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A NOTE ON THE MECHANISM OF SCALE FORMATION IN NUCLEATE BOILING

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An examination is made of the physical and chemical processes that take place on a bubble surface and intensify scale formation during boiling of salt solutions.

Experimental research [1–3] has established that formation of salt deposits is usually more intense at evaporation centers than on other parts of a heating surface. It was shown in [4], however, that the increase in salt concentration at the surface of a bubble is small and evidently cannot be the chief cause of increase in rate of growth of scale during boiling.

The formation of vapor bubbles on the heating surface is associated with the action of factors whose influence, so far as we know, has not hitherto been taken into account. These factors are: a) the increase in the concentration of suspended particles at the base of a vapor bubble, b) the existence of conditions along the vapor-water-wall interface facilitating transfer of salt ions to the crystal lattices of scale particles, and c) improved conditions of supply of "fresh" solution to the growing scale crystals due to the wall layer being made turbulent by the bubbles.

Investigations of boiler water, evaporator water, heater water, etc., show that, in addition to dissolved salts, they always contain a definite amount of solid particles of various degrees of dispersion. These particles result from crystallization of part of the dissolved salts in the bulk of the solution and from breakdown of scale (which may occur, for example, when the operating conditions of the equipment are changed), particles of which are carried away into the bulk of the solution. The number and sizes of particles depend on the properties of the water entering the heat exchanger and on the latter's conditions of operation.

Since the inertia of the suspended particles is greater than that of the water particles, the concentration of these particles at the surface of a bubble growing on the heating surface must increase with movement of the boundary of the bubble. The surface of the bubble acts, so to speak, like a net that catches the solid particles and carries them to the periphery of the active center.

Let us examine a solid particle at the surface of a growing vapor bubble. The boundary of the bubble moves at velocity ω. We assume that the flow of water bathing the particle moves relative to the heating surface at the same velocity. Under the action of the flow the particle moves with velocity v, which may be determined from the relation

$$m\frac{dv}{d\tau}=\zeta F\frac{(w-v)^2}{2g}\gamma_1. \tag{1}$$

For a spherical particle (1) may be written as

$$\frac{dv}{(w-v)^2}=\frac{3}{4}\zeta\frac{\gamma_1}{\gamma}\frac{1}{d}\,d\tau=A\,d\tau. \tag{1a}$$

It follows from the graph presented in [5] for the dependence of the diameter of a growing bubble on time that the greatest rate of growth occurs in the initial period of its existence on the heating surface. According to the data of [6], this initial period $\tau_1 \approx 0.25\ \tau_{sep}$ for boiling at atmospheric pressure.

During time τ_1 the bubble grows to the size $d_1 = 0.7 - 0.75\ d_{sep}$. The variation of bubble diameter during its growth to d_1 is essentially linear, since it may be assumed that in this interval ω = const, approximately. Integrating (1a) and applying this condition, we obtain

$$w-v=A\tau+C. \tag{2}$$

Determining the constant from the condition that when $\tau = 0$ $v = 0$, we obtain

$$v=Aw^2\tau/(1+Aw\tau).$$

Particles located at a distance $r_1 = 0.7\ r_{sep}$ from the active center at the time the bubble starts to form, traverse during time τ_1 a path of length

$$\delta=\int_0^{\tau_1}v\,d\tau=\int_0^{\tau_1}\frac{Aw^2\tau}{1+Aw\tau}\,d\tau=\frac{1}{A}\left[Aw\tau_1-2{,}3\lg\left(1+Aw\tau_1\right)\right].$$

If the particle concentration in the bulk of the solution is c_0, in the layer δ it will be

$$c = c_0 (d_1 + 2\delta)^3 / [(d_1 + 2\delta)^3 - d_1^3] = K_1 c_0.$$

Dependence of Coefficient K_1 for Spherical and Lamellate Particles on Their Greatest Linear Dimension

p, N/m²	K_1 sph (upper figure) and K_1 lam (lower) for l, mm.				
	0.3	0.2	0.1	0.01	0.001
$1 \cdot 10^5$	2.608 1.473	2.023 1.347	1.464 1.225	1.159 1.147	1.147 1.143
$5 \cdot 10^5$	2.083 1.362	1.702 1.279	1.348 1.197	1.151 1.145	1.143 1.142

The table shows the dependence of the coefficient K_1 characterizing the degree of increase in mean concentration of solid particles in a layer δ around the vapor bubble on the greatest linear dimension, l, of the particle for pool boiling conditions. Values of the separation diameter of the bubbles were calculated from:

$$d_{\text{sep}} = 0.02\vartheta \sqrt{\sigma/(\gamma' - \gamma'')}.$$

The value $\tau_{\text{sep}} = 0.008$ sec for a pressure of 10^5 N/m² was taken from the experimental data of [7]. For a pressure of 5×10^5 N/m², τ_{sep} was determined from the relation obtained in [6], $(d_0 u)_{10^5\,\text{N/m}^2} (d_0 u)_{5 \cdot 10^5\,\text{N/m}^2} = 5$, where τ_{sep} was taken to be 1/2u.

K_1 was determined for spherical and lamellate particles of identical mass and cross-sectional area. (The lamellate particle has the greatest resistance coefficient among particles with the same mass and area.) The resistance coefficient for a spherical particle was determined as a function of Re number from the table given in [8]. For a lamellate particle, the resistance coefficient was determined from the relation given in [9], $\zeta_{\text{lam}}/\zeta_{\text{sph}}$.

The specific weight of the particles was assumed to be 26 460 N/m³. At large concentrations fine particles may cluster to form larger ones, and, since the rate of motion of the bubble boundary decreases substantially beyond ~ 0.25 τ_{sep}, solid particles may be deposited on the heating surface in the form of a circular layer around the active center.

The influence of the evaporation process on the rate of formation of scale is also seen in the fact that conditions for transfer of salt ions to the crystal lattice of the scale particles from the surface of a vapor bubble are more favorable than from the bulk of the solution. It is known that crystal growth takes place under the influence of molecular attractions, when ions of dissolved substances from the liquid phase surrounding the crystal enter the surface field of the crystal, are oriented by attraction, and, on being attracted, attach themselves to the crystal lattice.

An ion at the surface of a crystal experiences the attraction of the crystal F_2 and an opposing attraction due to the surrounding molecules and ions of the solution F_1 (resultant of the forces of attraction). The possibility of transfer of the ion to the crystal lattice is determined by the relative values of these attractions.

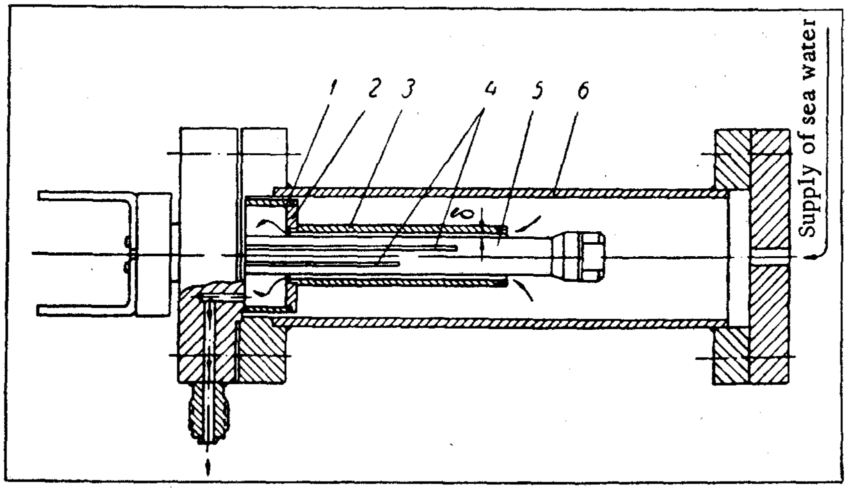

Fig. 1. Working element for heating water in an annular gap: 1) unheated ring; 2) disc; 3) detachable sleeve; 4) thermocouples; 5) tube of working element; 6) chamber

Let us consider the same ion, located at the same distance from the surface of a crystal but on the surface of a vapor bubble. Since the interaction of the ion with the vapor is negligibly small, the resultant F_1 of the attractive forces on the ion due to the solution and the vapor is directed toward the solution, not normal to the crystal surface, but at some angle to it. It is evident that, in this case, the force F_1' opposing the attraction due to the crystal will be less than it was in the case considered above, and there is therefore a greater probability of the ion being transferred to the crystal lattice. Finally, because of the turbulence of the boundary layer created by the vapor bubbles, there is an improvement in the influx of salt ions into the "crystallization range" of the growing scale crystals, which leads to an acceleration of their growth.

It may be assumed that the effect of vaporization on the rate of growth of scale is influenced by all the factors enumerated.

By way of illustration to confirm the supposition that conditions for transfer of salt ions to the crystal lattice, and hence for formation of scale, are more favorable along the vapor-solution-wall interface, the following fact may be advanced. We ran a test in which sea water was heated in the annular gap, $\delta = 0.6$ mm, between a tube of outside diameter 24 mm and a detachable sleeve (Fig. 1). Inside the tube there was an electric heater, which produced a specific heat flux that was constant along the tube. The working element was mounted in a chamber into which the sea water was fed. The water flowed out through a flange on this element. The tube wall temperature was measured with thermocouples. The test was conducted at a pressure $p = 5 \times 10^5$ N/m^2, the specific heat flux was 9×10^4 W/m^2, and the water flow rate through the annular gap was 7.8×10^{-6} m^3/sec.

The outward appearance of the working element and the inner surface of the detachable sleeve after the test are shown in Fig. 2. The arrow indicates the direction of motion of the water. It may be seen on the photograph that the profile of the deposit on the inner surface of the sleeve accurately reproduces the deposit on the tube of the working element. This phenomenon may be explained as follows. The temperature of the tube wall in the annular gap exceeded the boiling temperature at the pressure at which the test was performed. At this pressure the maximum bubble diameter, $d_{max} = 0.8$ to 1 mm [10], is greater than the size of the gap δ. The bubble must therefore touch the inner surface of the detachable sleeve. Since enhanced conditions for transfer of salt ions to the crystal lattice are created at the points of contact along the vapor-water-wall interface, scale is deposited strongly on the inside surface of the sleeve, in spite of the fact that no heat was supplied to it.

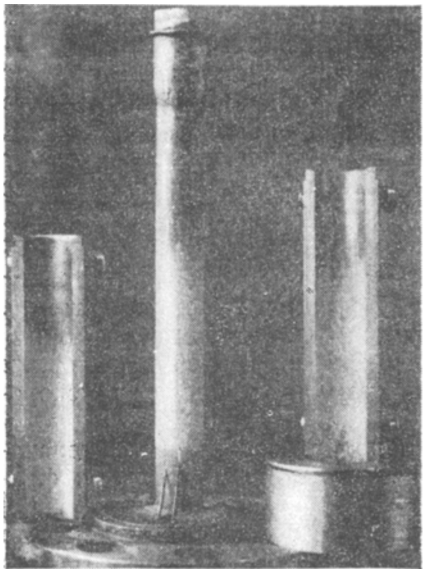

Fig. 2. External view of working element and detachable sleeve after test.

In other tests, carried out under similar conditions but with a much larger gap between the tube and the unheated sleeve ($\delta \sim 25$ mm), there was no deposit of scale on the unheated surface. It should also be noted that in the test described above ($\delta = 0.6$ mm) there was no deposit of scale on the inside surfaces of the unheated ring and disc. The gap between the tube and the ring was 20 mm, i.e., much greater than the maximum bubble size.

NOTATION

m—particle mass; ζ—resistance coefficient; F—midsection area of particle; γ_1, γ_2—specific weights of liquid bathing particle and particle material; d—particle diameter; d_{sep}—bubble diameter at separation; τ_{sep}—time from beginning of formation of bubble to its separation from surface; K_1—coefficient determining the rate of increase of mean concentration of solid particles in a layer δ around the bubble; l—greatest linear dimension of particle; ϑ—contact angle; σ—surface tension at the liquid-vapor boundary; γ' and γ''—specific weights of liquid and vapor; u—bubble separation frequency.

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