EVAPORATING-FREEZING PHENOMENA OF WATER DROPLETS DURING QUICK DEPRESSURIZATION

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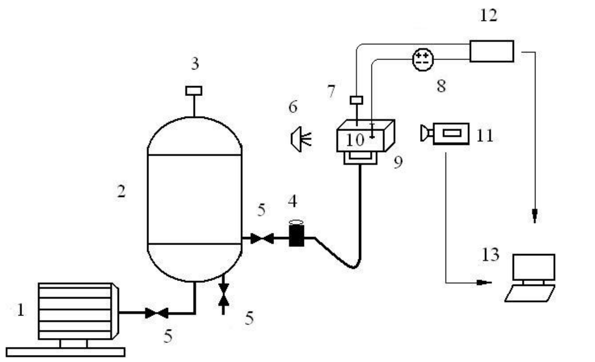
Summary The evaporating-freezing process of single pensile water droplet during quick depressurization is studied experimentally. The typical characteristics of the thermal-dynamical behaviors of this process are obtained. Based on the experimental observations, the influences of non-condensable gases on the process are analyzed and discussed in detail. It is pointed out that the subcooling limit corresponding to the onset of freezing of the droplet is nearly a constant, and the freezing temperature is approximately equal to the solid-vapor equilibrium temperature determined by the vapor partial pressure at the terminal state. The present results are helpful for predicting correctly the evaporating-freezing processes of liquid droplets in high vacuum environment.

Flash evaporation may occur in two cases. One is that the liquid is heated quickly so its temperature is much higher than the saturation temperature corresponding to the system pressure, the other is that the system pressure is suddenly dropped to a value far below its saturation pressure corresponding to the system temperature. Liquid discharging into vacuum environment during space orbital flight is one of important applications of the second case. Generally, the liquid jet quickly breaks into small droplets, and the rapid evaporation leads to a quick decrease of the droplet temperature, which may eventually lead to freezing of the droplets and possible blockage of the discharge pipe, and then cause the failure of the discharging process[1~3]. The objective of this study is to experimentally investigate flash evaporation process of water droplets released into vacuum, particularly on the influence of non-condensable air on the characteristics of the process.



1-vacuum pump, 2-vacuum chamber, 3-gauge tube, 4-electric-magnetic valve, 5-ball valve, 6-lighting, 7-pressure sensor, 8-temperature transmitter, 9-test vessel, 10-thermocouple, 11-high speed camera, 12-data acquisition system, 13-computer

Fig. 1 Schematic diagram of experimental system

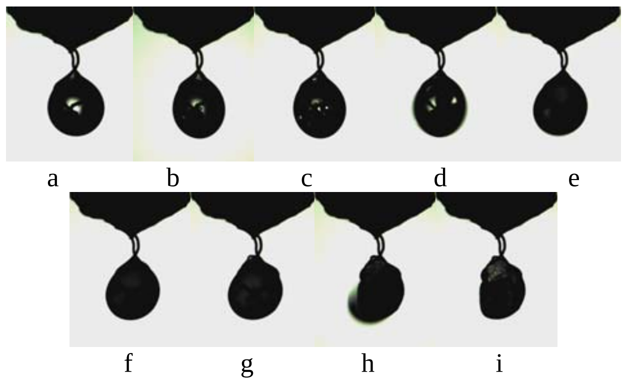


Fig. 2 Typical evaporating-freezing process of water droplets during quick depressurization

A schematic drawing of experimental system is shown in Fig. 1. A droplet was hung in the test vessel with a thin thermocouple (Fig. 2). Then the air inside the test vessel was evacuated quickly by opening the electro-magnetic valve connecting to the vacuum chamber. As soon as the quick depressurization began, small bubbles usually emerged within the droplet, which may come from not only the internal air separation, but also the thermocouple junction due to the existence of embryo core of nucleation center. The liquid droplet temperature dropped quickly, which was caused not only by the expanding of air around it but also by the quick evaporation on its surface. After the temperature exceeds some low limit, the droplet was frozen from the surface. Generally, the surface of the frozen droplet was not smooth. The coagulation contact surface moved from the droplet surface to its center. The liquid transformed the solid state, releasing the coagulation latent heat. Then the temperature rise to a value near the freezing point. After the whole droplet was frozen, its temperature dropped again due to the surface sublimation (Fig. 3). Sometimes, the droplet may split during the freezing process, which was caused by the increase of the pressure inside the frozen surface, as shown in Fig. 2h.

Pressure-temperature (*p-t*) curves of liquid droplets at different terminal pressure and rate of depressurization are shown in Fig. 4, which are corresponding with those shown in Fig.3. Phase equilibrium lines of solid-vapor (OA), solid-liquid (OB), and liquid-vapor (OC) are also shown in the same figure for comparison. The subcooling limit is defined as the differences between the subcooled temperature and the freezing temperature near recalescence, which is also marked in Fig. 4. It can be observed that the subcooling limit is approximately a constant in different cases.

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In the case of lower terminal pressure, the depressurization process is much quick. The state of the droplet, which locates initially in the liquid region, descends quickly and passes across the liquid-vapor phase equilibrium line firstly. Its trajectory approximates a vertical line. Then, it moves nearly horizontally at constant terminal pressure with decreasing temperature, and passes across the solid-vapor phase equilibrium line. Till the subcooling limit achieves, freezing occurs, and a sudden temperature jump caused by liberation of the latent heat of transformation is observed, which is known as recalescence. A constant freezing temperature can be maintained some period after recalescence, which is approximately equal to the solid-vapor phase equilibrium temperature corresponding to the terminal pressure. In the case of higher terminal pressure, however, the depressurization process is much slow. The state of the droplet can't reach the vapor region at all. Furthermore, freezing and recalescence can also be observed, but the freezing temperature is obviously lower that the solid-liquid phase equilibrium temperature corresponding to the terminal pressure.

Clearly, the atmosphere in the test vessel is a non-saturated wet air originally (the air humidity is low in Beijing, so relative humidity indoor is generally about 40% in the present experiments). Therefore, the depressurization process may be affected greatly by the residual non-condensable air in the local environment surrounding the droplet. Vapor partial pressure in the local environment may deviate from the measured pressure inside the test vessel, causing the change of characteristics in the process.

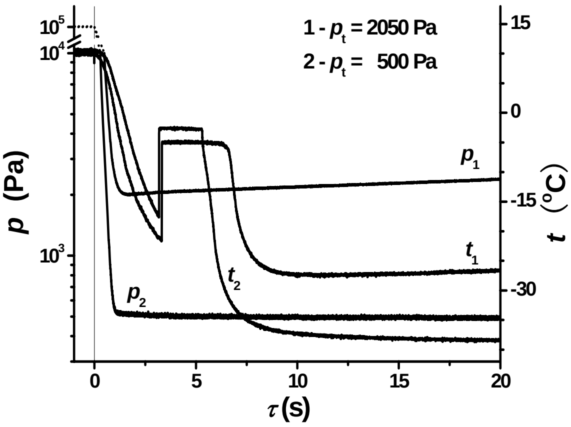

Fig. 3 Variations of the liquid droplet temperature at different terminal pressure and rate of depressurization

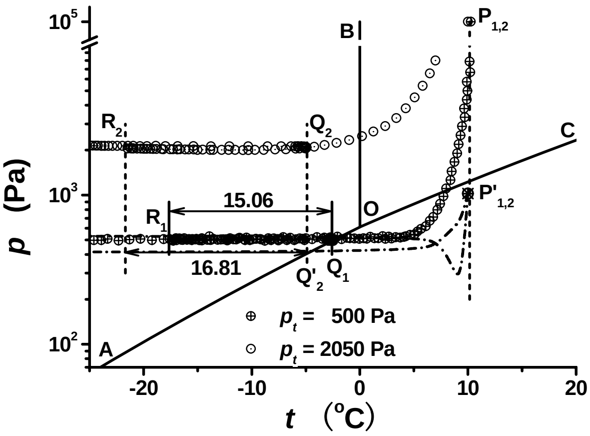

Fig. 4 Pressure-temperature curves of liquid droplets at different terminal pressure and rate of depressurization

Possible processes are shown in Fig. 4. Due to freezing occurs from the surface of the droplet, the state of the droplet ought to be represented by the vapor partial pressure, which is then locates initially in the vapor region. In the case of lower terminal pressure, quick depressurization deflates air much thoroughly. On the other hand, large amount of vapor releases due to flash evaporating driven by large potential difference. Thus, nearly hundred-percent vapor may remain inside the test vessel, and the vapor partial pressure in the local environment surrounding the droplet may approximate the terminal pressure. That is the reason that the freezing temperature is approximately equal to the solid-vapor phase equilibrium temperature corresponding to the terminal pressure in this case. On the contrary, slow depressurization in the case of higher terminal pressure may result in larger amount of non-condensable air in the local environment surrounding the droplet. Then, the freezing temperature may be determined by the solid-vapor phase equilibrium temperature corresponding to the actual vapour partial pressure at the terminal state. That is why the freezing temperature is obviously lower that the solid-liquid phase equilibrium temperature corresponding to the terminal pressure in this case.

In summary, the influences of non-condensable gases on the process are analyzed and discussed in detail based on the experimental observations. The freezing temperature is approximately equal to the solid-vapor equilibrium temperature determined by the vapor partial pressure at the terminal state. Furthermore, the subcooling corresponding to the onset of freezing of the droplet is nearly a constant. The present results are helpful for predicting correctly the evaporating-freezing processes of liquid droplets in high vacuum environment[4].

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