FLASHING LIQUID JETS IN LOW-PRESSURE ENVIRONMENT

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In the present paper, highly expanded flashing liquid jets in a low-pressure environment are studied experimentally, particularly focusing upon the physics associated with liquid flashing regimes. A long, straight stainless steel capillary with an inner diameter of 0.23 mm and a length of 17.0 mm is used as the nozzle, which is connected with a syringe. Through a solenoid valve, a test vessel is connected with a vacuum chamber with a volume about 800 times bigger than that of the test vessel, in order to keep constant pressure inside the test vessel throughout every experimental run. Distilled water of about 1 mL is filled into the syringe at first, while the syringe is open to the ambient. Then, opening the solenoid valve, the air inside the test vessel will be evacuated quickly, resulting in a quick depressurization and a low backpressure inside the test vessel. The water in the syringe is then driven by the difference between the ambient pressure and the backpressure to form a highly expanded flashing liquid jet into the test vessel. For the case of low initial temperature and high backpressure, there is no evaporation, and then the flow of the liquid jet from the nozzle exit section remains intact and follows a straight path. On the other hand, if the initial temperature is high and/or the backpressure is low enough to lead a superheated exit condition, evaporation will take place, irregular evaporation waves around the liquid core are visible, and the jet shattering occurs. On further decreasing the backpressure, the liquid jet shatters giving rise to a cloud of droplets with a spray angle usually bigger than 90°, indicating a large number of nucleation sites and rapid bubble growth. It is also shown that there is flow choking behavior as the flow rate becomes constant and is insensitive to pressure reduction below some backpressure threshold.

KEY WORDS: flashing liquid jet, vacuum, flow choking

1. INTRODUCTION

In some situations, a pressurized liquid may suddenly be exposed to a low-pressure environment. If the environmental pressure is lower than the corresponding saturation pressure at the injection temperature, the liquid will undergo a fast phase transition process, commonly known as liquid flashing. Fundamental knowledge of the mechanism of flashing liquid jet is important due to its broadness of practical applications in many thermodynamic processes, such as chemical and process plants, water desalination plants, and steam and refrigeration systems. It is vital in nuclear power plant safety, and also plays a leading role in environmental control systems of space vehicles.

Liquid flashing studies have been made by many researchers. As examples, one can mention the following: Edwards and O’Brien (1970) studied the flashing phenomena connected with depressurization of water reactors as it could occur in the case of rupture of pressurized water pipes. Fuchs and Legge (1979) reported an experimental study of the flashing phenomena for the development of a useful nozzle for dumping water into space overboard the Spacelab cabin. Reid (1979) discussed the flashing phenomenon as a possible mechanism of rupturing a pressurized liquefied gas storage tank. Miyatake et al. (1981) investigated experimentally the flash evaporation phenomenon that occurs when the subcooled water undergoes a sudden reduction of the surrounding pressure below its boiling pressure, focusing upon the application of seawater desalination processes. Oza and Sinnamon (1983) investigated the flash-boiling fuel injection as a method of increasing fuel atomization for improvement of fuel injector technology. Simões-Moreira and Bullard (2003) studied the flashing mechanisms occurring in expansion devices of refrigeration...
2. EXPERIMENTAL SETUP

A schematic diagram of the experimental system for studying the flashing phenomenon is shown in Fig. 1 (Du et al., 2012). It consists of several parts: test vessel, vacuum system, data collection system, and high-speed photography system. The test vessel is made of aluminum with glass windows on two opposite sides. An absolute pressure transducer DMP331, with a range of 0–0.01 MPa, an uncertainty of 0.175%FS (Full Scale), and a response time <5 ms, is connected to the test vessel to measure the pressure change during an experiment. The vacuum system includes a vacuum pump, a vacuum chamber, and a solenoid valve. The vacuum pump, with a pumping rate of 8 L/s and a final vacuum of $6 \times 10^{-2}$ Pa, is connected to the vacuum chamber. The volume of the vacuum chamber is 1 m$^3$, about 800 times bigger than that of the test vessel. Therefore, it can keep a constant pressure in the vessel during an experiment. A solenoid valve (I.D. = 25 mm) between the test vessel and the vacuum chamber is used to make the depressurization process quick enough.

To study the flashing phenomenon of a single liquid drop during quick depressurization, a thin T-type thermocouple (O.D. = 100 µm) is located inside the vessel to hang a liquid droplet and to measure the temperature change of the droplet simultaneously (Du et al., 2012). In the present study, the thermocouple is replaced by a 17.0-mm long, straight stainless steel capillary connected with a syringe, which is used as a nozzle (Fig. 2). The inner diameter of the capillary is 0.23 mm, while its outer diameter is 0.4 mm. A water bath is used for adjusting the temperature of the syringe and the liquid inside it.
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1 – vacuum pump
2 – vacuum chamber
3,7 – pressure transducer
4 – solenoid valve
5 – ball valve
6 – lighting
8 – temperature transducer
9 – test vessel
10 – thermocouple
11 – high speed camera
12 – data acquisition system (DI710)
13 – computer

FIG. 1: Schematic diagram of experimental system.

FIG. 2: Schematic diagram of experimental facility for liquid jets in low-pressure environment (a) and that of the connection structure between the capillary nozzle and the syringe.

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The pressure signal is recorded by a data collection system DI-710, while the shape of the liquid jets is recorded at a record speed of 400 fps (frames per second) by a high-speed digital camera (AOS Vitcam CTC). A signal fed back from the solenoid valve is used to trigger the high-speed camera, which is also recorded by the DI-710 to make a time base between the measured pressure data and the images. A digital camera (Sony DCR-TRV900E) is used to record the movement of the surface inside the syringe at a normal record speed of 25 fps, which is used to determine the flow rate of the liquid jets after the experiments.

In the present experiment, pure distilled water is used as the test material. At first, about 1 mL water is filled inside the syringe, while the syringe is open to the ambient. The water bath is then started and usually lasts for 1 h to keep the preset temperature of the syringe and water inside it. Then, opening the solenoid valve, the air inside the test vessel will be evacuated quickly, resulting in a quick depressurization and a low backpressure inside the test vessel. The water in the syringe is then driven by the difference between the ambient pressure and the backpressure, to form a highly expanded flashing liquid jet into the test vessel.

Figure 3 shows a typical history of the measured pressure in the test vessel. The initial ambient pressure and those pressures above the range of the pressure transducer during the depressurization were not measured directly, which were shown schematically as a dashed line in Fig. 3. It is obvious that the pressure inside the test vessel can be reduced within a period no longer than 2 s from an atmospheric pressure to the designed terminal pressure. It’s also verified by replaying the recorded video of the movement of the surface inside the syringe that a steady flow rate can be maintained after the transient beginning stage. Then, the flow rate is averaged in the duration of the steady stage. The uncertainty of the flow rate is evaluated to be no more than 0.05 mL/s.

3. RESULTS AND DISCUSSIONS

Two groups of experimental runs have been performed. The outcome of the experiments reveals the pattern or structure change as well as the respective quantities of liquid jets into low-pressure environment. Figure 4 shows some typical liquid jet patterns observed in the present experiments. The liquid jets can be categorized as the following three physically distinguishable regimes:

(a) Continuous liquid jet (CLJ) is the one which retains its column structure for extended distances after being released from the nozzle exit. It is similar to the nonshattering liquid jet defined by Peter et al. (1994), except

FIG. 3: Typical history of the measured pressure inside the test vessel.
FIG. 4: Liquid jet patterns at different conditions: (a) $p_b = 4800$ Pa, $t = 25^\circ$C, $p_{sat} = 3166$ Pa; (b) $p_b = 540$ Pa, $t = 25^\circ$C, $p_{sat} = 3166$ Pa; (c) $p_b = 910$ Pa, $t = 60^\circ$C, $p_{sat} = 19920$ Pa.

that one was accompanied by a sporadic spew of undispersed ligaments falling parallel to the main liquid column which is not observed in the present experiments. It is observed at the nozzle exit conditions of subcooled and low superheated degree.

(b) Partially flashing liquid jet (PFLJ) with irregular evaporation waves is the one whose column shatters only in its outer layer and retains its inner column downstream up to a certain distance from the nozzle exit. Its shattering is accompanied by irregular evaporation waves. The jet structure is highly irregular with fluctuations of the length of the nonshattering inner liquid column and of the position and shape of evaporation waves. Sporadically, an
angle more than $90^\circ$ between the movement of shattered liquid droplets and the main jet flow direction may be observed. This characteristic occurrence is found to prevail at moderate superheated degree levels, especially in the case of low initial liquid temperature. The irregular characteristic is not reported in the literature.

(c) Completely flashing liquid jet (CFLJ) with a backward action is the one in which liquid shatters erratically just at the nozzle exit and the spray angle is usually bigger than $90^\circ$. The shattered jet phenomenon indicates a large number of nucleation sites and rapid bubble growth occurring inside the liquid jet near the nozzle exit. It is also observed periodically that liquid can climb upwards along the outer wall of the nozzle, form a large liquid drop, oscillate and extend breadthwise, and break into two almost equal pieces. One piece of liquid remains attached to the nozzle outer wall, while the other flies horizontally at first and then falls down under the action of gravity. This kind of liquid jet occurs in the case of a very high superheated degree, especially in high initial liquid temperature and low terminal pressure inside the test vessel. No report of the backward structure in flashing liquid jets is found in the literature, except for Yarygin et al. (2009, 2011) who reported a similar backward structure of liquid droplet flow in a joint jet of gas with near-wall liquid film from a supersonic nozzle into vacuum.

In order to determine the characteristic of the flow rate of the liquid jets, the frictional factor for the nozzle used in the present experiment is measured in a standard procedure. Figure 5 shows the results obtained from several groups of experiments at ambient temperature, in which the downstream pressure is set as constant, i.e., the atmosphere pressure, while different ways are used to change the upstream pressure. In one way, a container with a changeable height of the free surface of water is connected to the syringe to make a different pressure drop across the nozzle. In another way, a pumped loop with adjustable valves is used to regulate the upstream pressure. Pressure at the inlet of the syringe is also measured by a gauge pressure transducer, which gives the same values as the calculated ones by the static pressure caused by the water height of the free surface above the inlet of the nozzle in the first case. It is found in Fig. 5 that the frictional factor for the nozzle used in the present experiment satisfies the Poiseuille laminar law, namely

$$f = \frac{\Delta p}{\rho u^2/2} = 2.824 + \frac{l}{d} \frac{64}{Re}$$

where the Reynolds number $Re = \frac{\rho_L u d}{\mu_L}$.

**FIG. 5:** Frictional factor vs Reynolds number of the straight stainless steel capillary connected with the syringe.
Figure 6 shows the experimental data of the flow rate of the liquid jets at different conditions of the backpressure inside the test vessel and the initial liquid temperature. Choking-type behavior is observed as the backpressure is decreased to a certain value which is lower than the saturated pressure corresponding with the initial liquid temperature, while keeping the liquid injection conditions unchanged. The critical pressure corresponding to the choking-type behavior is dependent on the temperature, being higher at 60°C than that at 25°C. Furthermore, the deviation between the experimental results and the incompressible prediction is also higher at higher temperature, which is mainly caused by the higher critical pressure.

According to Simões-Moreira et al. (2002), the reason for the choking-type behavior may be interpreted by the occurrence of a shock wave of a two-phase mixture coupled with the flashing jet. They observed a complete structure of the shock wave from Schlieren still pictures. Usually, the shock wave has a spheroidal or ellipsoidal frontal surface and a flat rear portion parallel to the solid wall at the nozzle exit. It may also be true in the present study, though the Schlieren method is not adopted to observe the shock wave. In other words, shock wave may occur in the case of a completely flashing liquid jet, according to the observed floating large liquid drop above the nozzle exit and the occurrence of choking behavior of the measured flow rate of the liquid jets.

Some differences, however, are observed in the present study due to a different structure of the nozzle exit used in the present experiment compared with that in Simões-Moreira et al. (2002). The upper (rear) portion of the shock wave may not be restricted due to the thin thickness of the capillary nozzle. Then, it can extend upwards, and push water climbing upwards along the outer wall of the nozzle to form a large liquid drop oscillating breadthwise. It will depart from the outer wall of the nozzle, and fly horizontally at first. Furthermore, it is evident that the boundary of the flashing liquid jet is under a highly unsteady state. Extending and shrinking are observed with time. This characteristic suggests that a regular and steady shape of the flashing liquid jets with evaporation wave and shock wave, as proposed and analyzed by Simões-Moreira et al. (2002) and Vieiro and Simões-Moreira (2007), may be not suitable in the present cases.

4. CONCLUSIONS

Highly expanded flashing liquid jets into a low-pressure environment are studied experimentally in the present paper, in which the major objective is particularly focused upon the physics associated with liquid flashing regimes. Distilled water jets from a long, straight stainless steel capillary into a lowbackpressure environment are observed and classified.
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into three categories. For the case of low initial temperature and high backpressure, there is no evaporation, and then the flow of the liquid jet from the nozzle exit section remains intact and follows a straight path. On the other hand, if the initial temperature is high and/or the backpressure is low enough to lead a superheated exit condition, evaporation will take place, irregular evaporation waves around the liquid core are visible, and the jet shattering occurs. On further decreasing the backpressure, the liquid jet shatters giving rise to a cloud of droplets with a spray angle usually bigger than 90°, indicating a large number of nucleation sites and rapid bubble growth. Flow choking behavior occurs when the backpressure is lower than some threshold, where the flow rate remains constant and insensitive to pressure reduction.

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REFERENCES


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