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Numerical study of the solid walls effect on the velocity of a liquid jet formed as the result of vapor bubble collapse near a rod

The paper presents the results of numerical simulations of the vapor bubble collapse near the end face of a thin laser waveguide immersed in a cold liquid. The effect of solid walls located near the waveguide on the dynamics of the flow field and the velocity of the jet formed as a result of bubble collapse is studied. It is shown that the average jet velocity significantly depends on the configuration of the walls and can either increase, compared to the case when there are no walls, or decrease, down to zero.

Key words: *numerical simulation, subcooled boiling, cumulative jet, two-phase flow.*

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Introduction

Cavitation processes in a cold liquid, accompanied by the formation of a high-velocity jet, attract the attention of researchers due to many practical applications, in areas from microsurgery [1] to surface cleaning [2]. At subcooled boiling, first, due to the energy of laser radiation the liquid near the end face of the waveguide is evaporated resulting in the growth of a vapor bubble. Condensation of vapor at the interface between the gas phase and the cold liquid leads to the fact that the bubble growth phase is replaced by the squeeze phase, ending with the collapse of the bubble and the formation of a cumulative liquid jet directed perpendicular to the end of the waveguide [3, 4]. The characteristics of the jet depend on the power and wavelength of laser radiation, as well as on the temperature, viscosity and pressure of the liquid surrounding the bubble. The influence of these parameters was studied in [3–5]. However, these studies were restricted by consideration of the cavitation process at the end of a thin waveguide placed in an

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unbounded liquid domain. In [6], the results of experiments with two perpendicularly placed rods demonstrate the vector summation of the jet velocities generated by each individual waveguide. These results suggest that the presence of solid surfaces near the waveguide can significantly affect the flow field and jet velocity. In this work, we study the effect of solid walls located near an optical fiber on the flow field and the velocity of a jet formed as a result of the vapor bubble collapse near the waveguide.

1 Mathematical model

To describe the two-phase flow the Volume of Fluid method is used. The mathematical model includes the conservation equations for the mass, momentum, energy and volume fraction of liquid phase, closed by the equations of state for gas and liquid phases and the condensation model [7]. A detailed description of the mathematical model, its verification, as well as the results of convergence tests are given in [4].

In this paper, we consider the process of a spherical bubble collapse in the axisymmetric configurations shown in Fig.1. The lengths of the computational domain and the waveguide are l_0=5 mm and l_f=2 mm, respectively. Computations were performed for different values of the radius of the computational domain (R_{tube}=0.2,. . . ,∞ mm), the radius of the waveguide (R_{tube}=0.2,. . . ,∞ mm) and the radius of the bubble at the initial time moment (R_{bubble}=0.1,. . . ,0.6 mm). In Fig.1, the dashed line shows the axis of symmetry, the constant pressure condition $p_0 = 10^5$ Pa is set at the dash-dotted lines, the solid lines correspond to solid walls on which the no-slip condition is set.

2 Results and discussion

The results of numerical simulation showed that if the radius of the optical fiber is greater than the initial radius of the vapor bubble ($R_{fiber} > R_{bubble}$), the flow field and jet velocity are almost independent of the presence of the solid walls near the waveguide. For each of the configurations shown in Fig.3, the average jet velocity is maximum in the case when $R_{fiber} = R_{bubble}$. Herewith, the streamlines in the case of the vapor bubble collapse in free space (Fig. 1a) and in a space bounded by walls (Fig. 1b-d) have no significant

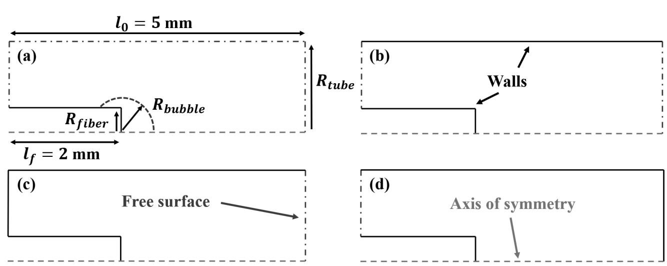

Fig. 1: Schemes of geometric configurations with a waveguide in unbounded space (a); in a tube (b); in a tube with a left end wall (c); in a tube with a right end wall (d).

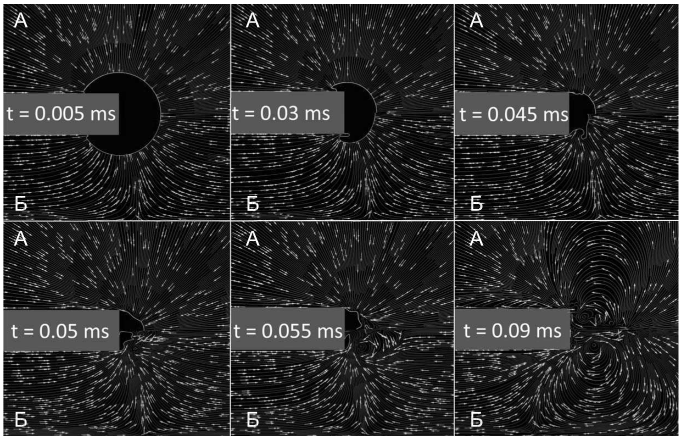

Fig. 2: Streamlines of the liquid flow field at different times, calculated for waveguide in unbounded space (top half of each snapshot) and for the waveguide inside the tube (Fig.1b) (bottom half of each snapshot).

differences. Finally, if $R_{fiber} < R_{bubble}$, the bubble shape resembles a mushroom cap, as shown in Fig. 2.

In the case of a waveguide in an unbounded space, this "mushroom cap" collapses almost evenly from all sides (Fig. 2A). In this case, the liquid flows from all directions and the volume of liquid involved in the movement induced by vapor bubble shrinking is the largest compared to other cases. The presence of a tube (Fig. 2B) leads to a change in the directions of the streamlines, which become almost parallel to the waveguide, since the inflow of liquid is possible only from the left and right ends of the computational domain. As a result, the lateral part of the bubble shell is practically motionless, and the jet moving along the waveguide from left to right cuts off part of the bubble volume (Fig. 2B, t=0.045 ms). The average velocity of the cumulative jet formed after the bubble collapse in an unbounded space turns out to be slightly higher than in the case when the waveguide is placed in a tube with a radius of less than 4-5 waveguide calibers. Figure 3 shows the values of the average jet velocity calculated for various geometrical configurations of the computational domain shown in Fig.1 and R_{fiber}=R_{bubble} (solid bars), $R_{fiber} < R_{bubble} = 2 \cdot R_{fiber}$ (hatched bars).

As inferred from Fig.3, the presence of solid walls significantly affects the average jet velocity. In a tube with a closed left end (Fig. 1c) the left boundary of the shrinking bubble turns out to be practically motionless, while the right boundary moves uniformly. Such shrinking pattern is due to a weak fluid flow, in the area around the waveguide bounded by the walls. As a result, the bubble shrinks mainly in the right-to-left direction, and after the collapse the most of the liquid forming the jet propagates along the waveguide to the left, while a small part is reflected from the fiber end face and moves to the right. Hence, the average velocity of the cumulative jet propagating from the waveguide end is almost zero. The highest jet velocity is achieved when the fluid inflow is limited by the right end wall (Fig. 1d). In this case the left boundary of the collapsing bubble moves

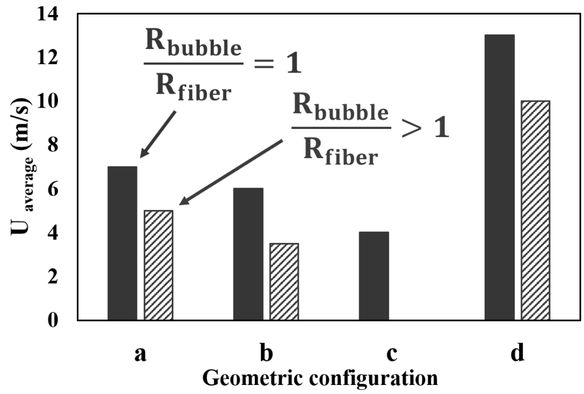

Fig. 3: The average jet velocity for various geometrical configurations, shown in Fig.1 and R_{fiber}=R_{bubble} (solid bars), $R_{fiber} < R_{bubble} = 2 \cdot R_{fiber}$ (hatched bars)

faster compared with other geometrical configurations due to the absence of a counter fluid inflow, which is hampered by the end wall. This results in formation of more intense cumulative jet after the bubble collapse.

It should be also noted, that for all considered configurations, the average jet velocity is higher if the bubble and waveguide radii are equal.

3 Conclusions

The presence of solid walls significantly affects the liquid flow field and the average velocity of the jet formed as a result of the vapor bubble collapse near the thin waveguide. In a tube with a wall opposite the waveguide (Fig.1d), the jet velocity can increase by a factor of 3 compared to the case when the fiber is located in free space. On the contrary, if the tube is closed on the waveguide insertion side (Fig.1c), a pronounced jet may not form at all.

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АННОТАЦИЯ

В работе представлены результаты численного моделирования процесса схлопывания парового пузырька на торце тонкого волновода, погруженного в холодную жидкость. Исследовано влияние твердых стенок, расположенных вблизи волновода, на динамику поля течения и скорость струи, формирующейся в результате схлопывания пузырька. Показано, что средняя скорость струи существенно зависит от конфигурации стенок и может как увеличиваться, по сравнению со случаем, когда стенки отсутствуют, так и уменьшаться, вплоть до нуля.

Ключевые слова: *численное моделирование, недогретое кипение, кумулятивная струя, двухфазное течение.*