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MECHANISM OF STEAM BUBBLE FORMATION

by
I. G. Shekriladze

Soobshcheniya Akademii Nauk Gruzinskoy SSR, 41, No. 2, 391-398(1966)

Translated from the Russian

January 1967

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The study of the process of steam bubble formation (boiling) is one of the most important problems of modern thermophysics. Despite the large number of studies, there are no sufficiently substantiated concepts of the mechanism of this process. Available quantitative generalizations are actually of an empirical nature and frequently do not take into account the role of a number of basic factors that influence the process.

The results of recently conducted studies on the mechanism of steam bubble formation contradict certain generally accepted concepts of the specific features of this phenomenon.

This paper presents briefly the results of a theoretical study which revealed the determining role of a phase change on the surface of the steam bubble that originated on the heating wall in the hydrodynamics of the process of steam bubble formation. The new physical model of the process, built on the basis of the results of this study, which differs essentially from those known, makes it possible to explain the basic experimental facts that characterize the process of steam bubble formation.

Most researchers of the process of steam bubble formation start on the assumption that the high intensity of heat transfer, which characterizes this process, is determined by the mixing of the liquid, which is caused by the origin and breakaway of steam bubbles from the heating surface[1, 2, 3, 4, 5, 6].

In order to clarify the experimentally discovered periodic sharp drops in the temperature on the heating surface during steam bubble formation, a hypothesis was advanced[7], which differs in principle from that examined. This is the so-called hypothesis of the evaporation of a microlayer; it assumes that the heating surface is cooled by evaporation of the microlayer of liquid, which separates the bubble from the heating surface. Later, more detailed experiments on the study of the fluctuation of the wall temperature[8, 9] showed that immediately after the origin of a bubble in the zone of the center of steam formation the temperature of the heating surface undergoes a sharp drop and again reaches a maximum value only after the breakaway of the bubble. This important experimental fact contradicts the assumption made in the studies[1, 2, 3, 4, 5, 6] that immediately after the breakaway of the bubble the heating surface should have a minimum temperature in connection with the replacement of the volume of the bubble by cooler masses of liquid. As regards the hypothesis of the evaporation of a microlayer, it satisfactorily explains the nature of the fluctuations recorded[8, 9]. However, the indicated hypothesis contradicts the generally known experimental fact that at moderate heat flows (it is precisely such conditions that were studied[8,9]) most of the heat is removed by the liquid from the heating surface and the share of the heat of evaporation directly on the heating surface in the total amount of heat being removed is insignificant.

In analyzing the resulting situation, a number of researchers come to the conclusion that in real conditions of steam bubble formation the removal of heat is accomplished by the joint action of both indicated mechanisms of the process[10, 11, 12]. But even with such an approach, the above indicated contradictions are still not removed, and to this day there is no substantiated physical model of the process.

Let us examine the phenomena on the interface during the origin and growth of a steam bubble on the heating surface (Figure 1).

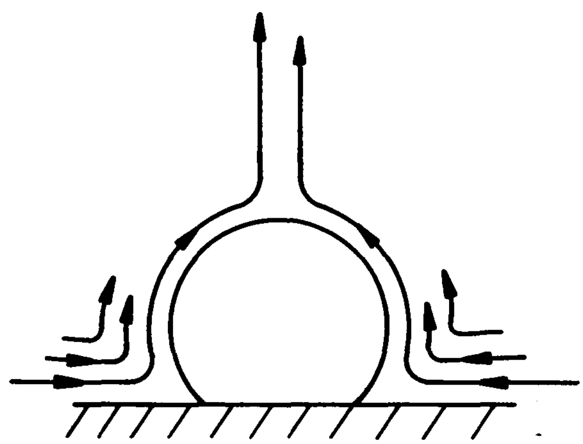

Figure 1

After the surface becomes somewhat overheated with respect to the temperature of saturation, a steam bubble originates in the center of the steam formation, which represents a pocket on the heating surface. The new bubble is surrounded with overheated liquid and the evaporation process takes place over its entire surface. The conditions of heat flow to the surface of the bubble are nonsymmetric. On sections of the interface close to the wall, the evaporation proceeds more intensively than on the opposite side of the bubble, and the specific flow of the evaporating liquid drops sharply with increasing distance from the base of the bubble to its front section. In view of the fact that evaporation represents a process of the escape from the liquid of molecules which have the highest speeds, a definite reactive force directed toward the liquid acts on the interface. This force, which causes a local increase in pressure due to the curvature of the bubble surface, leads to a certain local decrease in the surface tension.

In connection with the nonuniformity of the evaporation on the bubble surface, the magnitude of the indicated local change in surface tension will vary with the displacement from the base, where it will have a maximum value, to the front section of the bubble. As a result of this, a gradient of surface tension will appear on the bubble surface, and tangential forces will appear which will lead to the origin of circulation flows in the liquid as well as in the vapor phases (Figure 1).

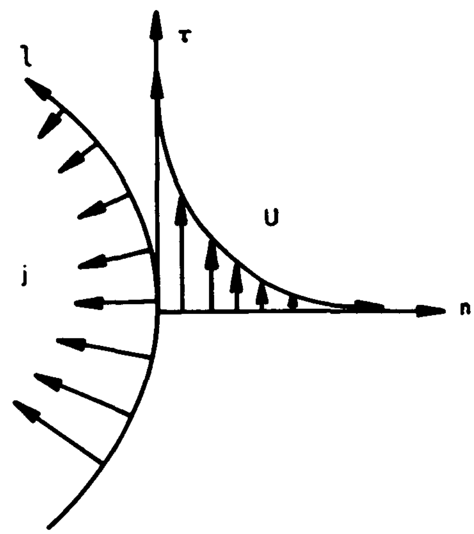

Figure 2. Diagram of Flow Along Interface Surface

It should be pointed out that the nonuniformity of evaporation through the bubble surface will lead also to nonuniformity of the temperature on the interface, which will also cause the origin of a surface tension gradient directed to the same side as in the first case. However, in connection with the fact that the thermal resistance of the phase transition during the evaporation of the liquid is very small, the temperature on the interface will differ insignificantly from the saturation temperature of the steam within the bubble.

Let us carry out an approximate evaluation of the intensity of the circulation flows that originate in the liquid phase.

The local pressure change caused by evaporation of the liquid can be represented as follows:

$$\Delta P = \frac{q}{r}\,\overline{C} \approx 1.27\,\frac{q}{r}\sqrt{r - P(v'' - v')}\quad , \tag{1}$$

where q = the local value of the specific heat flow
r = the latent heat of evaporation
$\overline{C}$ = the average arithmetic value of the normal speed components of the escaping molecules
P = the absolute pressure
v'' = the specific volume of the steam
v' = the specific volume of the liquid.

In case of a bubble with radius R, the indicated pressure increase will lead a corresponding decrease of the surface tension

$$\Delta\sigma = -\frac{R\,\Delta P}{2} \approx -0.635\,\frac{Rq}{r}\sqrt{r - P(v'' - v')}\quad . \tag{2}$$

The tangential tension, which originates on the bubble surface in connection with the nonuniformity of evaporation, will be equal to

$$\tau = \frac{d\sigma}{de} \approx -0.635\,\frac{R}{r}\sqrt{r - P(v'' - v')}\;\frac{dq}{de}\quad . \tag{3}$$

Since the flow determined by this tangential tension is accompanied by intensive evaporation on the interface, the transverse flow of the mass will - similarly to the case of flow with suctioning of the boundary layer - sharply compress the area of the speed gradients in the liquid phase. For this reason, the flow essentially takes place in a narrow layer directly at the interface, and it can be described by the Prandtl equation for a boundary layer:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial e} + V\frac{\partial U}{\partial n} = -\frac{1}{\rho}\,\frac{\partial P}{\partial e} + \nu\,\frac{\partial^2 U}{\partial n^2}\quad , \tag{4}$$

where U = the speed along the axis l
V = the speed along the axis n
t = the time
ρ = the density of the liquid
ν = the coefficient of the kinematic viscosity of the liquid.

The existence of a considerable transverse flow makes it possible, as a first approximation, to disregard also the longitudinal inertia member $U \cdot \partial U/\partial e$ in comparison with the transverse $V \cdot \partial U/\partial n$. Further, by regarding the flow as steady and considering the absence of a pressure gradient, Equation (4) can, for our case, be rewritten in the following simplified form:

$$-j \frac{dU}{dn} = \mu \frac{d^2U}{dn^2} \quad , \tag{5}$$

where

$$j = \frac{q}{r} = -V\rho \quad , \qquad \mu = \nu\rho \quad .$$

Equation (5) is solved for the boundary conditions

$$U = o$$

when

$$n = \infty \quad ,$$

$$\mu \frac{dU}{dn} = -\tau$$

when

$$n = o \quad . \tag{6}$$

The solution gives a profile of the speeds

$$U = \frac{\tau}{j} e^{-jn/\mu} \quad . \tag{7}$$

By integrating the profile of the speeds from the interface to infinity, we obtain the relationship for the determination of the flow of liquid which rolls by as a bubble along the zone of its surface with a width per unit length:

$$W = \int_0^\infty U dn = \frac{\tau}{j} \int_0^\infty e^{-jn/\mu} dn = \frac{\tau\mu}{j^2} \quad . \tag{8}$$

In order to determine τ, we shall undertake to determine the distribution of the heat flow through the interface:

$$q = \frac{\overline{q}}{2} \left(\frac{L}{l}\right)^{1/2} \quad , \tag{9}$$

where l is counted from the base of the bubble

$$\overline{q} = \frac{1}{L}\int_0^L q\,dl \quad .$$

In determining τ with the help of the expressions (9) and (3) and introducing into (8), we get the final relationship for the determination of W:

$$W \approx 0.159 \frac{\mu R}{jl} \sqrt{r - P(v'' - v')} \left(\frac{L}{l}\right)^{1/2} \quad . \tag{10}$$

The evaluation of the amount of liquid which rolls by a single bubble of water vapor under conditions of steam bubble formation at atmospheric pressure, which was conducted by means of approximate Equation (10), shows that during the residence time on the heating surface the bubble rolls by a volume of liquid which exceeds its own volume by approximately three orders. (The quantitative data necessary for this evaluation were taken from Fritz and Ende[13].) The result, considering the obviousness of the circumstance that the mixing of the liquid in connection with the replacement of a volume of the bubble by colder masses during its breakaway from the heating surface is immeasurably less intensive, gives grounds for assuming that the above described mechanism of heat removal in the near-wall layer plays a basic role in the process of steam bubble formation.

Let us examine, in the light of the results, the cycle of origin, growth, and breakaway of a steam bubble.

After the breakaway of a previous bubble from the heating surface, a period of smallest convection mixings of the liquid takes place in the vicinity of the center of steam formation, i.e., the period of worse conditions for heat removal. The surface becomes overheated (in complete agreement with the data of Kin-ichi et al[8] and Rogers and Mesler[9]) and conditions for the origin of a new bubble develop. The new bubble finds itself in the area of the greatest temperature gradient and the specific flow of the evaporating liquid on its periphery becomes sharply nonuniform. In connection with this, the bubble, simultaneously with growth, begins to intensively pump the liquid from the layers that are situated in immediate vicinity of the heating surface. The colder masses of liquid, which come in place, cause a sharp cooling of the surface. This period corresponds to a period of sharp drop in the wall temperature, recorded at the moment of the origin of the bubble in the studies[8,9]. The rolling of the liquid by the bubble from its side leads to the appearance of hydrodynamic forces that squeeze the steam bubble to the heating surface. Considering the circumstance that, according to the latest experimental data[8], the surface of direct contact of the bubble with the wall is much less than assumed earlier[13], it can be concluded that the resulting hydrodynamic forces will exceed the forces of surface tension in the cross section of the bubble breakaway and that the breakaway diameter of the bubble will essentially be determined by the balance between the lifting and indicated hydrodynamic forces.

This conclusion is confirmed by the results of observations on the breakaway of steam bubbles, in accordance with which, during the residence period on the heating surface, the horizontal axis of the bubble is longer than the vertical[7,14,15,16]. The indicated breakaway mechanism explains also the statistical range of the magnitudes of the breakaway diameters of the bubbles, which is observed in the experiments. After the bubble reaches a certain diameter, which depends on the local heat conditions, the lifting force exceeds the squeezing forces and the bubble breaks away from the heating surface. In the vicinity of the center of steam formation, the surface again starts to overheat, and conditions again develop for the origin of the next bubble, etc.

On the basis of this presentation, it should be concluded that the physical model of the process, described in this work, makes it possible to give an explanation to all experimental facts that characterize the process of steam bubble formation.

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Discussed are the results of a theoretical study which revealed the determining role of a phase change on the surface of the steam bubble that originated on the heating wall in the hydrodynamics of the process of steam bubble formation. The new physical model of the process, built on the basis of the results of this study, which differs essentially from those known, makes it possible to explain the basic experimental facts that characterize the process of steam bubble formation.

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14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Idenfiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.