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Features of dynamics of a jet flow generated on a laser heater by surface boiling of liquid

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Received July 6, 2021
Revised October 1, 2021
Accepted October 1, 2021

It was experimentally found that speeds of hot submerged jets appearing in case of laser induced nucleation boiling of water near the tip of optical fiber submerged in water decrease exponentially with increasing laser power (heat flux). This result was obtained for a closed cylindrical cuvette where hot jets collided with walls and slipped the cuvette boundary transferring heat to it. The obtained result is to be taken into account in performing precise laser−induced surface cleaning inside confined volumes, in developing medical technologies for laser therapy of pathologically changed vessels or cysts, and in other applications.

Keywords: laser radiation, submerged jet, boiling, bubbles, cavity, heat transfer.

DOI: 10.21883/TPL.2022.01.52472.18949

Thermal effects induced by laser radiation supplied via optical fiber attract great attention because of vast application of optical fiber technology in engineering and, especially, in medicine. In this connection, laser heating of liquids near the tips of optical fibers submerged in liquid is of essential interest. Even in case of a low laser power at the optical fiber outlet tip $100-600\,\mu$m in diameter by quartz it is possible to form a tremendous heat flux amounting up to tens of MW/m^2. In this case, the liquid is being rapidly heated to the boiling point and boils up. In practical applications, water is of most interest. If the optical fiber tip is coated with a layer of material absorbing the radiation (tip blacking), then heating of this layer leads to near−surface water boiling independently of the incident radiation wavelength. Selecting such a laser wavelength that the radiation is efficiently absorbed by water, it is possible to initiate bulk boiling without blacking the optical fiber tip.

If boiling is localized near the laser optical fiber tip while the surrounding liquid remains cool, then at a certain moment the condensation of vapor in bubbles inflating near the tip will become faster than generation. At that moment, the bubbles will stop inflating and begin collapsing. Such boiling is referred to as boiling underheated to the saturation point [1]. Contrary to developed boiling, underheated boiling is accompanied by not only inflation of vapor−gas bubbles but also by their collapsing, which can lead to generation of submerged cumulative jets of hot liquid directed from the heater surface inward the liquid bulk [2].

Submerged jets arise either in the case of collapsing of nonspherical bubbles or in the case of loss of sphericity during collapse [2–6]. For such bubbles, collisions between radial liquid flows moving beyond the bubble walls result in conversion of the radial movement into axisymmetric submerged jets [2–6]. These jets have gained a wide application in engineering and, especially, in medicine [7–12]. Due to their great practical importance, investigation of properties of hot submerged jets arising in boiling liquid is a quite topical task.

In this study, an $0.97\,\mu$m semiconductor laser was used. The radiation was conducted through a quartz–quartz–polymer fiber $600\,\mu$m in diameter. The proximal tip of the optical fiber (waveguide) was connected to the laser radiation source operating in the continuous mode. The experiments were carried out at the laser powers of 7, 5, 3, 1.5, 1, and 0.5 W. Since the laser radiation absorption at the wavelength of $0.97\,\mu$m is very weak (with the absorption factor of $0.47\,\mathrm{cm}^{-1}$ [13]), the optical fiber tip was precoated with a layer of radiation absorber, namely, by ferrous iron oxide (FeO). Conversely to a layer of amorphous carbon [14], the iron oxide coating exhibited high resistance to impact loads occurring during the cumulative jet formation.

The measurements were performed in a cylindrical cuvette $2.3\,\mathrm{cm}^3$ in volume (Fig. 1, *a*). The cuvette inner volume was formed by an aluminum ring 4.4 mm in height, 26 mm in inner diameter and 32 mm in outer diameter. A quartz plate 1.3 mm thick was adhered to one of the cylinder bases, to the other base light filter C3C25 with the 280−900 nm passband was attached, which allowed cutting off the radiation emitted by the laser during video recording. In the lateral side of the aluminum ring, a through hole was made for mounting a thin ceramic tube through which the optical fiber was inserted into the cuvette.

The optical fiber was arranged horizontally in the center of the working cuvette filled with bidistilled water at the temperature of 293 K, the distance between the fiber tip and cuvette wall was 13 mm. For cooling, the working cuvette was placed into a transparent vessel with water; the vessel size was $100 \times 100 \times 50$ mm. Video recording

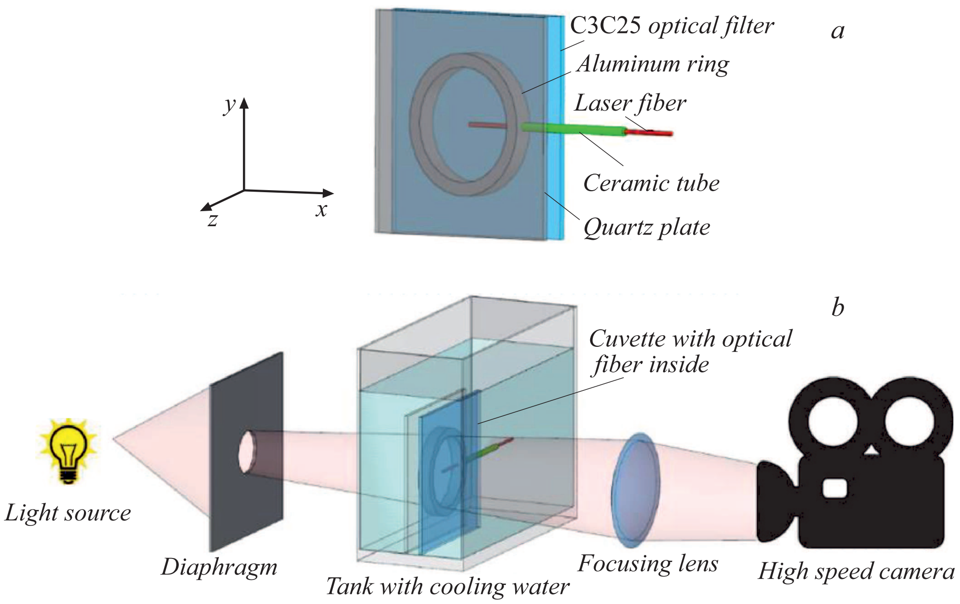

Figure 1. Layout of the experimental setup.

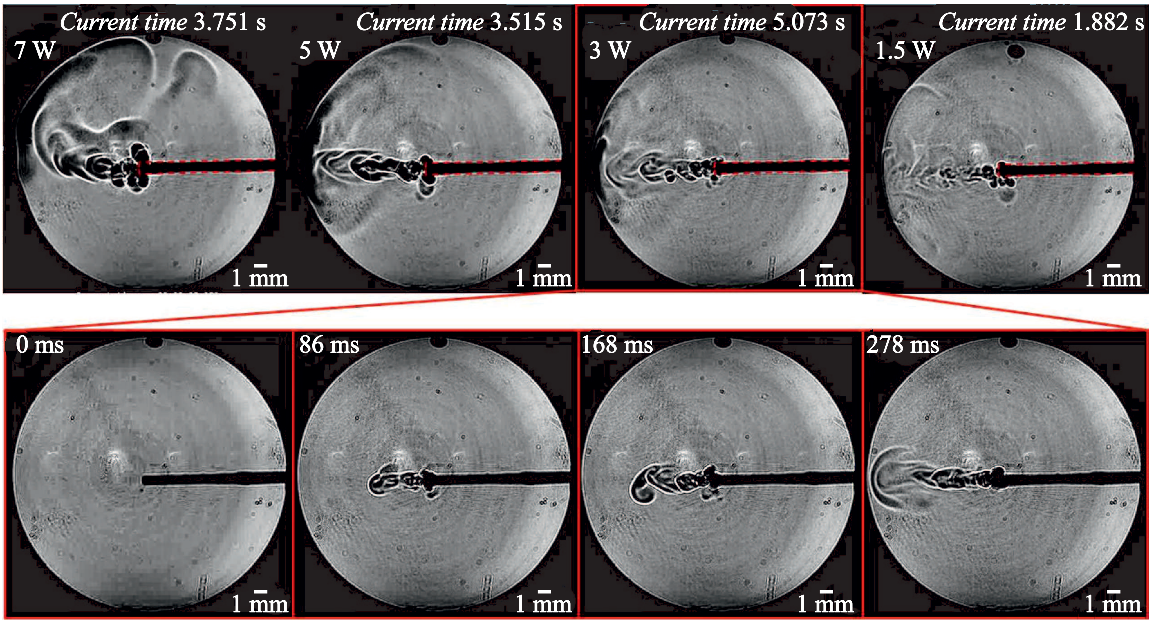

Figure 2. Photos of submerged hot–liquid jets at different laser powers in different times after the beginning of the experiment: in 3.751 s for 7 W, 3.515 s for 5 W, 5.073 s for 3 W and 1.882 s for 1.5 W (upper row). The lower row illustrates the hot jet propagation for different time moments at the laser power of 3 W. The dashed line represents the optical fiber contour. The video recording speed was 1000 fps.

was performed with a high-speed video camera Photron Fastcam SA-Z with the 1000 fps speed at the resolution of 1024×1024 pixels. For lightning, a 650 nm laser diode was used whose light flux was directed towards the camera matrix through a diaphragm. The working cuvette was installed in the cooling tank between the laser diode and camera so that the cuvette wall made from the light filter was turned to the camera. The shadow pattern was projected directly to the video camera matrix by using a lens. The setup layout is presented in Fig. 1, *b*.

In the experiments there was measured a laser–power dependence of time in which the jet front moving from the optical fiber tip reached the cuvette wall after passing the distance of 13 mm. Dividing the distance by this measured time, obtain the average speed with which the heat contained in the jet reaches the cuvette wall. This parameter is of the main interest in laser technologies for interstitial treatment of true cysts.

Fig. 2 (upper row) illustrates the submerged jets of hot liquid obtained as a result of underheated boiling on the

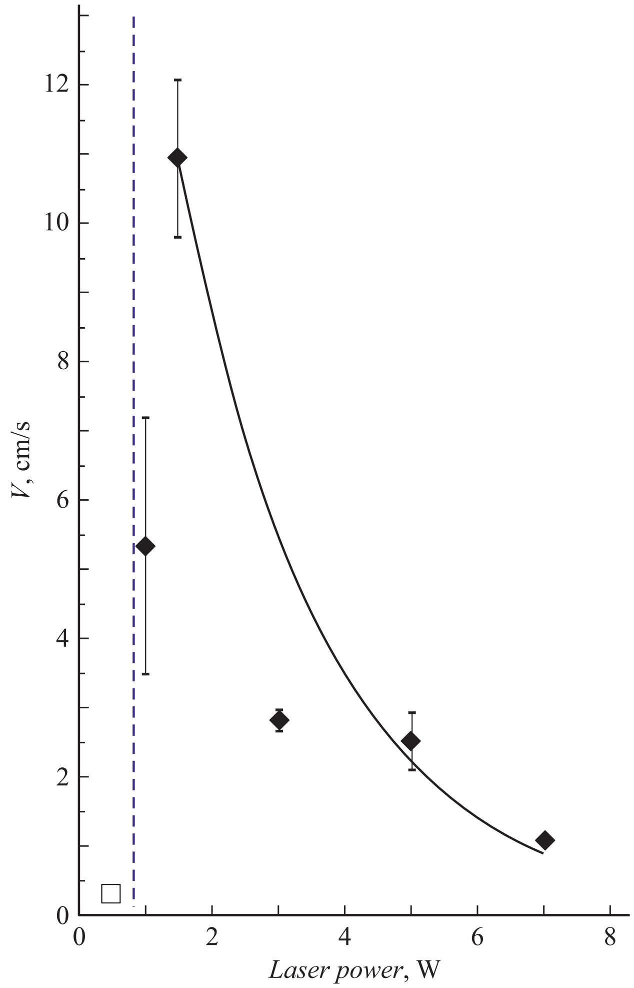

Figure 3. The speed at which the jet approaches the cuvette wall versus the laser power. Solid line is the exponential approximation of the experimental data. Dashed line is the laser power at which surface boiling with the jet formation begins.

optical fiber tip at different laser powers. The submerged hot water jets are directed from the tip towards the cuvette side wall where they collide with the cuvette wall and spread over its surface. Heating causes variations in the liquid density, which are clearly seen in the „transmission"image as shaded areas against the background of the underheated liquid. The Fig. 2 lower row demonstrates the hot liquid jet propagation at different time moments at the laser power of 3 W.

The pattern of boiling with jet formation essentially depends on the laser power. This dependence is shown in Fig. 3. There are given averaged speeds of the hot jet propagation, and confidence intervals are indicated. The figure demonstrates variation of the speed with which the jet front edge approaches the cuvette side wall versus the laser power. Fig. 3 shows that there exists a power threshold separating the free convection region from the water boiling region (vertical dashed line), while the speed with which the jet front edge approaches the cuvette side wall decreases exponentially with increasing radiation power.

In the region of free convection, when the laser power is 0.5 W (below the boiling threshold), the speed of hot liquid approaching the cuvette wall is the lowest of all (~ 0.4 cm/s). When the laser power increases to 0.9 W, even freer convection turns to the mode of underheated surface (nucleation) boiling with formation of hot liquid jets. In this case, the speed of hot liquid approaching the cuvette wall increases drastically. However, this speed begins decreasing exponentially with increasing laser power. The curve illustrating the reduction of the jet average speed versus the laser power may be extrapolated with the following exponential relation:

$$V = 21.5 \exp(-0.454W).$$

With further increase in the laser power, the boiling gets the „film boiling"character. The film boiling onsets when a vapor bubble fully embraces the heat source surface (fiber tip), which results in a drastic reduction of the heat release into the liquid [1]. During the film boiling, heat is spent on heating the optical fiber tip and can heat it to high temperatures, up to the quartz melting point (~ 2000 K).

Reduction of the submerged jet speeds with increasing laser power (heat flux) is a rather unexpectable result, which, to our mind, may be explained by enhancement of heating (reduction of underheating) of liquid surrounding the tip with increasing laser power. When the radiation power increases, the heat flux from the optical fiber tip into water also increases, which promotes heating of a larger volume of surrounding liquid and, hence, a reduction of underheating of the aqueous medium surrounding the tip. Bubbles arising in hot water collapse significantly slower than in an essentially underheated medium (in a cooler environment). Due to a slower collapse of bubbles, the speed of generated jets will be essentially lower in hot water than in underheated (cooler) medium [2,6]. The total flux speed that is a sum of microjet speeds also decreases.

Notice that this result was obtained in the case of surface boiling when water boils up on the surface of the optical fiber tip coated with a radiation−absorbing layer of ferrous iron oxide. In the case of bulk boiling when laser radiation is efficiently absorbed by water (at the radiation wavelengths of 1.94, 1.56, 1.47 μm), the jet dynamics and, hence, dynamics of heating the cavity boundaries, may be different. It is known that bulk boiling causes fast inflation and collapse of vapor bubbles, which is accompanied by impact waves (flaps), high pressure surges, and also rapid increase in the liquid fraction background temperature in the entire fraction volume [2].

Financial support

This work was financially supported by the Ministry of Science and Higher Education of the Russian Federation (project 075-15-2019-1878).

Conflict of interests

The authors declare that they have no conflict of interests.

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