



## Technical Note

## Jet flow phenomena during nucleate boiling

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**Abstract**

Boiling phenomena are with highly complex nonlinear and nonequilibrium characteristics, which cause diversity and complexity of boiling nucleation. In the present paper, an experimental investigation was conducted to investigate the nucleate boiling behavior on a very fine heating wire. Using zoom routine and CCD camera system, the dynamical process of nucleate boiling was visually observed and several modes of jet flows were explored during nucleate boiling. This phenomenon is quite different from the usual observation of nucleate boiling. High-energy liquid jet, fog-like jet, cluster-like jet, bubble-forming jet, bubble-bunch jet and bubble-top jet were described in detail. The microscopic mechanism concerning the phenomena was discussed. © 2002 Published by Elsevier Science Ltd.

*Keywords:* Boiling; Nucleation; Jet flow; Bubble

**1. Introduction**

Classically, vapor bubbles are generated from active nucleate sites, growing up to a critical diameter, and then departing from the heating surface, which is so-called nucleate boiling [1]. Actually, the study of nucleate boiling is quite comprehensive, and nucleate boiling phenomenon might be one of the very well-investigated modes among three different boiling regimes [2]. However, there are still a great number of unsolved and/or unclarified problems and phenomena remaining. Boiling nucleation, bubble dynamics, interactions between bubbles, the liquid and the heating wall, liquid flow and the temperature field around the bubbles, and the physical nature of boiling regimes all need to be investigated theoretically and experimentally [3].

As traditional nucleate boiling theory, bubbles usually generate from active nucleate sites on heating surface. At these sites, bubbles grow up to critical size and then depart from the heating surface with the impact of buoyancy and interfacial tension. Whether gen-

eration or departure, it is necessary for sites or bubbles to reach some critical sizes. Critical size of bubble departure usually fluctuates around an average value within a range. Bubble departure can be clearly seen by our naked eyes. More often, the heat transfer associated with liquid–vapor phase change is calculated through these normal bubbles [1–3]. As we have known, these normal bubbles could not completely explain the high heat transfer rate of boiling. Researchers considered some other mechanisms, for example, microlayer evaporation, capillary flow, bubble allure convection, etc. [3,4]. In recent years, researchers also considered the nonlinear characteristics of nucleate boiling, and some meaningful results were obtained [5,6], as well as investigation concerning micro-size boiling [7,8].

In the present paper, an experimental investigation was conducted to visually observe the nucleate boiling phenomenon on an extremely fine heated platinum wire. Some phenomena, unusual or just ignored by most investigators, were explored in the present experimental investigation using zoom routine and CCD camera. Several modes of jets, high-energy liquid jet, fog-like jet, cluster-like jet, bubble-forming jet, bubble-bunch jet and bubble-top jet were described in detail. The microscopic mechanism concerning the phenomena was discussed. Experiment indicated that at the early stage of boiling

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these jets played a critical role in the heat transfer and associate heat transfer rate was obviously higher than that of the usual nucleate boiling.

## 2. Experiment description

The experimental device employed in this investigation consists of three major parts, as shown in Fig. 1; a heating wire in a transparent vessel, a vision acquisition system and a direct current power supply. The heating wire is a platinum wire with diameter of 0.1 mm and 30 mm long. The transparent vessel is cylindrical one made of visual glass with diameter of 50 mm and height of 110 mm. To maintain the constant bulk liquid temperature, a temperature trigger heater and a heat dissipating device were used and placed in the vessel, and the vessel was insulated.

The vision acquisition system included a CCD camera, Matrox Pulsar high-speed video imaging card, zoom lens and tripod. The CCD camera was a WAT-505EX camera with a set of zoom lens to capture the phenomena image. The captured video was sent to the Matrox Pulsar high-speed video imaging card through the connection cable. The video imaging card was set in a PC platform. The whole system was able to record 20 s of experimental image one time. The direct current power supply was a HP Agilent Model-6031 A power supply system which can provide the maximum power of 1200 W and the maximum current of 120 A.

The pressure in the vessel was kept at atmospheric pressure. Direct current was applied to heat the platinum wire, and then, to induce nucleate boiling on the wire surface. By measuring the current and voltage of the platinum wire, the applied power as well as the resistance of the wire could be determined, and accordingly the temperature of the platinum wire could be obtained. The bulk liquid temperature was measured using thermocouples placed in the vessel. For each ex-

perimental run, the working liquid was kept at situation state for several hours before the test began, to get rid of dissolved gases in it. The platinum wire was also operated for several hours to steady its properties. When the test began, the work liquid was adjusted to some specified temperatures, and then DC power was applied to the wire. Vision information was recorded by acquisition system. In the experiment, water, 75% alcohol and 99% alcohol were employed as working fluids.

## 3. Observations and analysis

By using the experimental device, a series of observations was conducted to investigate the dynamic process of nucleate boiling on the fine wire. Kinds of interesting phenomena were observed and recorded, especially jet flow phenomena by means of zoom routine and CCD camera. Jet flows generated from the sites on the wire or top part of some bubbles, and formed track-like tails in the bulk liquid. Jet flow phenomena were complex and diverse, and occurred either before common nucleate boiling beginning or during the nucleate boiling process. Furthermore, several jet phenomena, such as high-energy liquid jet, fog-like jet, cluster-bunch jet, bubble-top jet, were very difficult or impossible to be observed by bare eyes. A detailed discussion about the jet flow phenomena is described as follows. The associated microscopic mechanism is discussed, also.

### 3.1. High-energy liquid jet flow

Fig. 2 shows the configuration of this kind of jet for liquid alcohol with temperature 23 °C and applied current to the wire with 2.07 A. It is not difficult to affirm that the liquid did not entirely reach the nucleate boiling condition. There was no bubble appearing in this case. However, some jet flows were observed in some local place on the wire, the part circled by black circles in

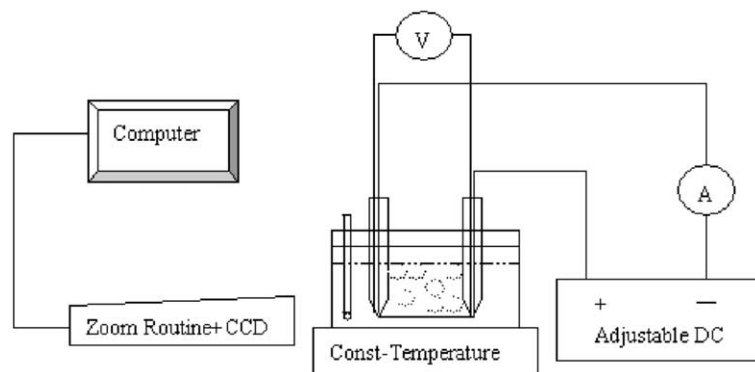


Fig. 1. Experiment device.

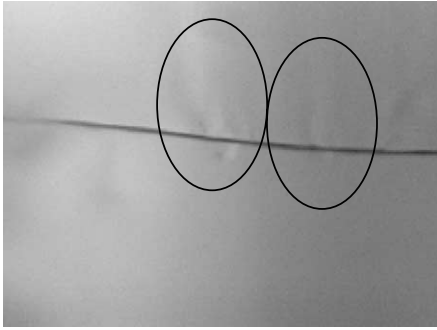


Fig. 2. High-energy liquid jets.

Fig. 2. Jets generated, or more accurately, from nucleate sites of the wire and sprayed into the bulk liquid. Though there was no bubble generated from these nucleate sites, the applied heat fluxes were enough to reach some critical values for activating these nucleate sites. These jets could be clearly distinguished from their ambient liquid through zoom light routine, but nothing could be seen by naked eyes.

This kind of jet usually comes forth when the heat flux is comparatively low in our experiments. Since the momentum of the jet flows is weak, the jet would disappear completely after departure from the wire for some short distance (usually 1–3 mm). It is reasonable to assume this kind of jet consisting of the liquid that has absorbed much local energy and yet not reaches the energy level for nucleation. So, here this kind of jet is termed as “high-energy liquid jet”.

### 3.2. Fog-like jet flow

For liquid alcohol with temperature of 45 °C at atmospheric pressure, fog-like jets on the heating wire appeared in the bulk liquid when the heating current was 4.5 A, as shown in Fig. 3. These fog-like jets generated

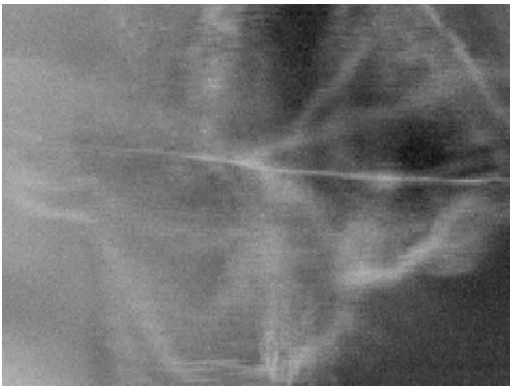


Fig. 3. Fog-like jets.

from active nucleation sites on the wire and sprayed in all directions. The direction of jet ought to be relative to the special structure and characteristics of each site. Fog-like jets would disappear gradually after leaving away from the wire for some distance. The distance might be even as long as 7 mm. These jets could not be identified by naked eyes even with much carefulness. By means of the zoom lens, the jet phenomena could be clearly observed and differed from the liquid.

The formation of these fog-like jets may attribute to the high heat flux and high subcooling of the working fluid. The liquid immediately close to the wire absorbed much heat but this was not enough to cause nucleation and formation of bubbles. The local heated liquid carried energy, especially at the active sites and sprayed from the wire surface into the bulk liquid. There might be vapour–liquid mixture in the sprayed jets. These jets were cooled by subcooled liquid around, like the condensation of vapor in the jets, and displayed the fog-like behavior.

### 3.3. Cluster-bunch jet flow

For a liquid almost reaching saturation jet flows became clearer and more regular. Though common bubbles were not observed, it was obvious that jets consisted of bunches of small liquid masses, here we called them “cluster-bunch jet flows”, as shown in Fig. 4. The cluster-bunch jets are considered mainly as consisting of liquid masses and have characteristics of a liquid that has absorbed much amount of heat energy but have not nucleated yet. In Fig. 2, especially in Fig. 3, high subcooling liquid made the high-energy clusters “condense” and collapse. On the contrary, in the saturated bulk liquid, bulk liquid would not impose “condensation” effect on the high-energy liquid masses or clusters spraying away from the wire. So clusters kept their sequence and form strong cluster-bunch jets in the bulk liquid.

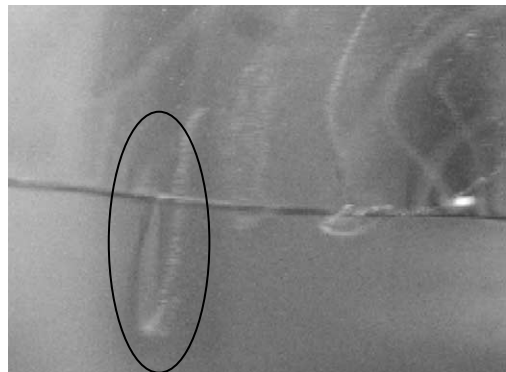


Fig. 4. Cluster-like jets.

### 3.4. Nucleation jet flow

When the thermofluid conditions reached the nucleation or nucleate boiling, vapor bubbles formed, growing and departing from the heating wire. At this time, it was also observed that some jets would evolve to miniature bubbles and even common bubbles, as shown in Fig. 5. Some bubbles generated at the end of jets, some in the middle of the jet evolving process, some occurred in the whole process of jet spraying. The black circle in Fig. 5 shows the process of the formation of small bubbles at the end of the nucleation jets. Three small bubbles became clearer and bigger with jets flowing away from the wire.

### 3.5. Bubble-bunch jet flow

Fig. 6 shows another jet phenomenon, bubble-bunch jet flow. This phenomenon can be found in some local



Fig. 5. Nucleation jets.

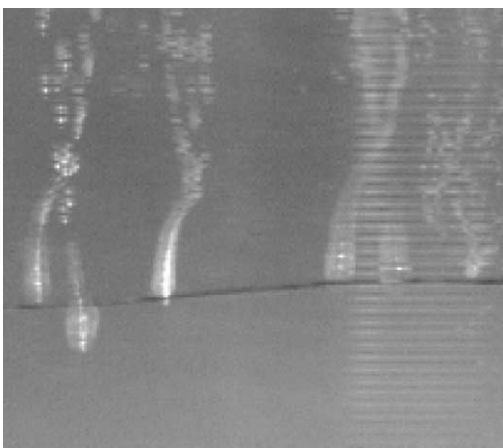


Fig. 6. Bubble jet.

region of the heating wire in Fig. 5. Bubble-bunch appeared when the bulk liquid was saturated and heat flux was higher and approaching the critical value for nucleate boiling. The jets highly looked like consisting of vapor bubbles. However, these were neither exactly like the normal bubbles nor like the liquid clusters as those in cluster-bunch jet in Fig. 4. The bubbles stably and continuously generated and sprayed from active nucleate sites on the heating wire to form jet flows in the liquid. They behaved as a bunch and formed a tail-like "gas channel".

Cluster-bunch jet, nucleation jet and bubble jets are all concerned with liquid nucleation. These phenomena indicate that diversity of nucleation in boiling is extremely complex and interesting.

### 3.6. Bubble-top jet

As observed and mentioned above, jet flows almost just generated and sprayed directly into the bulk liquid from active sites of the heating wire. But in some cases, it was surveyed that the jets came from the top of bubbles, as shown in Fig. 7. This kind of jet did not spout directly from sites in our vision observation.

The bubbles from the top of which the jets spouted could not be observed growing and departing from the heating wire. These bubbles just stayed at the sites and kept as part of spheric balls. The formation of bubble-top jets lies in two possibilities. First one, the jets formed at and sprayed directly from the sites, then broke the interface of the bubble that already grow up to form the jets on the top of bubble; Secondly, when the subcooling was high, there was strong evaporation at the bottom of the bubble and condensation at the top part of the bubble, which might cause the jet flows.

The jet flows generated from the wire and sprayed into the bulk liquid in all directions. The downward jet

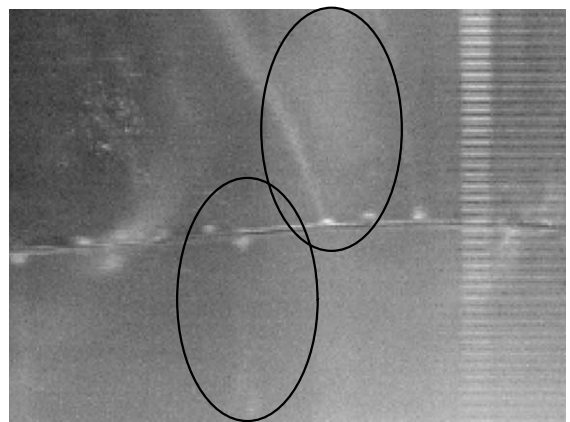


Fig. 7. Bubble-top jets.

flows will change direction upward gradually with the impact of both buoyancy, no matter what kind of jet it was. This behavior indicates that jet flow has an apparent density difference from the ambient liquid. The estimate of the preliminary measurements evidenced that the heat transfer associated with jet flows was very high, much higher than the free convection and even higher than the normal nucleate boiling heat transfer. What the accurate composition of jets is, what happened when jets sprayed from the wire, the diversity of jets, and many other questions are necessary to be answered in future investigations.

#### 4. Conclusions

- (a) Diversity of boiling nucleation was observed in the present boiling experiment. Jet flows were found generating at the active sites on the heating wire and forming track of tails in bulk liquid.
- (b) An attempt was made to class and identify the jets flows observed. High-energy liquid jet, cluster-bunch jet, fog-like jet, nucleation jet, bubble-bunch jet, bubble-top jet were described and discussed, respectively.
- (c) Possible mechanisms of jets were discussed. The direction of jets ought to be relative to the special structure of active nucleate sites. The accurate composition of each kind of jet needs more work to be understood.

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