ROLE OF WORKING-SURFACE ROUGHNESS IN MECHANISM OF BOILING

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This paper is an attempt to establish the general principles underlying the effect of roughness of the heating surface on boiling heat transfer in relation to the conditions in which the process occurs. The concept of a region of undeveloped boiling is established. The special features of the process in this region and the boundaries of the latter are indicated.

The question of the role of roughness of the working surface in boiling is not a new one. The first stage of investigation of this problem is associated with the names of Cryder and Gilliland [1], Jakob and Linke [2], Fritz and Ende [3], Rachko [4], Cichelli and Bonilla [5], and others. The most significant investigations in the last decade are those of Bankoff [6], Clark, Strenge, and Westwater [7], and Griffiths and Wallis [8]. Their results, however, must be regarded as special relationships. None of these investigations led to general, physically substantiated principles governing the role of roughness in the mechanism of boiling.

Some engineers hold the view that the nature and degree of roughness of the working surface have no radical effect on boiling heat transfer. This view is due to extension of the conclusions from a number of experimental investigations to cases lying outside the region investigated in these works. In certain conditions, however, roughness must affect boiling considerably and may be the decisive factor affecting heat transfer.

Attempts to attribute the appearance of vapor nuclei de novo in boiling to statistical fluctuations of molecules have been a failure. According to current ideas the existence of stable vapor-forming centers depends on the mechanical and physicochemical properties of the working surface, as well as on the nature of the boiling liquid and its thermodynamic parameters. It was believed for a long time that vapor nuclei could originate only on projections. This initial assumption led to a fairly consistent and soundly based physical theory of the growth of a bubble from nucleation to breakaway, but did not explain nucleation itself. Advocates of this line were Jakob and Linke [2], Sarukhanian [9], and others. This idea also became firmly established in Soviet technical literature. Bankoff [6] absolutely rejected the possibility of nucleation on projections and convincingly demonstrated the advantages of surface depressions as potential vapor-forming centers. Harvey et al. [10] claim that minute gas cavities in depressions in the hydrophobic surface act as nuclei in boiling.

No matter which of these theories we favor, there are two indisputable associated facts:

1. Each vapor-forming center has a linear dimension R_n, which determines the conditions for conversion of this center from a potential to an active one. (According to one view this is the radius of the projection; according to the other it is the radius of the cavity opening).

2. In particular conditions this radius has a critical value R_{min}, which is given by the Gibbs and Clapeyron-Clausius equations. This is the radius of the smallest vapor-forming center which can become active at given values of p and t_σ.

Taking these facts as a basis we used in our treatment our previously derived relationship [12] for the bubble breakaway frequency in a boiling liquid:

$$u = 2.5 \frac{\sigma}{\beta R_{min}} \frac{1}{p(R_0 - R_n) + (pR_{min} + 2\sigma)\ln \dfrac{R_0 - R_{min}}{R_n - R_{min}}}. \quad (1)$$

In the deduction of expression (1) the breakaway radius was determined from Teletov's formula [11]

$$R_0 = \varphi(\theta)\sqrt{\frac{\sigma}{\gamma' - \gamma''}}.$$

The critical radius R_{min} was determined from the Gibbs formula

$$R_{min} = \frac{2\sigma}{p' t_\sigma},$$

and the derivative p' from the Clapeyron-Clausius equation.

The complex

$$\ln \frac{R_0 - R_{min}}{R_n - R_{min}} \quad (2)$$

contained in the denominator of expression (1) can be regarded as the criterion which determines the limit of boiling on an individual center of radius R_n. When the denominator of the expression in (2) is greater than zero ($R_n - R_{min} > 0$) the complex (2) takes a finite positive value. In this case the breakaway frequency u differs from zero, as directly follows from formula (1). When the difference is less than zero ($R_n - R_{min} < 0$), expression (2) ceases to have meaning. Relationship (1) in this form states that boiling cannot occur on centers with a radius less than the critical radius. If $R_n = R_{min} = 0$, the complex (2) vanishes. This case must be interpreted as phase equilibrium of the vapor and its surrounding liquid without stimulation of growth of the bubble or its condensation, i. e., as the limit of boiling for a center of given radius R_n.

Let us put the conditions which determine this limit in a more general form. The difference $R_n - R_{min}$ vanishes for certain combinations of parameters p, t_σ, and R_n, which are the primary arguments in function (2). Each two of these quantities uniquely determine the value of the third for which $R_n - R_{min} = 0$. At smaller values of the third parameter boiling is impossible. These minimum values of the three parameters can be called, respectively: p_{min}, the pressure boiling limit; $(t_\sigma)_{min}$, the temperature boiling limit; $(R_n)_{min}$, the limiting roughness.

Curves of u = u(p), plotted from formula (1) for different values of the parameters R_n and t_σ (see Fig. 1), were illustrated in [12]. An analysis of these curves showed that each individual vapor-forming center has two regions: a region of undeveloped boiling and a region of developed boiling. We found that the complex

$$(pR_{min} + 2\sigma) \ln \frac{R_0 - R_{min}}{R_n - R_{min}}$$

in the denominator of formula (1) significantly affects the breakaway frequency only close to the pressure boiling limit. At the limit it is equal to infinity and the breakaway frequency becomes zero. This complex then decreases rapidly and in developed boiling becomes negligibly small. For developed boiling the breakaway frequency can be represented without appreciable error by the approximate formula

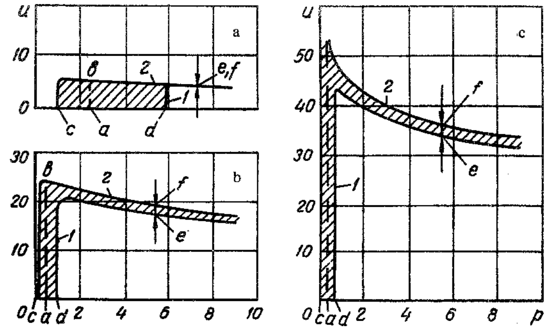
$$u = 2.5 \frac{\sigma}{\beta R_{min}} \frac{1}{p(R_0 - R_n)}. \qquad (3)$$

Proceeding to the next stage of the approximation we can neglect at moderately high pressures the radius R_n of the vapor-forming center in comparison with the breakaway radius R_0 of the bubble in formula (3). Then the breakaway frequency becomes

$$u = 2.5 \frac{\sigma}{\beta R_{min}} \frac{1}{pR_0}. \qquad (4)$$

Formulas (1) and (3) contain the variable R_n. This can be used to determine the effect of the radius of the active center on boiling at this center.

We turn now from boiling on an individual center to boiling on a heating surface with a roughness prescribed by a particular range of values of R_n. The role of roughness in heat transfer becomes clear when we examine particular cases of the curves of bubble breakaway frequency (Fig. 1), as mentioned earlier.



Curves of bubble breakaway frequency as function of pressure for a given roughness of working surface and different values of the parameter t_σ (for water) (u, 1/sec; p, bar): 1) for parameter $R_n = 0.68 \cdot 10^{-5}$ m; 2) $R_n = 5 \cdot 10^{-5}$ m; a) $t_\sigma = 1°$; b) 5°; c) 10°.

On each of the three graphs two curves of u = u(p) are drawn for two values of R_n and the same superheat t_σ. Graphs a, b, and c differ only in the value of the parameter t_σ, which was 1°, 5°, and 10°, respectively.

We assume that the roughness of the heating surface is given by the range $R_n = (0.68-5) \cdot 10^{-5}$ m. The hatched area of each of the graphs is the locus of the curves u = u(p) for all values of R_n in this range. Since all these curves begin on the x-axis then a particular value of R_n is associated with each point of segment cd of this axis. The pressure p, determined by each point of segment cd, is the pressure boiling limit for the center of radius R_n associated with this point on the axis. Thus, segment cd is the locus of the pressure boiling limits for a roughness given by this range of R_n at a given t_σ.

Comparing Fig. 1a, b, c we note that, with increase in superheat t_σ, interval cd, in which the pressure boiling limits lie, is reduced in approximate proportion to the increase of t_σ and is shifted considerably into the region of lower values.

We can conclude from what has been said that the concept of roughness as a factor affecting boiling is very relative and depends on the conditions in which the process occurs. For instance, if the process takes place at a pressure p on the right of point d (see figure), then the surface can be regarded as ideally rough, since all the centers in the range $R_n = (0.68-5) \cdot 10^{-5}$ m can be active vapor-forming centers. On all the active centers the process will be developed and the breakaway frequencies will be almost the same. Its variation in relation to the radii of the individual centers depends on the segment ef (graphs a, b, c). The very small relative size of these segments provide a justification for formula (4), which neglects the effect of roughness on bubble breakaway frequency in developed boiling.

If the process occurs at a pressure p on the left of point c, then the same surface is ideally smooth, since none of the centers in the range $R_n = (0.68-5) \cdot 10^{-5}$ m can become active.

If the process occurs at a pressure somewhere within the interval cd we can speak of different degrees of roughness of the same heating surface depending on the position of the point a, which determines this pressure. The value of R_n corresponding to the point a is the limiting roughness, since only centers with radii lying in the interval ac can become active. Thus, the number z of active, vapor-forming centers depends on the position of point a. Equal shifts of point a cause a greater alteration of z, the higher the superheat t_σ, since interval cd decreases in proportion to the increase of t_σ (graphs a, b, c).

Thus, in its effect on the mechanism of boiling the heating surface passes through all degrees of roughness, from ideally smooth to ideally rough in the range of pressures cd, whose size and position on the axis depend on the superheat t_σ.

The bubble breakaway frequency u can vary from zero (point a) to a maximum (point b). The range of variation of u (segment ab) is proportional to the superheat t_σ.

NOTATION

R_n is the radius of vapor-forming center; R_{min} is the critical value of R_n; R_0 is the bubble breakaway radius; p is the absolute hydrostatic pressure near the vapor-forming center; t_σ is the superheat of liquid close to heating surface relative to saturation temperature at pressure p; u is the bubble breakaway frequency; γ' and γ'' are the specific gravities of liquid on saturation line and dry saturated vapor at pressure p; σ is the surface tension at bubble phase interface; θ is the bubble contact angle; $p' = dp/dt$ is the derivative of saturated vapor pressure with respect to temperature; z is the number of active vapor-forming centers.

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