultaneously considering the effects of mechanical breakup. The liquid phase is assumed to exit the orifice as large droplets or "blobs" with diameters of the order of the orifice diameter. A single bubble is assumed to nucleate and expand within each parent droplet causing it to breakup into smaller secondary droplets. The effects of mechanical deformation of the parent droplet are also considered. By using a breakup criterion relating the bubble size to the parent droplet size, the resulting average size, number and velocity of secondary droplets could be determined. The model was applied to a fuel injection problem and results indicated that flashing did, indeed, substantially reduce droplet sizes. However, the results were not validated with experimental data and the model assumptions appear to be valid only for the situation of slug internal flow and external flashing.

Aside, from modeling efforts, researchers have also attempted to develop empirical correlations to predict flow properties, particularly the conditions for onset of flashing and spray droplet sizes. Kitamura *et al.* [5] developed a criterion for the flashing threshold by correlating dimensionless *Ja* and *We* numbers:

$$\mathrm{Ja}\psi = 100\mathrm{We}^{-1/7} \tag{2}$$

Ja is the ratio of liquid superheat to heat of vaporization and accounts for a liquid's tendency to flash. It was found that critical *Ja* decreases with increasing *We*, but the correlation fails for high *We* and for situations in which a two-phase effluent existed at the orifice exit. Cleary *et al.* [23] later revised the coefficient of Equation (2) to account for each of the three shattering modes identified in Figure 2. Witlox *et al.* [24] also presented a review of existing flashing droplet size correlations and showed poor agreement among all of them with experimental data. They developed

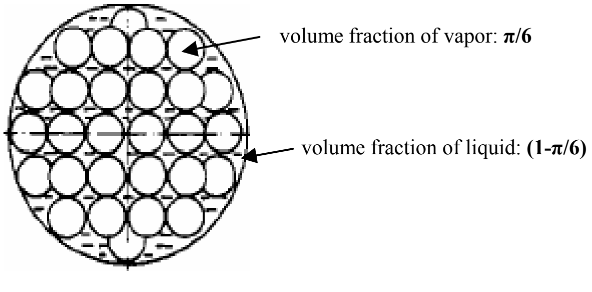

Figure 3. Simple cubic array of internal bubble growth (taken from [13]).

a new correlation predicting Sauter Mean Diameter (SMD) as a function of flow properties and nozzle aspect ratio (L/D) for subcooled releases:

$$\frac{SMD}{D} = 64.73\left(\frac{L}{D}\right)^{0.114} \mathrm{Re}\,L - 0.014\mathrm{We}_l^{-0.533} \tag{3}$$

This predicted droplet sizes due to mechanical jet breakup. Transition criteria of the form of Equation (2) were implemented to determine regions of flashing with increase in superheat and Equation (3) was then reduced linearly in order to conform to a measured data point. The proposed arbitrary linear decreases in diameter are, however, highly questionable as they do not represent any physical processes.

The problems with explanation of the physical processes of flashing, and with modeling and correlating measured data stem from the fact that internal flow characteristics within the nozzle are not thoroughly considered. Park and Lee [4] have demonstrated the importance of internal flow characteristics on the external spray, albeit from a strictly qualitative degree. A novel, transparent nozzle was used to visualize internal flow regimes and related to external spray characteristics.

In order to better quantify internal flow conditions, Vu et al [ref] used a one-dimensional, semi-empirical model of flow parameters along the nozzle length which were then related to measured external flow characteristics. It was found that for the conditions of high superheat and larger *L/D* ratio nozzles, significant vaporization takes place within the nozzle and critical flow conditions are reached with choking at the nozzle exit. Both liquid and gas phases were found to accelerate for some distance away from the nozzle. Some new correlations were also developed describing the interaction of the two phases. These assume that droplets are suspended within the vaporized gas phase and accelerated by its expansion. A new empirical correlation for C_D was developed for droplets under the higher acceleratory fields of flashing sprays.

Recently, Vu et al [ref] discovered new flashing atomization modes previously unknown. Through combined high-speed video imaging (Figure 2) and Phase Doppler optical measurements of droplet characteristics, it was found that at lower superheats and large L/D aspect ratios, jet breakup may occur by way of discrete bubble explosions with ballooning and disintegration. These modes were believed to arise due to internal slug flow within the nozzle from bubble merging. Characteristic frequencies in explosive bubble breakup were observed and increased with increasing initial liquid superheat, although the reasons for this are still unknown. With sufficient superheat, flashing moves into a regime of flaring in which an annular flow is believed to be established and fine atomization is observed immediately at the nozzle exit.

Because of the limitations of internal flow modeling, further studies are required to understand the dynamic and spatial distribution of internal two phase flows and their relation to resulting spray characteristics. This is the focus of ongoing research efforts by the authors.

Materials and Methods

Internal flow is visualized using transparent glass tubes with internal diameters ranging from 0.5-3 mm and lengths from 5-100 mm. Water is used as the working fluid and flashing is induced by heating and pressurization within a stainless steel cylinder. The liquid is introduced to the glass tubes through a large ball valve to minimize flow disturbances. Imaging is performed using a Phantom v7.1 camera at 10000 fps and is backlight with a high-intensity tungsten lamp with diffuser. Because of the limited field of view of the camera, the entire nozzle is captured by scanning the camera along the nozzle length using an electronic translational stage. This method does not allow one to follow individual structures as they progress through the nozzle, but provides a picture of the bubble nucleation dynamics and spatial distribution.

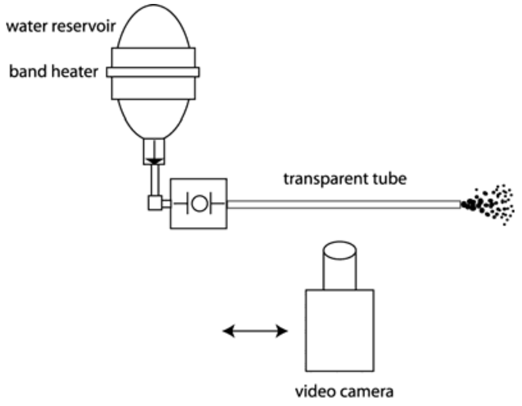

Figure 4. Experimental Setup.

Preliminary Results

Figure X shows preliminary images of water flow at high superheat in a 0.5 mm diameter tube nozzle near the tube entrance and exit. Clear bubble formation is visible near the tube wall. At the tube exit, an annular flow appears to exist in which the bubbles have merged into a vapor core surrounded by a liquid sheath. These findings appear to support previous conjectures of internal annular flow during the flare flashing regime.

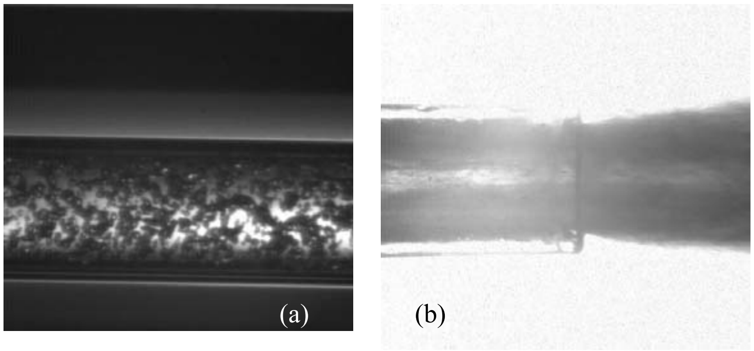

Figure X. Internal flow imaging of water through a glass tube.

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