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 breakup modes emanating from vertically downward-oriented 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, internal flow phenomena during flashing were observed using transparent glass tube nozzles of 0.6 mm and 1.2 mm ID. These nozzles allowed for imaging of the developing internal two-phase flow with a high-speed video camera set at 25000 fps. Water was used as the working fluid and was preheated and pressurized at saturation conditions within a sample cylinder prior to release through the nozzle to the atmosphere. Gravitational effects were also studied by orienting the nozzle vertically upward, vertically downward, and horizontally. Internal flow phenomena were then related to observed external jet breakup characteristics emanating from stainless steel tube nozzles with similar surface roughness.

Results reveal that the bubble nucleation process is often unstable and unpredictable. Nucleation tends to occur near the nozzle exit due to the superheat required from wall frictional pressure drop. Due to wall confinement effects, narrower nozzles require higher superheat to initiate boiling. Buoyancy effects also appear to influence nucleation characteristics, as downward facing nozzles exhibit the most unstable behavior.

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.

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.* [12] 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.

Most recently, Vu *et al.* [13] discovered new flashing atomization modes previously unknown. Through combined high-speed video imaging 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.

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 [14-16]. 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 [17, 18], especially for diesel or direct injection applications where atomization and, thus, combustion efficiency is poor. Also, of great public concern is the risk of release of hazardous pressure liquefied gases (PLG's) during transportation or storage [19, 20].

This study expands on existing knowledge of flashing breakup mechanisms by employing high-speed video imaging of the internal flow and time-dependent flow phenomena, and corroborates explanations of the new breakup modes found previously.

Materials and Methods

Internal flow is visualized using transparent glass tubes with internal diameters of 0.6 and 1.2 mm and corresponding lengths of 80 and 270 mm. Water is used as the working fluid and flashing is induced by heating and pressurization within a stainless steel cylinder at saturation conditions to temperatures ranging from 105-180 ˚C. A schematic of the experimental setup is given in Figure 1. The cylinder is heated using a band heater, controlled by feedback from a thermocouple in direct contact with the water. The water is introduced to the glass tubes through a ¼" ball valve to minimize flow disturbances which is then attached to the nozzle using a custom-made adaptor. The nozzle is pressed against the adaptor with using a retaining arm and sealed with a high temperature o-ring. Imaging is performed using a Phantom v7.1 camera at 25000 fps and is backlit with a high-intensity tungsten lamp. Because of the limited field of view of the camera, flow through the entire nozzle could be captured by scanning the camera along the nozzle length using an electronic translational stage. However, nucleation generally only occurs very near the nozzle exit, so the camera is kept in this position. Additional ¼" fittings are used as necessary to adjust the nozzle orientation with respect to gravity while keeping the storage cylinder fixed. Because the end plate of the retaining arm affected the resulting spray characteristics external spray characteristics are imaged separately using stainless steel tube nozzles of 0.51 and 1.2 mm ID and 80 and 130 mm lengths, respectively.

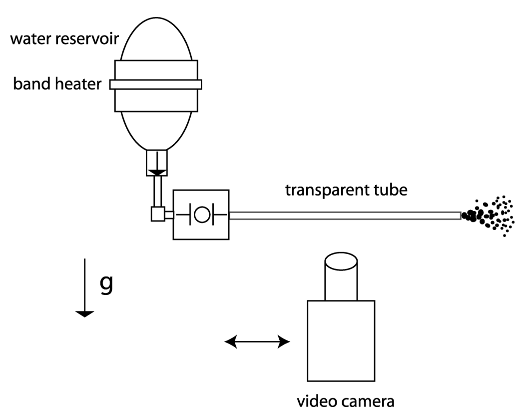

Figure 1. Experimental Setup.

Results

Several flow regimes are observable within the experimental parameters tested and are depicted in Figure 2. Bubbly flow occurs when bubbles form and predominantly reach an equilibrium diameter less than the nozzle width. This transitions to slug flow when the bubbles expand to the nozzle width and continue expansion by lengthening and merging with other bubbles. Slugs may become unstable when the trailing gas-liquid interface trips and becomes unstable, leading to a chaotic mixing of phases that spreads throughout the slug. Often, however, bubble nucleation sites do not become active and phase change only occurs very near the nozzle exit where pressure has undoubtedly dropped significantly. This phenomenon is denoted here as tip evaporation.

Figure 2. Flow regimes observed in the present study: (a) bubbly, (b) slug, (c) churn, and (d) tip evaporation.

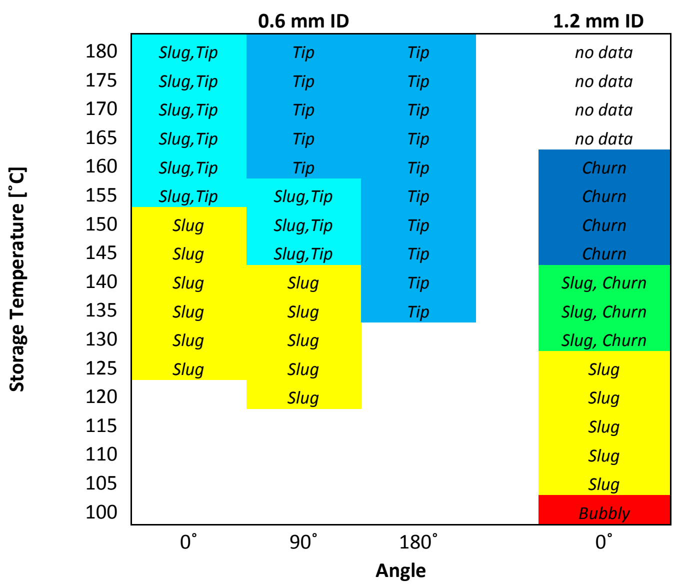

Figure 3. Flow regime map for tested conditions. Angles are in respect to gravity. Regimes indicated are the most dominant for the given conditions.

Figure 3 is a regime map of the dominant regimes observed for each tested condition. When more than one regime is prevalent for a given condition, both regimes are noted. Due to leakage from the nozzle entrance junction, tests could not be performed above 180 ˚C for the 0.6 mm nozzle and above 160 ˚C for the 1.2 mm nozzle. The locations of nucleation sites may change sporadically, but generally reside near the nozzle exit. With the 0.6 mm nozzle, significant superheat, with respect to atmospheric conditions, is required to initiate nucleation. This is likely due to a wall confinement effect that resists bubble growth. As the nozzle rotates to point vertically upward, the frequency of slug formation decreases at 90˚ and is virtually eliminated at 180˚. In fact, at 180˚ the internal flow only exhibits tip evaporation. Buoyancy, therefore, likely affects nucleation site activation. With the larger 1.2 mm nozzle, nucleation occurs at a much lower temperature with the bubbly flow regime. This transitions to slug flow, and as flow velocities continue to increase with increasing temperature and pressure, the slugs destabilize to churn flow.

The external breakup phenomena with stainless steel nozzles can generally be correlated to the observed internal flow. Generally, flashing jet break up occurs when some of the liquid phase boils to gas and expands violently, causing the surrounding liquid to break up into droplets. For long nozzles with high L/D ratios, as is the case for this study, the boiling initiates within the nozzle and the external break up characteristics depend on the internal flow regime and the remaining energy of expansion of the gas upon exiting. For the vertically downward facing nozzles, complex breakup mechanisms were observed as described by Vu et al [13]. Figure 4 shows a breakup sequence in which a slug breeches the nozzle exit with the balloon formation and collapse that ensues. This sequence would appear to occur with slugs that have nucleated further upstream and have lost most of their expansion energy within the nozzle. With slugs that nucleate near the nozzle tip, the expansion energy causes an explosive breakup and fine atomization termed "flaring", as shown in Figure 5a. This flaring is intermittent and separated by periods of unbroken jet. As tip evaporation manifests at higher temperatures, flaring becomes steady. With the nozzle at 90˚, the frequency of nucleation and slug formation decreases significantly. As tip evaporation emerges, the external flow transitions to a steady spray. With the nozzle at 180, a steady breakup process occurs in which bubble nucleation and explosion appear to occur externally just beyond the nozzle exit (Figure 5b). With increasing temperature, this transitions to a flaring breakup (Figure 5c). The larger 1.2 mm nozzle at 0˚ and low superheat exhibits complex breakup phenomena very similar to that for the 0.6 mm nozzle. The onset of churn flow causes a very violent break up resulting in a dense spray which may also be qualitatively called flaring (Figure 5d).

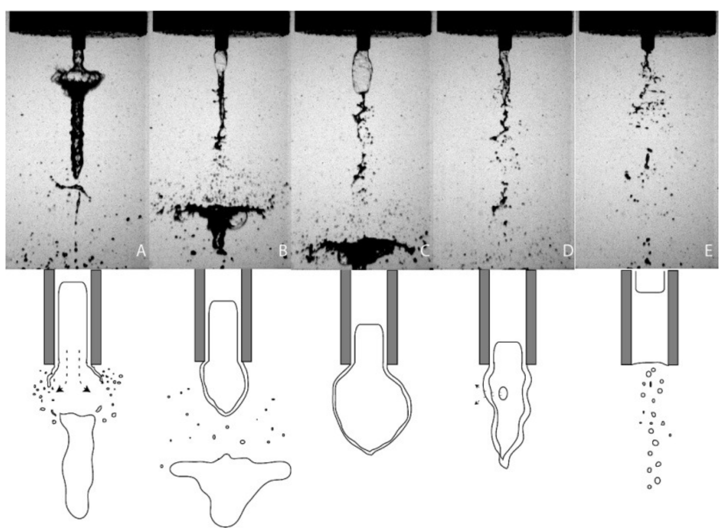

Figure 4. Breakup modes for highly expanded slugs with accompanying illustrative diagrams.

Conclusions

This paper characterizes, through high-speed video imaging, the internal flow characteristics of flashing of initially saturated water within straight tube glass nozzles in order to explain external breakup modes. Complicated breakup modes are observed for downward facing nozzles because of the irregularity of nucleation sites and varying degrees of expansion of gas slugs within the nozzle. Bubble nucleation begins at a much lower temperature for the larger diameter nozzle and also displays churn flow patterns at higher temperatures. Gravity, when acting in the same direction as flow velocity seems to promote nucleation site activation. Horizontally and vertically upward facing nozzles exhibited far fewer nucleation events. Tip evaporation was the predominant internal regime for the latter cases, producing a generally stable external breakup.

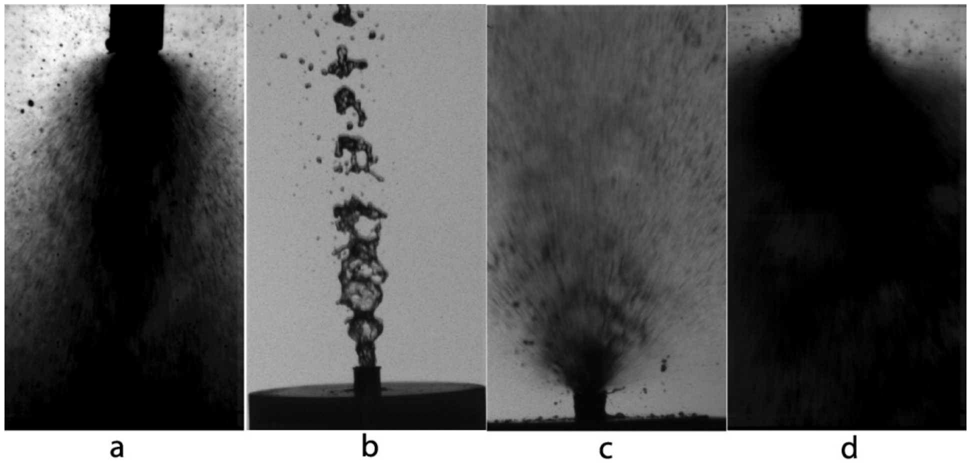

Figure 5. Examples of other external breakup modes: (a) flaring from a 0.5 mm ID nozzle at 0˚, (b) steady breakup from tip evaporation in a 0.5 mm ID nozzle at 180˚ and (c) transition to flaring, (d) very dense flaring spray resulting from churn flow in a 1.2 mm ID nozzle at 0˚.

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