Water flow generation owing to interaction between pulsing bubble and rigid wall

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The experimental investigation of directed water flow generation owing to vapor-gas bubble pulsing near a rigid wall has been performed. Periodical bubble formation has been produced in the hole of thin dielectric film under heating water salt electrolyte solution by an electrical current. Alternate formation of two water flows moving in opposite directions due to growth and collapse stages has been found. It has been shown that due to variation of the distance between a pulsing bubble and a rigid wall it is possible to control velocity and direction of the total flow of water through the hole. It has also been shown that the water flow generation is due to acoustical non-symmetrical acoustic field formation. The maximum value of total flow velocity has reached 40 cm/s in the experiment.

1 Introduction

An interaction between the boundary surface (rigid wall, free surface of water or phase interface) and a pulsed bubble has been obtained during experimental and theoretical investigations. For instance, it is shown experimentally in the paper [1] that the non-symmetrical single bubble collapse occurs if the distance between the bubble and free water surface is less than $5 \cdot R_0$, where R_0 is the maximum bubble radius.

It is theoretically demonstrated in the paper [2] that if two bubbles of different sizes are shocked by a plane wave, there are two variants of bubble moving, i.e., either the bubble of smaller size starts to oscillate near its mean position in the liquid or a high speed water jet is formed inside the smaller bubble. It should be noted that the jet deformation occurs if $4 < L/d < 6$, where L is the distance between the centers of the bubbles and d is the maximum radius of smaller bubble.

Moreover, a high-speed water jet formation has been obtained during the bubble collapse near the rigid wall (see, for instance, [3]).

In this paper there is found the interaction between pulsed vapor-gas bubble and rigid wall appearing as directed water flow formation owing to generation of non-symmetrical acoustic wave field.

2 Experimental set-up

Figure 1a shows the schematic drawing of set-up. All experiments have been performed in either water caustic soda solution (NaOH) or water sodium chloride solution (NaCl). The weight concentration of electrolytes is 0.33 % and 1%, accordingly. The flat electrodes are on both sides of dielectric diaphragm under dc voltage U = 0-400 V. The electrode is made of stainless steel foil. It should be noted that the polarity of electrodes does not influence acoustic processes investigated.

Dielectric cuvette 1 is filled with water (HxLxD: 35x50x18, where H, L, D are height, length and depth of cuvette, accordingly. The values are specified in millimeters). The diaphragm 3 is made of Teflon film 0.2 mm thick. The plate 2 is made of Plexiglas of thickness H = 1-11 mm. The hole radius r and distance R are changed in the ranges 0.25-0.75 mm and 2-19 mm, accordingly. The bubble dynamics has been investigated with the help of high-speed cameras “Troubleshooter” and “MotionXtra HG-LE” in regimes of 8000 and 20000 frames per second, accordingly.

Figure 1b shows the schematic drawing of another set-up to model the physical processes occurring close to the diaphragm hole and forming the liquid flows. The figure denotes the bottom of cuvette (80x135x4) having one hole 6. The cuvette is divided into two parts with lavsan barriers 0.2 mm thick. The cuvette is filled with water layer about 2 mm thick. Solid particles 4 and 5 are placed on the water surface to indicate the water moving toward the hole. The construction of cuvette allows controlling the flow velocity through the hole 6. The particle motion and, as a result, the liquid flow velocity have been investigated with the help of digital camera “Canon S2 IS” in the regime of 30 frames per second.

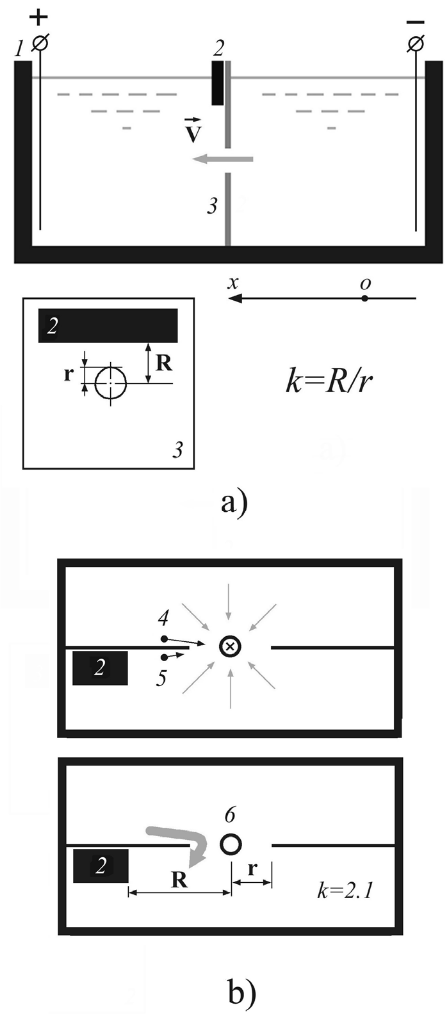

Fig. 1 a – schematic drawing of set-up for periodic bubble formation, b – schematic drawing of set-up to model the physical processes. 1 – cuvette, 2 – rigid wall (plate), 3 – diaphragm, 4 and 5 – particles for visualization of the flow, 6 – hole on the bottom of cuvette, V – vector of total flow velocity, +/- – possible polarities of metal electrodes.

3 Experimental results

If dc voltage is applied to metal electrodes (Fig. 1a), the electrical current flows through the hole and heats the electrolyte. It results in vapor-gas bubble formation in the hole. The amplitude of voltage influences the power of water heating. The periodical bubble formation has been in the regime of electrohydrodynamical auto-oscillations [4] due to specific electrical and geometrical parameters of the set-up.

The dynamics of bubble growth and collapse can be presented by several stages (Fig. 2). The first stage is the creation of bubble population on the edge of hole. The second stage is the bubble growth and coalescence into one big bubble overlapping the hole (see Fig. 2a, t = 15 ms). And the third stage is the collapse of the big bubble in the hole. During the collapse the big bubble is divided into two parts. Then the parts are disintegrated in smaller bubbles, which are picked up by vortexes and moved from the hole and do not influence the formation of another big bubble in new period of auto-oscillations. All stages repeat periodically until the voltage is switched off.

It has been found that parameter k = R/r (see Fig. 1a) influences the direction of water flow through the hole and does not depend on the power of water heating. The maximum velocity of total flow V = 40 cm/s is obtained at U = 400 V.

Figure 3 shows the dependence of mean velocity projection on parameter k. If the projection is positive, the total water flow moves toward the plate 2 and direction of vector V coincides with OX axe, and if the projection is negative, the total water flow moves from the plate (see Fig. 1a).

The magnitude of mean velocity is about zero at k = 5.8±0.5.

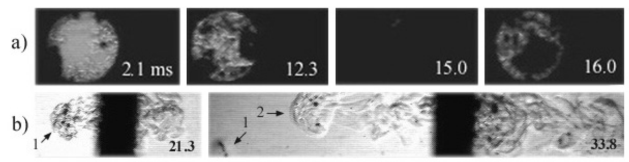

Fig. 2 Bubble dynamics in diaphragm hole at k > 5.8. The hole radius is 1.75 mm. a – front view, b – lateral view. 1, 2 – vortexes with picked up bubbles.

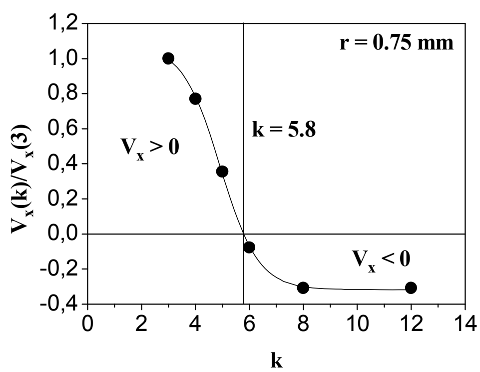

Fig. 3 Water flow direction vs k.

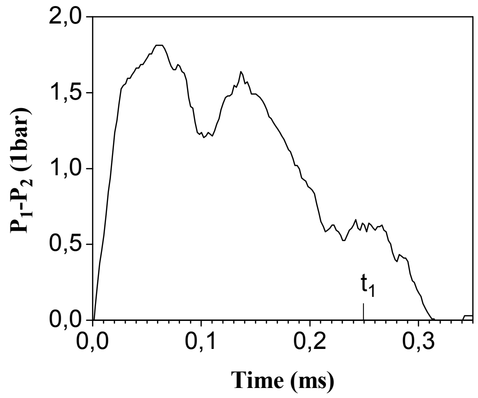

Fig. 4 Pressure differential vs time.

4 Results of model experiments

It is impossible to explain the mechanism of water flow formation due to results of optical investigations (see Fig. 1). To find the mechanism, two model experiments have been performed.

4.1 Experiment 1

Figure 1b shows the set-up to model physical processes at k < 5.8. To explain the character of liquid flow, the particle motion into the hole has been recorded. As a result, it has been obtained that particles have different velocities, i.e., particle 4 moves faster than particle 5. If the liquid flow motion through the hole is rapidly stopped, water is flowing from one part of cuvette to another for some time (it is shown with a wide arrow). On the contrary, at k > 5.8 there are a lot of separate flows and they do not provide the directed water flow motion.

4.2 Experiment 2

To perform the scale modeling the dynamics of creation, growth and disintegration of bubble in the hole during one period, the second model experiment has been done. To do it, the cuvette, having sizes of 150x150x150, is divided into two equal volumes with Plexiglas plate. The plate thickness, hole radius, thickness of the rigid wall 2 and magnitude of parameter k (Fig. 1a) are 1 mm, 2.5 mm, 10 mm, and 9, accordingly. The bubble is created during the single electric discharge of capacitor (U = 6 kV, C = 2 μF). The characteristic time of discharge τ is 8 μs. The piezoelectric transducer has recorded the acoustic wave amplitudes on both sides of plate. It is situated at equal distances from the hole.

Figure 4 shows how the pressure difference P_1-P_2 depends on time while the bubble is overlapping the hole (P_1 – pressure measured under rigid wall, P_2 – pressure measured on another side of the plate). The time t_1 = 0.25 ms corresponds to the moment of hole overlapping. Thus, during the bubble growth the pressure differential is positive and the flow is in negative direction.

Figure 5 shows a set of photographs of collapsed bubble in the hole of diameter 5 mm. The bubble is photographed at angle of about 30º and two parts of bubble can be seen as the plate is transparent. Moreover, the chain of small bubbles 1 connecting two bubble parts has been found.

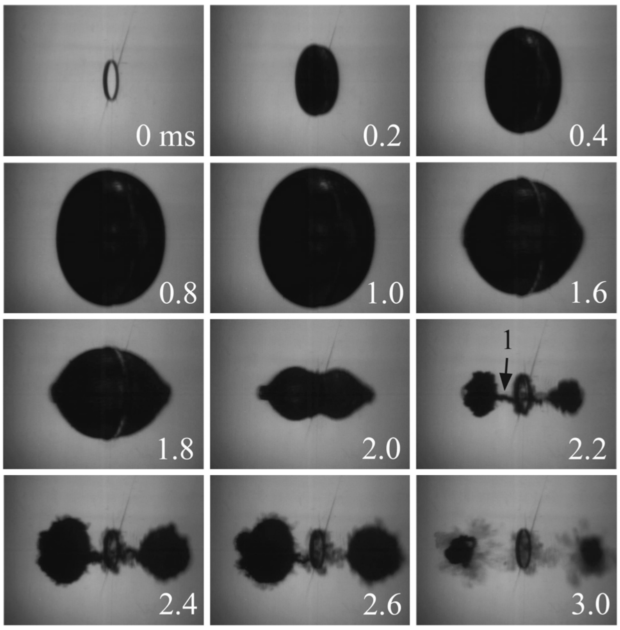

Fig. 5 Bubble dynamics in the hole at k = 9.
1 – chain of small bubbles. The plate was above the left part of the collapsed bubble.

5 Discussions

The results of modeling and experiments allow us to suggest the mechanism of directed liquid flow formation. If the rigid wall 2 is only on the one side of diaphragm, local streams flow through the hole during the bubble growth up to its maximum size and when the bubble collapses down to the size of hole. Owing to such bubble dynamics the non-symmetrical acoustic wave field has been formed and it forms the pressure differential during each period of bubble pulsation.

One part of wave front moving along the diaphragm surface toward the rigid wall goes less distance to phase interface (liquid-solid) than another part moving toward free surface of water. This is the reason why acoustic wave powers dissipate in different volumes of cuvette in different ways.

We denote the wave resistances of air, water and Plexiglas as ρ_a, ρ_w and ρ_p, accordingly. In this case the ratios ρ_w/ρ_p and ρ_w/ρ_a are equal to 0.022 and 3507, accordingly. As a result of these ratios the majority of acoustic wave power are transformed into the power of rarefaction wave in the part of cuvette without rigid wall 2. This is the reason why pressure differential occurs during the bubble growth. Thus, the negative flow is formed at any magnitudes of parameter k used in experiments above.

If the bubble is collapsed, two flows move to the hole edge along diaphragm surface. If k < 5.8, the velocity of flow moving from the rigid wall is less than that of another flow moving from the opposite side of diaphragm. When the bubble size becomes smaller than the hole diameter, two flows interact with each other. As a result, water vortex is generated and it provides the water motion in positive direction.

When the velocities of opposite flows are equal to each other, i.e., the positive velocity is equal to the negative one, the velocity of total flow trough the hole is zero. It is at k = 5.8.

Using the Figure 3, it is possible to calculate the magnitude of negative velocity at k > 5.8 and at given power of water heating. For instance, using that magnitude at k = 12 we calculate the magnitude of positive velocity at k = 3. For data presented in Figure 3 the magnitude of positive velocity is 65 cm/s. Thus, the velocity in positive direction is 1.6 times more than that of the total flow at k = 3.

6 Conclusions

(i) There are two mechanisms of water flow generation. The first mechanism exists at k < 5.8 and results in water vortex formation. The second mechanism exists at any magnitudes of parameter k presented above and results in creation of pressure differential during the bubble growth. If k = 5.8±0.5, the velocity of total flow is equal to zero.
(ii) To generate the directed flows, it is not necessary to use only a rigid plate. For instance, cylindrical surface can be used as well.
(iii) The obtained results can be used to develop devices using plasma of diaphragm electric discharge for water treatment as well as to develop new methods of heat transfer intensification between water and heater.

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