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Features of cavitation initiated on a laser heating element near a solid flat surface

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The effect of a flat solid boundary on the dynamics of a cavitation steam bubble arising from the boiling of water with subcooling on a laser heating element, accompanied by the generation of jets, is investigated. The boiling of water is caused by the absorption of continuous laser radiation with a wavelength of $\lambda = 1.47\,\mu$m in the vicinity of the tip of an optical fiber immersed in water. Using high-speed video filming, it is established that the presence of a solid flat surface near the laser heating element (the tip of the optical fiber) leads to a rotation of the generated jet towards the surface, forming an angle between the direction of jet propagation and the plane of the surface. This angle determines the degree of impact of the jet front on the flat boundary and depends on the distance from the tip of the optical fiber to the boundary — a flat solid surface.

Keywords: laser, cavitation, boiling, optical fiber.

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Methods of cavitation cleaning, hardening, and quenching of surfaces are well-established. With the advent of laser cavitation, these methods were developed even further, since selective localized micrometer-scale impact has become possible [1–3]. This approach has contributed to the emergence of new engineering, biotechnological, and medical applications [1–6]. Laser cavitation may be initiated by both pulsed [1–8] and continuous [9–12] laser radiation. In the latter case, cavitation is induced by laser heating and boiling of a liquid that is not heated to the saturation temperature (boiling with subcooling) [9–12]. One relevant line of laser cavitation research, which has numerous applications in practice, is associated with the use of optical fiber for laser radiation transport [9–12]. When optical fiber is used, laser radiation is converted into heat occurs under the conditions of efficient absorption of radiation by water or in a layer of radiation-absorbing material applied to the end surface of the fiber in the immediate vicinity of its tip immersed in liquid. The fiber tip then acts as a laser heating element of the laser device [9,10]. Since the typical diameter of the quartz core of optical fiber used in practice is small ($0.1-1$ mm), a significant heat flux is established at the end of the fiber. When the fiber tip is immersed in water, the intense heat flux in its vicinity rapidly heats water to a temperature exceeding the boiling point, producing a growing steam bubble. If this bubble grows in an environment with a temperature lower than the saturation one („cold“ environment), it starts collapsing due to steam condensation after reaching its maximum size (boiling with subcooling). Such growing and collapsing bubbles are called cavitation ones; if they lose their spherical shape while collapsing, they may generate cumulative jets and shock waves of great destructive power [1–12]. Sphericity is lost under the influence of adjacent boundaries that induce a pressure gradient on the bubble surface [7]. One such boundary the cylindrical fiber tip in the vicinity of which a vapor bubble is formed. Therefore, the collapse of a bubble near the fiber end leads to the emergence of two cumulative jets: one is directed toward the end, and the other propagates from the end into the bulk of liquid, where it turns into a submerged jet (Fig. 1) [9,10]. The study of the dynamics of a vapor bubble emerging in the vicinity of an optical fiber tip near a flat solid surface actually comes down to examining the influence of a complex configuration formed by the cylindrical fiber tip and the flat surface on which this jet acts. The impact of a cumulative jet on the treated surface depends on the behavior of this jet in the examined case. Note that optical fiber is highly flexible and is able to penetrate into narrow channels, gaps, and needles, generating cavitation bubbles in such conditions where other methods are virtually inoperative or completely inapplicable. This is the reason why a laser heating element for selective surface cleaning and processing may be of great practical importance.

The aim of the present study is to investigate the influence of a flat solid boundary on the dynamics of a cavitation steam bubble that forms on a laser heating element in the process of boiling with subcooling and collapses with the generation of jets.

A Photron FASTCAM SA-Z high-speed video camera with a shooting speed of 100 000 fps, optical fiber with a diameter (of the quartz core) of $600\,\mu$m, and a transparent glass cuvette $100 \times 100 \times 50$ mm in size filled with water with a temperature of $T \sim 295$ K were used in experiments.

The process of water boiling induced by continuous laser radiation with wavelength $\lambda = 1.47\,\mu$m, which is absorbed in water with coefficient $k = 25\,\text{cm}^{-1}$, at the fiber tip was recorded. The optical fiber was positioned parallel to a solid flat surface (boundary), which was one of the glass faces of the cuvette (Fig. 1). The dependence of the rotation angle of a cumulative jet on dimensionless distance $\gamma = L/D_{\text{max}}$, where L is the distance from the fiber axis to the boundary and D_{max} is the maximum bubble diameter (Fig. 1), to the flat solid surface (boundary) was investigated. The time dependence of the jet velocity was also examined at different distances L. Data were collected in experiments repeated three times for each distance.

The frames in Fig. 1 illustrate the evolution of a steam bubble from the moment it reaches its maximum size (frame 1) to the generation of a submerged jet as a result of bubble collapse (frame 4). The key geometrical parameters of the problem are also indicated. Frames 2 and 3 (Fig. 1) show the moment of jet formation at the fiber end and a fragment of secondary boiling of liquid moving in the flow („ricochet") [12], respectively.

Figure 2 illustrates the influence of a flat solid boundary on a submerged jet generated by the collapse of a steam-gas bubble. In frame 1 (Fig. 2), the bubble is at a distance L ($\gamma_1 \geqslant 3$), where the solid flat wall does not affect its dynamics and the jet propagates along the fiber axis (as in free space) [9,10]. In frame 2 (Fig. 2), the bubble starts „feeling" the presence of the wall ($\gamma_2 = 1.26$), which induces rotation of the submerged jet toward the boundary.

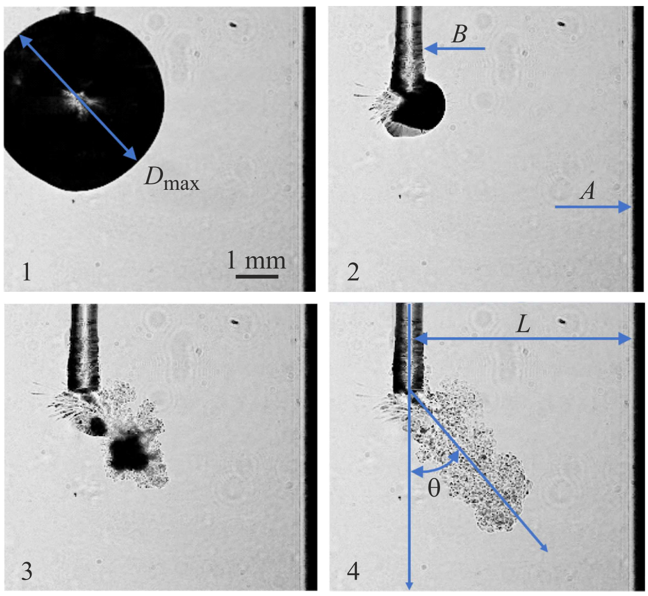

Figure 1. Evolution of a bubble from the moment of reaching the maximum diameter (frame 1) to the emergence of a submerged jet (frame 4). A — solid flat boundary, B — optical fiber, D_{max} — maximum bubble diameter, L — distance from the fiber axis to the boundary, and θ — angle between the jet and the fiber axis. The time between frames 1–2 $t = 280\,\mu$s, 2–3 $t = 180\,\mu$s, and 3–4 $t = 410\,\mu$s, and respectively. $D_{\text{max}} = 4.2$ mm, $L = 5.4$ mm, and laser radiation power $P = 8$ W.

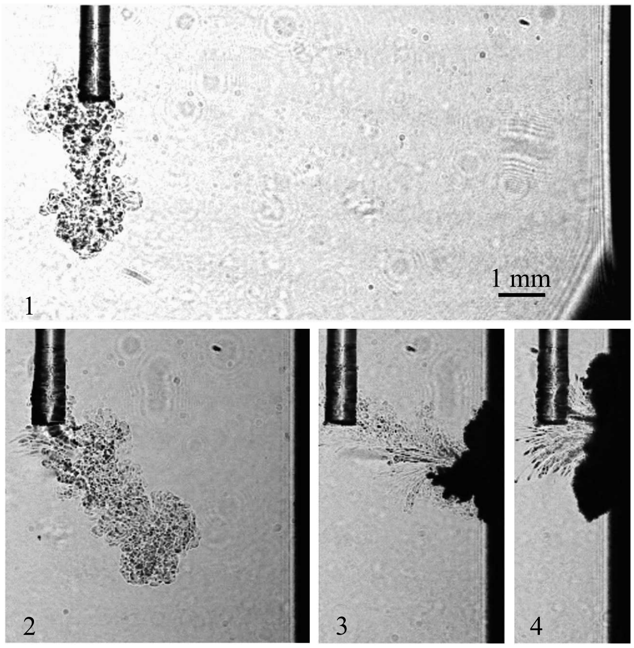

Figure 2. Response of a submerged jet to a flat solid surface as a function of γ: $\gamma_1 = 3$ (frame 1), $\gamma_2 = 1.26$ (frame 2), $\gamma_3 = 0.77$ (frame 3), and $\gamma_4 = 0.3$ (frame 4). The laser radiation power is $P = 8$ W.

In frames 3 and 4, the optical fiber gets even closer to the boundary ($\gamma_3 = 0.77$ and $\gamma_4 = 0.3$, respectively), which results in impact interaction of the cumulative jet with the flat surface.

Figure 3, *a* shows how angle θ of rotation of the cumulative jet toward the solid flat surface changes depending on γ, while Figs. 3, *b* and *c* present the time dependences of the submerged jet velocity at different distances L. Experiments were carried out at two laser radiation powers ($P = 8$ and 6 W).

It follows from Figs. 3, *a–c* that the presence of the solid flat boundary induces rotation of the submerged jet toward the surface and the variation of laser radiation power within the 6–8 W range has no effect on the dependence of rotation angle θ on distance L to the surface.

The jet rotation is induced by a sum of two forces that arise in the liquid under the influence of two boundaries near which the bubble grows and collapses: the solid flat surface and the cylindrical quartz fiber tip. The liquid spreads radially over the flat surface within the interval of bubble growth near the boundary, producing a pressure gradient on the surface of the bubble. When the growth stops, the liquid pressure at the pole of the bubble farthest from the flat surface is at its maximum and exceeds the pressure at the pole closest to the surface. Owing to this pressure difference, a cumulative jet forms at the far pole of the bubble when it collapses. The jet moves with acceleration through the bubble to the flat surface along the axis connecting the poles. These jets are called regular ones [6,8]. At the same time, the bubble collapses

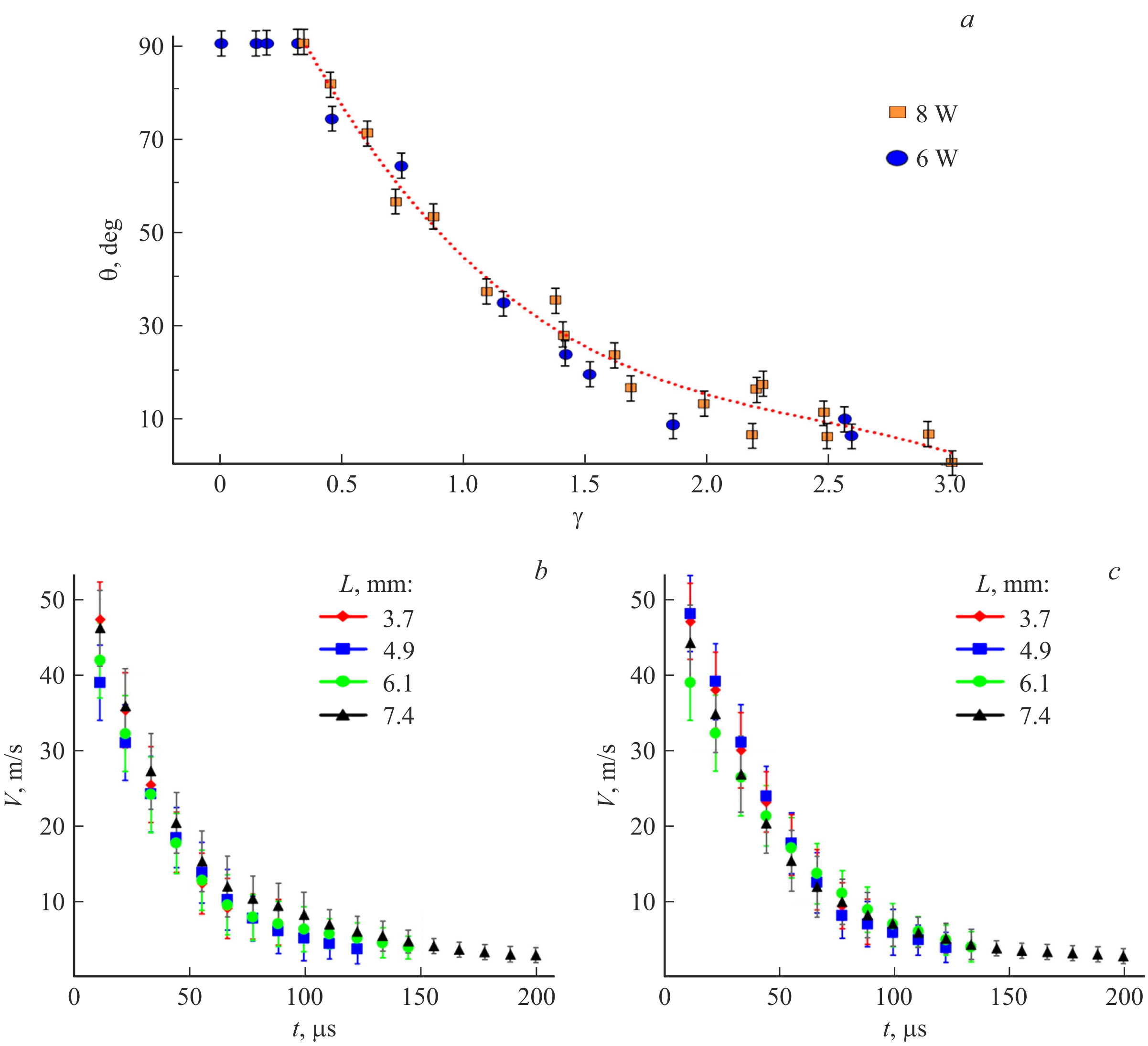

Figure 3. *a* — Dependence of the jet rotation angle on dimensionless distance γ. The dotted line represents the approximation of measurements by a third-degree polynomial. *b* and *c* — Time dependences of the submerged jet front velocity at different distances L and laser radiation powers of 6 (*b*) and 8 W (*c*).

in the vicinity of the cylindrical fiber tip, where a jet forms as a result of radial collision of liquid as it flows around the „backward-facing step“ formed by the cylinder (end) face [9,10]. These jets are called needle ones [6,8]. Their velocities are an order of magnitude greater than the velocity of a regular jet. In our experiments, the needle jet propagates from the fiber end into the bulk of liquid parallel to the surface in the direction of the optical fiber when the fiber tip is unaffected by the wall. As the fiber tip approaches the surface, the contribution from the pressure gradient induced by the wall comes into play. This contribution increases in inverse proportion to the distance to the flat solid surface, causing rotation of the jet. Near the wall, the bubble no longer „feels“ the optical fiber and is „captured“ completely by the surface.

Thus, it was demonstrated that the presence of a solid flat surface near a laser heating element (optical fiber tip) induces rotation of the generated jet toward the surface, setting a certain angle between the direction of jet propagation and the surface plane. This angle governs the intensity of impact of the jet front on the flat boundary and depends on the distance from the fiber tip to the boundary (flat solid surface). We believe that this phenomenon is likely to be universal in nature and the effects presented in Figs. 1–3 may also be observed with other boundary configurations.

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Conflict of interest

The authors declare that they have no conflict of interest.

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