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DEVELOPED BOILING HEAT TRANSFER

I. G. SHEKRILADZE
Scientific Research Institute of Stable Isotopes, Tbilisi, U.S.S.R.

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Abstract—In conformity with the heat transfer model considered, the developed boiling temperature conditions of the heating surface are mainly governed by the processes which are responsible for multiple start-ups of the different mechanisms of heat release. The analysis of the model yields a universal correlation for the developed boiling heat transfer on surfaces of known microgeometry and on commercial heating surfaces for all classes of heat transfer agents (water, organic liquids, cooling and cryogenic agents and liquid metals).

NOMENCLATURE

x, coordinate normal to the surface;
T, absolute temperature;
ΔT, $= \bar{T}_w - T_s$;
P, absolute pressure;
q, specific heat flux;
α, heat transfer coefficient;
λ, thermal conductivity;
ρ_0, effective radius of nucleation site (radius of the critical nucleus);
ν, kinematic viscosity;
c_p, heat capacity;
σ, surface tension;
r, heat of evaporation;
R_p, mean height of microscopic asperities of the heating surface;
ρ, density;
v, specific volume;
θ, contact angle of wetting;
β, apex angle of a conical recess;
R, radius of the conical recess mouth;
τ, time.

Subscripts
v, refers to vapour (quantities for liquid have no subscripts);
w, on the wall;
s, at saturation.

$$Nu = \frac{\alpha\rho_0}{\lambda}; \; K = \frac{q\rho_0^2 r\rho_v}{\sigma\lambda T_s};$$

$$Re^* = \frac{\sqrt{[P(v_v - v)]}\sigma T_s \rho c_p}{\nu(\rho_v r)^2}.$$

INTRODUCTION

ONE of the most important and reliably established features of developed boiling is the diversity of heat transfer mechanisms which participate at a time in cooling the heating surface. Among these are evaporative (microlayer) [1–2] and purely convective mechanisms of heat abstraction by the liquid phase of the medium, such as the bubbling [3–6], piston-like [7–9] and microcirculating (jet-like) [10–12] mechanisms. Another important and also well-established feature of the developed boiling process is the temperature behaviour of the heating surface being independent (at fixed pressure and heat flux) of the observed interphase flow patterns. Numerous experiments indicate that drastic changes in the pattern of mutual motion of liquid and vapour phases occurring, for example, as a result of a change in the strength of the field of body forces by several orders of magnitude or due to appreciable cooling of the bulk of liquid below the saturation temperature do not affect the heating surface temperature to any appreciable extent under the conditions of developed boiling. This conservatism of the heat transfer law as to variation in the contribution of different heat removal mechanisms suggests that in the process of developed boiling there is a mechanism which controls the total heat transfer and which, in the main, is independent of the interphase hydrodynamics parameters and relative contributions of separate heat removal mechanisms. In what follows, the analysis of the developed boiling heat transfer is based on the above starting premise with the use of the results of [13].

DEVELOPED BOILING HEAT TRANSFER MODEL

Consider the familiar typical case of the heating surface temperature time history in the local region of a separate nucleation site (curve a, Fig. 1). At the instant of time a the nucleus surface at this site surmounts the minimum curvature radius profile and the bubble commences to grow. The first stage of the bubble growth on the wall (a–b) is accompanied by a sharp and marked drop in the wall temperature. As the bubble grows further, the temperature increases and, on bubble departure, nearly regains its maximal level (b–c). This pattern of the wall temperature variation in time suggests a certain analogy between the temperature behaviour of the boiling surface and of the temperature-controlled object, the system of which provides for its cooling each time when the temperature of the object attains its specified upper limit because of internal heat release. In developed boiling, such an upper limit is the superheat $\Delta T'$ with the

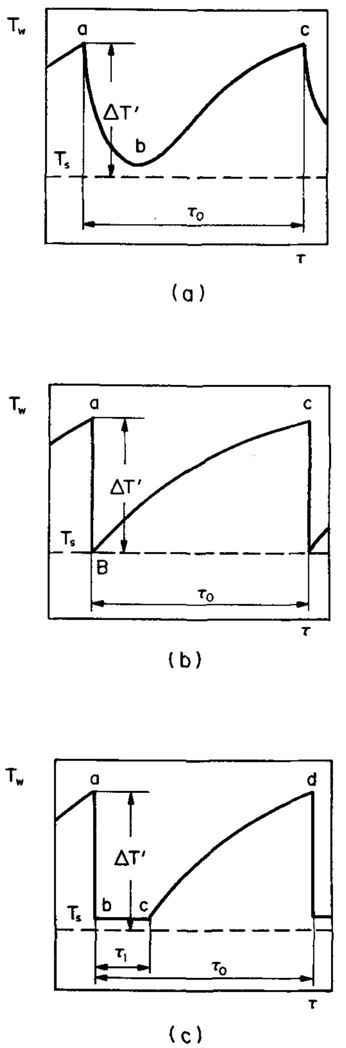

FIG. 1.

attainment of which (at time a) powerful mechanisms of heat removal come into action. It should be noted that there is an unambiguous evidence of the fact that, besides the microlayer mechanism [1], powerful purely convective mechanisms of heat removal by the liquid phase of the medium [12, 14] come into play on commencement of the bubble growth.

Correlation between the wall temperature history and the process of nucleation unequivocally indicates the existence of the 'system' which controls the start-up of heat removal mechanisms. In boiling, its part is played by thermodynamic conditions which are required for the bubble nucleus surface at the nucleation site to surmount the state with the minimum curvature radius and which determine the maximum superheat of the boiling surface. Further examination of the process requires introduction of certain initial ideas about the microgeometry of the surface of boiling.

The process of surface wetting by liquid, which starts on protruding portions of microrelief, spreads over the inner surfaces of recesses. It is not difficult to show that this process is accompanied by 'natural selection' of recesses which are more stable as nucleation sites and which are characterized by small apex angles, large depth, presence of microexpansions or any other physicochemical inhomogeneities that prevent complete wetting. Even if the overwhelming majority of the thousands of recesses available on each square millimetre of a commercial surface are wetted completely, the number of 'selected' recesses (those which have retained nuclei) will yet be more than sufficient for the most intensive regimes of developed boiling to become feasible. The data are also available on relatively small ranges of characteristic capillary dimensions for the bulk of the active nucleation sites [15]. According to what has been said above, the simplest idealized model of the commercial boiling surface can be represented as an assembly of an infinite number of identical conical recesses (having mouths of the same radius) with vapour phase nuclei inside.

The minimum curvature radius of the nucleus surface (effective radius of the nucleation site) for recesses which satisfy the condition

$$\tfrac{1}{2}\beta < \theta < 90^\circ \qquad (1)$$

is equal to the radius of the mouth of a recess [16]. It is not difficult to show that inequality (1) simultaneously determines the conditions of nuclei conservation in the process of boiling in nonoperating recesses. Hence, in the statement adopted, the quantity ρ_0, being equal to R both for active and potential nucleation sites, is the only characteristic of the boiling surface which influences the heat transfer rate. Then the analysis of the heat transfer rate can be reduced to determining the parameters of the wall temperature time dependence, on the average, for the whole region of action of one nucleation site.

FIRST APPROXIMATION

In the simplest form the problem of the wall temperature behaviour in time can be approximated by curve b of Fig. 1. This version of the curve presupposes an instantaneous drop in the wall temperature down to the temperature of saturation at the time of commencement of the bubble growth (instantaneous start-up and shut-down of intensive heat removal mechanisms) and further warming-up of the wall up to the moment of inception of the next bubble.

As is known, the superheat required for bubble nucleation in an isothermal region under equilibrium thermodynamic conditions [16] is determined by the relationship

$$\Delta T_0 = \frac{2\sigma T_s}{r\rho_0\rho_v}. \qquad (2)$$

Under the conditions of boiling the critical nucleus finds itself in the zone of a high temperature gradient and the wall superheat $\Delta T'$ required for the start of the nucleus growth is much above ΔT_0 [13, 17–18]. The unsteady-state process which is considered in the present paper is most in line with the case of liquid semispace warming-up at q = constant.

Solution of this problem [19], provided the initial temperature of the semispace is equal to T_s, acquires the form

$$T(x,\tau) - T_s = \frac{2q}{\lambda}\sqrt{a\tau}\,\mathrm{ierfc}\frac{x}{2\sqrt{a\tau}}. \qquad (3)$$

The mean wall superheat sought will accordingly be equal to

$$\Delta T = \frac{1}{\tau^*}\int_0^{\tau^*}[T(0,\tau) - T_s]\,\mathrm{d}\tau = \frac{2}{3\sqrt{\pi}}\frac{q}{\lambda}\sqrt{a\tau^*}. \qquad (4)$$

Written out in non-dimensional quantities this equation is

$$Nu = \frac{3\sqrt{\pi}}{2}\frac{\rho_0}{2\sqrt{a\tau^*}}. \qquad (5)$$

The time of the surface temperature growth is determined from the relation representing the superheat ΔT_0 attained by the temperature of the liquid in the layer $x \approx \rho_0$ for time τ^*

$$\frac{\rho_0}{2\sqrt{a\tau^*}}\,\frac{1}{\mathrm{ierfc}\dfrac{\rho_0}{2\sqrt{a\tau^*}}} = \frac{K}{2}. \qquad (6)$$

The results predicted by equations (5) and (6) are plotted in Fig. 2 in the coordinates $Nu = f(K)$. Also shown are the experimental data on mean heat transfer in boiling of nitrogen, water and sodium on stainless steel commercial heating surfaces of roughness grade 6 through 8 at atmospheric pressure [20–22] (in calculations it is assumed for the surface considered that $\rho_0 = 5\ \mu\mathrm{m}$). Correct analytical prediction of the order of magnitude of the boiling heat transfer coefficient for the above heat transfer agents essentially differing from one another in their properties provides support for the validity of the basic qualitative inference drawn from the analysis as to the effect on the boiling heat transfer rate of the number K which comprises the parameter of the heating surface microgeometry. As is known, the non-dimensional group K (with the departure diameter as a characteristic linear dimension) has been obtained for the first time in [4] as a result of using the laws governing thermodynamic equilibrium on the vapour bubble surface for description of the boiling process.

MEAN HEAT TRANSFER RATE

Mean heat transfer rate can be more accurately described by the wall temperature behaviour over the periphery of the region of action of the nucleation site, i.e. in the zone where the heat removal mechanisms induced by the bubble growth in the active nucleation site are capable of keeping other active recesses from operation. It is likely that in this zone the major role is to be played by the mechanisms of heat removal by the liquid phase of the medium.

The wall temperature behaviour in the peripheral zone can be approximated by curve c in Fig. 1. It is assumed that the period of action of the heat removal mechanisms can be represented by broken curve abc the equivalence of which to the real pattern of the process development can be ensured by suitably selecting the value of τ_1. The wall superheat in this period is considered to be small and its role in the time-average superheating is neglected. Segment cd characterizes the period of the wall warming-up. The maximum superheat in this case tends to $\Delta T'$ and may be approximated with it. The time-average superheat within the framework of the assumptions adopted will be equal to

$$\Delta T = \frac{1}{\tau_0}\int_{\tau_1}^{\tau_0}[T(0,\tau) - T_s]\,\mathrm{d}\tau \approx c_1\,\Delta T'\left(1 - \frac{\tau_1}{\tau_0}\right) \qquad (7)$$

where c_1 is the constant of the order of unity.

For the Nusselt number, equation (7) can be re-

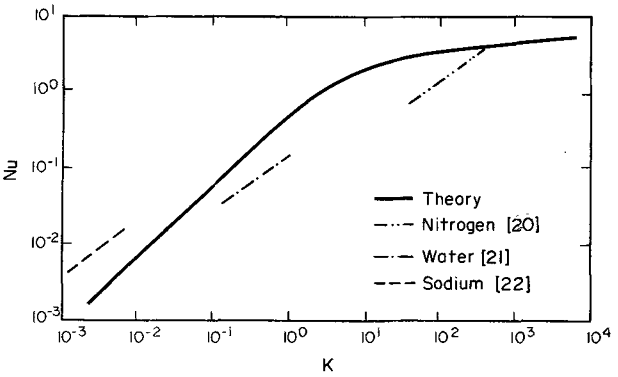

FIG. 2. Comparison of equations (5)–(6) with experimental data.

duced to the following functional relationship

$$Nu = f\left(K, \frac{\tau_1}{\tau_0}\right). \tag{8}$$

The ratio τ_1/τ_0 is determined by viscous dissipation of the energy of liquid motion continuing by inertia after its inception at the start of bubble growth. It is, therefore, the function of the appropriately specified Reynolds number. Accordingly, equation (8) will acquire the form

$$Nu = f(K, Re). \tag{9}$$

In the process of the growth of bubbles, the momentum is transferred to the liquid phase both along the normal and along the tangent to the phase interface [10–12]. Consequently, estimation of the intensity of motions occurring in the liquid phase based on the rate of growth of bubbles on the wall cannot be regarded as valid. In view of this, in the present study the characteristic mean velocity of motions appearing in the liquid phase is determined directly by the work of expansion of growing bubbles which is the main source of energy for all motions of the mass. It is presumed that the bubble exhibits the basic mixing effect on the liquid phase in the boundary layer at the first, most vigorous, 'explosive' stage of growth on the wall. This stage is assumed to correspond to the period of evaporation due to superheating of the liquid layer adjacent to the critical nucleus surface. At this stage, in view of exposure to substantial inertial effects of liquid directed to the wall, the bubble has the shape of a flattened semiellipsoid adjacent to the wall with the base area and the height (to the end of this period) equal to F and l, respectively. When the bubble starts to grow, the thickness and the superheat of the adjacent liquid layer are of the order of ρ_0 and $\Delta T'$, respectively. At this time, the bubble grows at the expense of the superheat of the layer covering the area F. The work done in this case by the bubble is

$$W = \frac{F\rho_0 c_p \Delta T' \rho}{r} P(v_v - v). \tag{10}$$

Assuming further that the mass of the agitated liquid is proportional to the mass of vapour formed at the stage considered, we shall obtain the following inequality for the characteristic liquid velocity sought

$$\bar{U} \sim c_2\sqrt{[P(v_v - v)]} \tag{11}$$

where the constant c_2 is much below unity.

In determining the Reynolds number for the characteristic linear dimension one should take the bubble size average with respect to the period of the effect on the boundary layer [23]. According to the model adopted, this period coincides with the first stage of bubble growth and the characteristic linear dimension can be estimated via the height of the first semiellipsoid attained to the end of this period. Since this dimension is of the order of the height of a cylinder with the same volume and base area and since, by equations (5) and (6)

$$\Delta T' = \Delta T_0 f_1(K)$$

we arrive at the characteristic dimension in which the kernel is the linear dimension first obtained in [4]

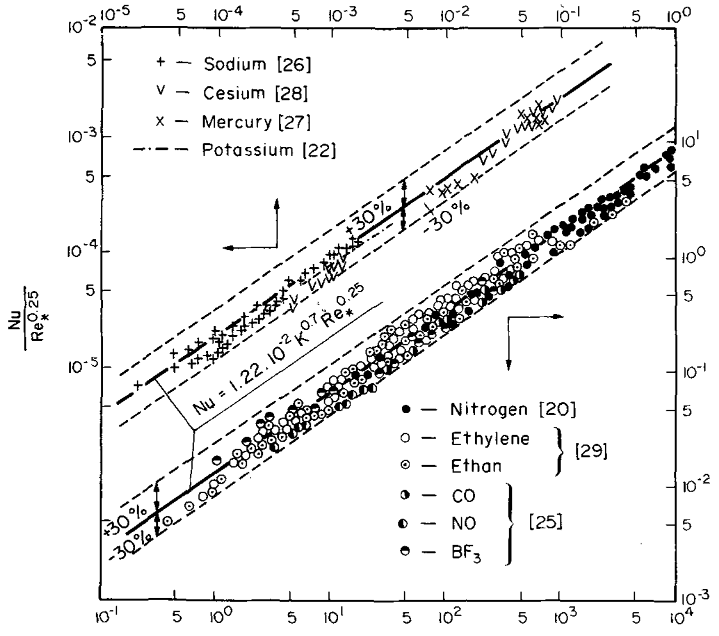

FIG. 3. Comparison of equation (14) with experimental data on heat transfer in developed boiling of liquid metals and cryogenic liquids on commercial heating surfaces.

$$l \sim \frac{F\rho_0 c_p \Delta T' \rho}{F r \rho_v} = \frac{\sigma T_s \rho c_p}{(\rho_v r)^2} f_1(K). \qquad (12)$$

Having discarded the constant c_2, we shall have the following expression for the Reynolds number which characterizes the scale for the time of action of convective heat removal mechanisms after their start-up, with equations (11) and (12) taken into account

$$Re = \frac{\sqrt{[P(v_v - v)] c_p \sigma \rho T_s}}{(r\rho_v)^2 v} f_1(K) = Re^* f_1(K). \qquad (13)$$

Comparison of the functional relation (9) with the experimental data on heat transfer in developed boiling of different liquids on stainless steel commercial heating surfaces leads to the equation of the following form suggested by the author and Ratiani [13]

$$Nu = 1.22 \times 10^{-2} K^{0.7} Re^{*0.25}. \qquad (14)$$

Figure 3 compares equation (14) with the experimental data on heat transfer in developed boiling on stainless steel commercial heating surfaces of highly different heat agents, i.e. liquid metals and cryogenic liquids. In correlating the experimental data, the same constant value of ρ_0, equal to 5 μm, was assigned to all of the commercial surfaces used in experiments.

The results presented in Fig. 3, with regard for the comparison [13] with the experiments on boiling of water, ethyl alcohol, benzol, diphenyl and a number of cooling agents on stainless steel commercial surfaces, allow a conclusion that equation (14) is an all-purpose generalizing relationship which describes heat transfer in developed boiling on a commercial heating surface of almost any one-component liquid in a wide range of saturation pressures.

Figure 4 compares equation (14) with the experimental data on developed boiling on the surfaces with the known values of ρ_0. In [15], water boiling took place on the surfaces with the active centres having the average value of ρ_0 equal approximately to 5 μm. The data on sodium boiling [24] have been taken for the surface with stable artificial centres having ρ_0 = 50 μm. Boiling of cooling agents [32] took place on the surface with numerous almost identical artificial centres of hexahedral cross-section with the radius of the circle inscribed equal to $\rho_0 = 86\,\mu$m. Taking into account a conspicuous difference in both the boiling media and the surfaces, the results of comparison can be regarded as very interesting. They allow a presumption that the approach suggested in the present paper is also good for interpretation of the boiling processes occurring on surfaces of different microgeometry. Furthermore, the comparison provides indirect support for the validity of estimation of commercial surfaces via the value of ρ_0 equal to 5 μm.

DISCUSSION OF RESULTS

The assumption that both the active and numerous potential vaporization centres contain the critical

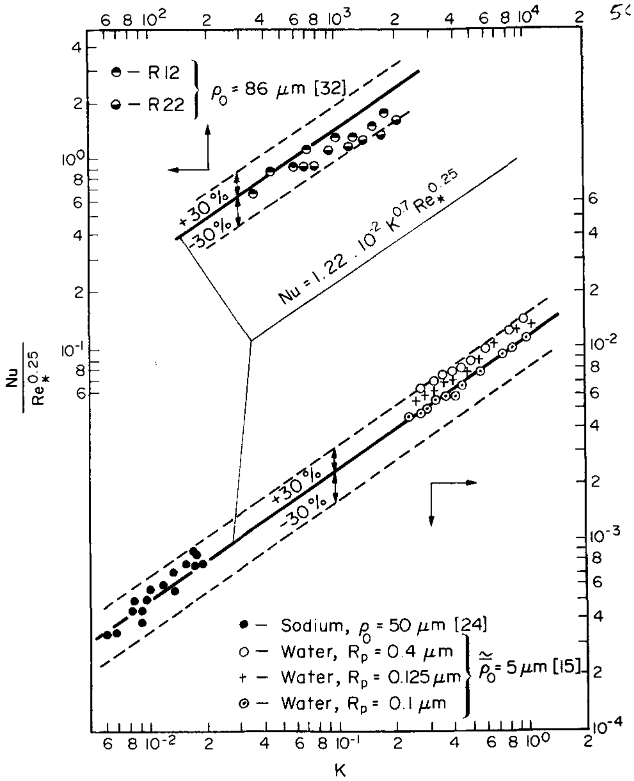

FIG. 4. Comparison of equation (14) with experimental data on heat transfer in developed boiling on the surfaces with the known values of ρ_0.

nuclei of about the same size has made it possible to describe the part played by the microgeometry of the heating wall—boiling medium interface in heat transfer enhancement by one parameter ρ_0 only. The results of the experimental data correlation appear to imply that in the majority of the developed boiling regimes this assumption rather adequately reflects the actual picture of the process. Besides, it is also apparent that within the framework of the proposed approach, much more complex combinations of characteristic dimensions and quantities of the active and potential sites can be chosen which would probably allow an interpretation of the diversity of heat transfer curves observed experimentally. This is qualitatively illustrated below with the heat transfer hysteresis used as an example.

In boiling of a perfectly wetting liquid ($\theta = 0$), condition (1) may not hold with the result that the parameter ρ_0 will become a function of the degree of liquid penetration into vaporization sites. It is easy to show that in this case the active centres will qualitatively differ from the potential ones. Since the transverse dimension of natural recesses becomes, as a rule, smaller down from the top, the formation of the first bubble in a potential centre (liquid displacement from the depth of the recess) requires a much higher superheat than generation of any one of the subsequent bubbles (associated with displacement of the liquid which only comes to wet the upper part of the recess after departure of the previous bubble). Consequently, under the conditions considered we have two highly differing levels of the parameter ρ_0, the one of order R in the active centres and the other, very low one, in potential centres. Transition of any one centre from the lower level to the upper one and the other way round may occur only at markedly differing wall superheats which, in fact, is the phenomenon of hysteresis. A different situation is to be observed on the heating surface the microgeometry of which provides the equality of ρ_0's of the active and potential centres even at $\theta = 0$. By the logic of our approach such a surface should not exhibit the heat transfer hysteresis. It seems that the above considerations can be illustrated by experimental data on the phenomenon of hysteresis during boiling of cryogenic liquids which manifest itself most vastly on rough surfaces and which is virtually absent on polished surfaces [30]. It is quite probable that many of the large recesses survive in the process of polishing with their mouths becoming polished only and contracted which provides stable equality of ρ_0 of such a centre to the radius of the mouth.

In addition, the results of the present work make it possible to postulate that the dependence of ρ_0 on the degree of liquid penetration into the centre forms also the foundation for the phenomenon of the effect of thermophysical properties of the wall on the heat transfer rate. It might be of interest to note that, similarly to hysteresis, this phenomenon in boiling of cryogenic liquid is also very appreciable on rough surfaces and almost negligible on polished ones [30–31].

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TRANSFERT THERMIQUE POUR UNE EBULLITION DEVELOPPEE

Résumé—En partant du modèle de transfert thermique considéré, les conditions d'ébullition développée pour une surface chauffée sont principalement gouvernées par les différents mécanismes d'arrachement de chaleur. L'analyse du modèle fournit une formule universelle pour le transfert thermique pendant l'ébullition développée sur des surfaces à microgéométrie connue et sur des surfaces commercialisées, pour toutes les catégories de fluides (eau, liquides organiques, agents réfrigérants et métaux liquides).

WÄRMEÜBERTRAGUNG BEIM AUSGEBILDETEN BLASENSIEDEN

Zusammenfassung—Übereinstimmend mit der betrachteten Modellvorstellung des Wärmeübergangs werden die Heizwandtemperaturen beim ausgebildeten Blasensieden besonders beeinflußt von dem wiederholten Einsetzen verschiedener Mechanismen der Wärmeabgage. Die Modellrechnung führt zu einer allgemeingültigen Gleichung für den Wärmeübergang beim Sieden an Oberflächen mit bekannten Oberflächeneigenschaften und an handelsüblichen Oberflächen. Die Gleichung gilt für Wasser, organische Flüssigkeiten, Kältemittel, Kryogene und flüssige Metalle.

ТЕПЛООБМЕН ПРИ РАЗВИТОМ КИПЕНИИ

Аннотация — Согласно рассматриваемой модели теплообмена температурный режим поверхности нагрева при развитом кипении в основном определяется процессами, управляющими многократными запусками различных механизмов теплоотвода. Анализ модели приводит к универсальной обобщающей зависимости, описывающей теплообмен при развитом кипении на технических поверхностях нагрева всех классов теплоносителей (воды, органических жидкостей, холодильных и криогенных агентов и жидких металлов).