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Spontaneous boiling of submerged jets generated during the collapse of vapor bubbles

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The effect of secondary spontaneous boiling of submerged jets formed during the collapse of vapor bubbles during the bulk boiling of water subcooled to the saturation temperature at the end of a laser optical fiber is experimentally discovered.

Keywords: submerged jet, subcooled liquid boiling, laser.

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In collapsing, non-equilibrium cavitation spherically symmetric bubbles shrink to minimal dimensions and, unless being destructed, restore themselves and perform several consequent cycles of attenuating oscillations [1]. This effect is well known under the name of „ricochet“ [1,2]. However, if the non-equilibrium cavitation bubble shape is not spherically symmetric, the collapse of such bubbles may cause their crush; in this case, a submerged cumulative jet is observed instead of „ricochet“ [3–12]. Despite their decent sizes, these jets can locally induce tremendous hydrodynamic pressures due to their high speed. Such jets are of essential practical interest in various fields, for instance, in the industrial chemistry for selective cleaning of surfaces and also in medicine for noninvasive sanitation of tissue cover or in surgery, including the case of heat transfer [3,12,13]. The jets may appear to be heated when they are formed in the collapse of vapor bubbles arising due to the subcooled liquid boiling [11,12].

The subcooled liquid boiling may be observed during hardening incandescent metal in cold water or at the very beginning of water boiling in the kettle. In boiling of such a liquid, vapor bubbles grow and collapse at once since the vapor in the bubble begins condensing on coming in contact with the cold liquid [14]. Under the conditions when the liquid is subcooled significantly, the bubble collapse near the concentrated heater leads to formation of heated submerged jets whose temperature is close to the boiling point [3,11,12]. A situation is possible when the heated jet moving with a high speed through the surrounding cold (subcooled) liquid will get boiling again. Such spontaneous secondary boiling can take place due to the pressure decrease in the moving liquid according to the Bernoulli's law. In this case, the boiling point of the heated liquid also decreases. Thus, the „ricochet“ in the form of the boiling restoration is possible at a sufficiently high jet speed. This effect is similar to that of boiling of heated moving liquid in pipe bends.

This paper informs on experimental observation of the effect of spontaneous secondary boiling in a cumulative jet arising during the vapor bubble collapse at the laser heater.

The experiments were performed by using a semiconductor laser with the radiation wavelength of $1.94\,\mu$m; its radiation was conducted through a quartz-quartz polymer fiber $600\,\mu$m in diameter. The $1.94\,\mu$m radiation is very highly absorbable in water with the absorption coefficient of $\sim 100\,\text{cm}^{-1}$, which enables initiation of the liquid bulk boiling near the optical fiber end. All the experiments were conducted on distilled water 30°C in temperature placed into a $16.5 \times 37 \times 20$ mm cuvette using rapid video camera Photron FASTCAM Mini UX100 with the speed of up to 100 000 fps. The experiment object was a unit event of boiling, namely, growth and collapse of a single bubble.

Fig. 1 illustrates formation and evolution of a vapor bubble in the process of bulk boiling of subcooled water in front of the optical fiber end. During the growth, the bubble envelopes the optical fiber tip and begins collapsing after reaching the maximal size. The bubble collapse at the optical fiber end leads to the loss of its sphericity since the liquid masses initially moving towards the bubble center have to flow about the so-called „backward facing step“. Radial flows rush towards each other, the bubble shrinks as shown in photo 8 (Fig. 1) and photo 1 (Fig. 2). After that, radial flows strike together and transform into axial jets that are directed oppositely, namely, towards the optical fiber end and away from it. The jet directed towards the fiber end strikes its surface, while the jet directed away from the fiber end forms the submerged cumulative jet propagating depthward into the liquid (photos 9–11 in Fig. 1) [11].

The formed jets appear to be heated since the water near the phase interface is heated and is the first that enters the forming flow. Heated water can arise both due the vapor

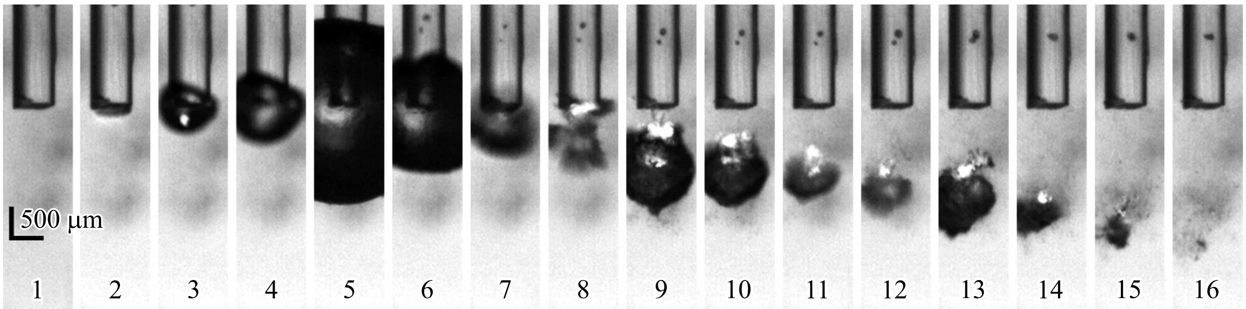

Figure 1. Formation and evolution of a vapor bubble in boiling of subcooled distilled water under the action of continuous laser radiation 1.94 μm in wavelength and 10 W in power. The optical fiber diameter is 600 μm. Digits are the photo numbers. The mean interval between the photos is 0.04 ms.

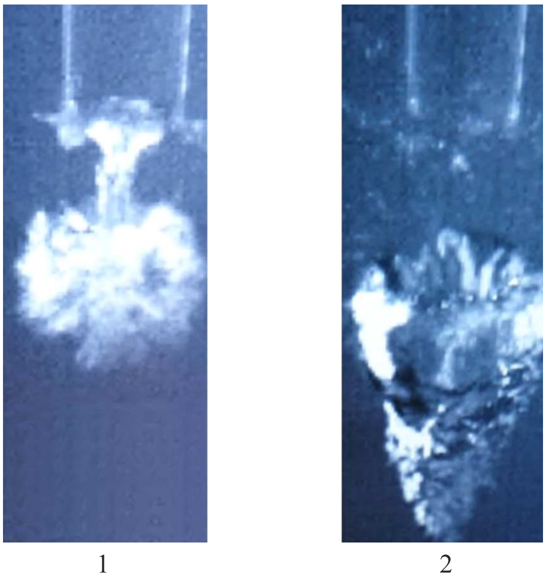

Figure 2. The onset of the water secondary boiling near the optical fiber end (photo 1) and intense boiling of liquid in the submerged jet moving away from the optical fiber end (photo 2). The interval between the photos is 0.04 ms.

condensation and because of that a part of water heated by the laser radiation has not evaporated but remained liquid at the bubble boundary. When the bubble collapses, these layers are the first that are entrained by the jet stream [12].

Fig. 1 shows that, under the conditions under study, the liquid jet initiates the process of secondary boiling. Photo 8 in Fig. 1 and photo 1 in Fig. 2 illustrate the beginning of the liquid boiling, while photos 9–15 (Fig. 1) and photo 2 (Fig. 2) present the typical picture of the moving liquid boiling. Probably, the crosspiece visible in photos 8 and 9 (Fig. 1) and photo 1 (Fig. 2) is also the liquid that has got boiled in the liquid jet stream. One can see that the secondary, i.e., the again formed bubble (photo 2 in Fig. 2) partly consists of a great number of small bubbles. The secondary bubble collapse also gives rise to oppositely directed submerged jets that may get added to the primary ones thus forming a flow of heated liquid.

The jet speed strongly depends on the distance to the optical fiber end. Its value at the initial time moment is $\sim 27 \pm 1$ m/s. Estimation of the jet pressure drop according to the Bernoulli's law gave a negative value of the pressure (~ 2.5 atm). It is evident that the Bernoulli's law may be used in this task to estimate the pressure drop in the jet only as a zero approximation; however, we can state with confidence that the pressure decreases so much that water boiling occurs at the temperatures essentially lower than 100°C.

An additional source of the pressure drop in the heated submerged jet leading to its boiling up may be acoustic waves generated by the vapor bubble collapse. These waves were studied in work [15]. Waves more than 12 atm in amplitude were detected. Analysis of the results of that work shows that, as though the medium were infinite, the acoustic waves contribution to the mechanism of the submerged jet spontaneous boiling would be insignificant. However, in the experiments considered here the pressure waves reflected from walls and, while returning, could affect the bubble collapse. To confirm this hypothesis, detailed numerical calculation is necessary.

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Conflict of interests

The authors declare that they have no conflict of interests.

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