LIQUID FLOW IN THE VICINITY OF A VAPOR BUBBLE

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In the present note we give some experimental results from an investigation of the flow behavior of liquid layers adjacent to a vapor bubble, along with data on the instantaneous velocities of liquid particles around a bubble during its growth and ascension. The motion of the liquid is visualized by the introduction of solid tracer particles into the flow, where they are photographed with a high-speed motion picture camera.

The heat-transfer mechanism associated with nucleate boiling, despite a host of investigations, remains far from being clearly understood. The significant relation for this mechanism between the latent and convective components of the heat flux depends on the kind of liquid, the pressure, and the heat flux density. This problem can be solved if the temperature distribution in the bubble boundary layer and the mixing intensity of the liquid during motion of the bubble over the heat-supplying surface are known.

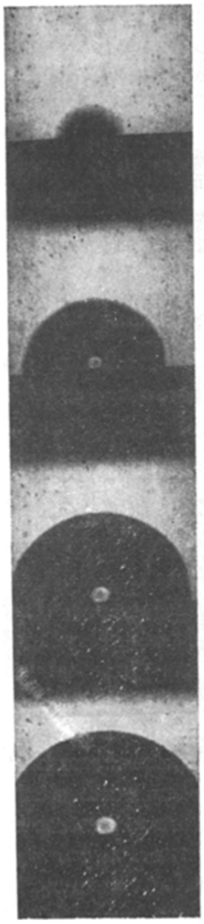

Fig. 1

The last few years have witnessed the publication of papers [1-3] in which the temperature fields in a vapor bubble and the surrounding liquid have been measured. It would also be extremely enlightening to explicate the flow behavior of a liquid in the vicinity of a bubble during boiling. However, there are no known data on this effect.

There are two techniques by which tracer particles can be photographed:

1) They can be photographed on a nonmoving film with strobed side illumination, in which case the particles appear as bright points against a dark background. This technique was developed by Orlov [4] and is called the stroboscopic flow visualization method.

2) They can be photographed in transillumination, in which case the particles appear as dark spots against a light background. This technique is amenable to the application of high-speed motion pictures.

For the study of the flow of liquid past a bubble it is more practical to use the motion picture technique. Then it is possible to trace the evolution of the bubbles and to obtain data on the instantaneous velocities, because each particle subtended within a frame is a "velocity sensor" at the given point. The particles injected into the flow as "tracers" must precisely follow the motion of the liquid surrounding them. For our tracer substance we decided on lycopodium powder (whose particle are very nearly spherical in shape, with an arithmetic-mean diameter $d = 22\ \mu$ and a specific gravity $\gamma = 9450\ N/m^3$). On the basis of analytical recommendations [4] concerning such parameters as the liquid velocity u_*, specific gravity γ_* of the liquid, and the velocity, diameter, and specific gravity of the solid particles, u_0, d, and γ_0, the condition $v_* \approx u_0$ is guaranteed. Inasmuch as the particles used have extremely small diameters, they must be photographed with the aid of magnification.

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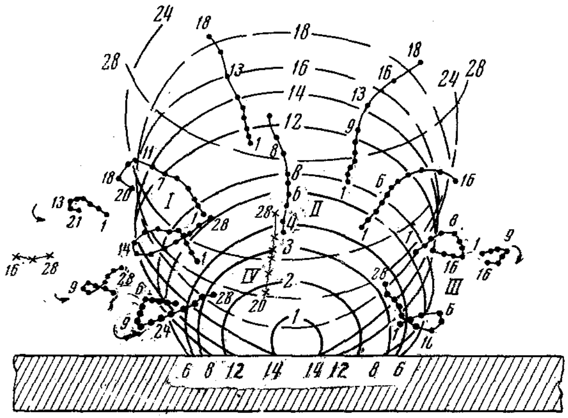

Fig. 2

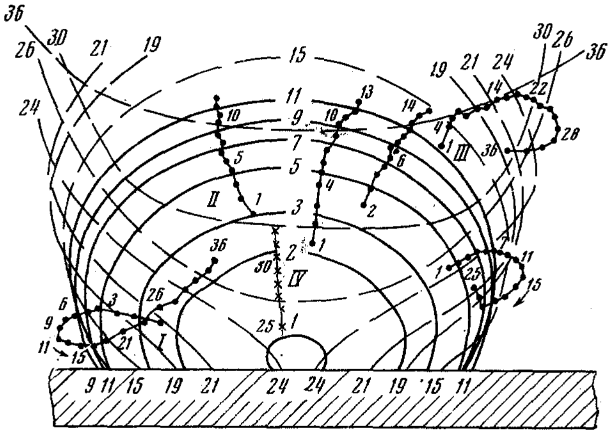

Fig. 3

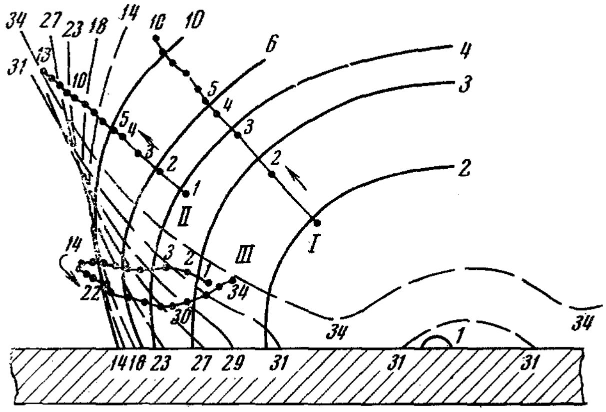

Fig. 4

The motion pictures were taken with a Pentatset-35 camera at a speed of 1000 to 2000 frames/sec through a specially constructed camera adapter unit providing a magnification of 4.

In the experiments we filmed the process of water boiling at the saturation temperature on a platinum wire 0.5 mm in diameter and 100 mm in length. Lycopodium particles having the requisite concentration were introduced into the liquid volume after having been prewetted in ethyl alcohol. The experimental apparatus and procedure were similar to those described in [5]. The character of the circulation currents was investigated at pressures $p = 1.0$, 0.6, and 0.4 bar. The films were processed as follows. The film images were magnified and projected onto a screen, the position of the working section and the bubble boundary were traced, and the position of the particles relative to them were ascertained. By successive

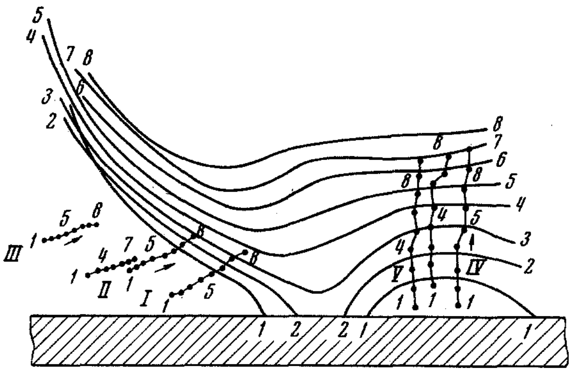

Fig. 5

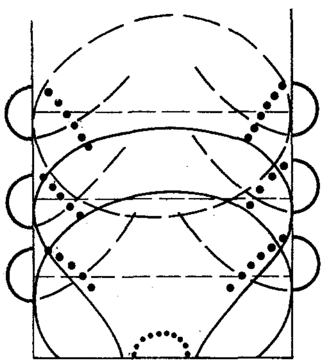

Fig. 6

overlaying of the frames an image of the bubble at various stages of its growth or breakoff was obtained, along with the particle trajectories. Photographs of the growth of a vapor bubble for $p = 0.4$ bar and $q = 1 \cdot 10^5$ W/m^2 are shown in Fig. 1 as an illustration. It is seen how the particles in the form of dark spots disperse in the radial direction.

The results of processing of the displacement pattern of liquid particles during the growth and breakoff of single isolated bubbles (i.e., when the waiting time is sufficiently long and adjacent bubbles do not exert a mutual influence) at different pressures are given in Fig. 2 ($p = 1.0$ bar, $q = 7.0 \cdot 10^4$ W/m^2), in Fig. 3 ($p = 0.6$ bar, $q = 1.5 \cdot 10^5$ W/m^2), and in Figs. 4 and 5 ($p = 0.4$ bar, $q = 2.3 \cdot 10^5$ W/m^2). The numerals given alongside the trajectories and the bubble boundary indicate the frame number; for example, the number 1 corresponds to nucleation of the bubble and the nominal inception of motion of the particles; the time interval between frames is $\Delta\tau = 5.5 \cdot 10^{-4}$ sec in all the figures. It is evident in Figs. 2, 3, and 4 that during growth of the bubble in the initial period the liquid particles move in the radial direction away from the center of the bubble. After the base of the bubble has attained its maximum size and the bubble has elongated in the vertical direction the motion of the particles changes direction. Thus, the particles situated near the surface (at distances ≤ 0.5 mm) change direction in position 6 in Fig. 2, in position 9 in Fig. 3, and in position 14 in Fig. 4. At a pressure $p = 0.4$ bar the vapor bubble does not enter completely into the frame, so that in Fig. 4 the growth, and in Fig. 5 the breakoff, of half the bubble are shown; breakoff takes place at two stems. After the particle trajectory turns, as occurs during the constriction of the bubble contact area, the liquid particles migrate behind the bubble, where they continue to move during its breakoff and subsequent ascension (for example, particle III in positions 12-28 in Fig. 2, particle I in positions 20-36 in Fig. 3, particle III in positions 27-34 in Fig. 4, and particles I, II, and III in Fig. 5). In the wake region of the bubble the particles move almost vertically: particles IV in Figs. 2 and 3, and particles IV and V in Fig. 5.

Liquid particles more distant from the heating surface experience a change in the direction of their motion (eddying) at a later time, during ascension of the bubble and the approach of its maximum cross section to the level at which the liquid particles are situated.

The character of the motion of the liquid layers adjacent to the bubble can be portrayed schematically as in Fig. 6, assuming for simplicity that the bubble diameter does not vary during its breakoff and ascension. The part of the curve marked by the dots is the path traversed by the liquid particles at the initial instant when the bubble attains the maximum contact area. The solid curve represents the path of a particle when it turns and flows underneath the bubble during constriction of the contact area. The dashed part of the curve corresponds to motion behind the bubble and entrainment in its wake.

The distance between two adjacent particle images makes it possible to determine the instantaneous value of the linear velocity $V = \Delta S / n\Delta\tau$ and the two components of the instantaneous velocity $V_x = \Delta x / n\Delta\tau$ and $V_y = \Delta y / n\Delta\tau$, where n is the magnification.

The values of the linear instantaneous velocities are shown in Figs. 7, 8, 9, and 10 for particles I, II, III, IV, and V (points 1, 2, 3, 4, and 5 in the graphs, respectively); the particle trajectories are seen in

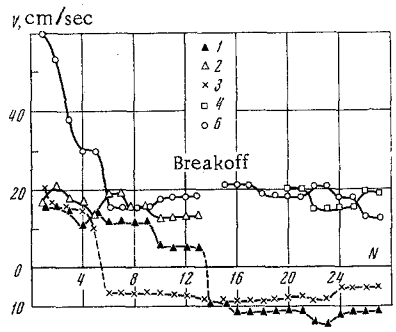

Fig. 7

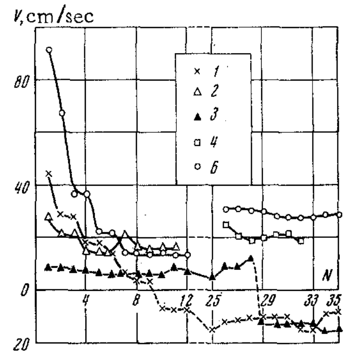

Fig. 8

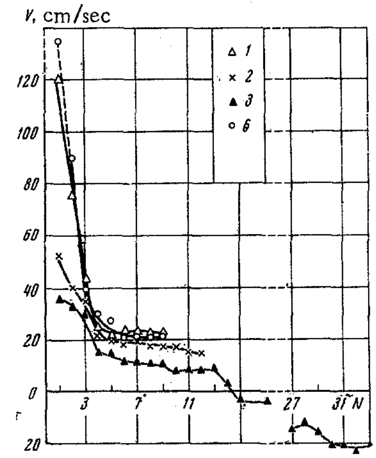

Fig. 9

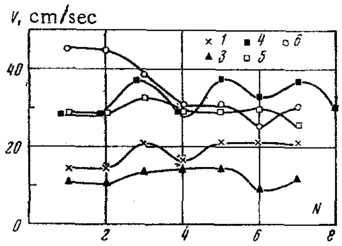

Fig. 10

Figs. 2, 3, 4, and 5. Also shown for comparison is the value of the instantaneous growth rate of the vapor bubble in the vertical direction toward the surface $V^{\circ}=\Delta h/n\Delta\tau$ (points 6 in the graphs). The numerals indicate the frame order numbers.

It is apparent from a comparison of these graphs that the maximum liquid particle velocities in the vicinity of the bubble are observed in the initial period of bubble growth; the rate is higher, the closer the particles are to the bubble boundary. The particle velocity slows down with a reduction in the bubble growth rate.

For processing of the films we used particles situated close to the bubble (at a distance of 0.5 to 2.0 mm). After turnaround of the trajectory, when the particles become entrained by the bubble their velocity becomes almost constant, depending only on the bubble diameter. The velocities of particles I and III in Figs. 7, 8, and 10 falls between the limits 10 and 20 cm/sec. In the wake of the detached bubble the particles move at a constant velocity roughly equal to the ascension rate of the bubble (particles IV in Figs. 7 and 8 and particles IV and V in Fig. 10). The bubble ascension rate in this case has a slight dependence on the pressure, i.e., on the bubble size, varying from 20 to 35 cm/sec.

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