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HYDRODYNAMIC FORMULATION FOR THE CHF IN BOILING THAT TAKES ACCOUNT OF WALL EFFECTS

L.G. Badratinova
Lavrentyev Institute of Hydrodynamics, Novosibirsk, Russia

The investigators of boiling report that values of the critical heat flux (CHF) are influenced by the heater properties such as the surface material, thickness, contamination, roughness, etc. Recently no theoretical basis exists to explain this dependence. The main aim of the present work is to show that the influence on the CHF of such characteristics as the material and thickness of the wall can be described in the framework of the hydrodynamic model.

In existing models and correlation for the CHF, one uses as the length scale the capillary length. One reason is that the Rayleigh-Taylor mechanism is assumed to be the dominating instability for a two-layer systems with the less dense phase lying below. We have formulated and studied several model problems of a stability of a motionless horizontal vapor-liquid layer heated from a bottom wall. Both phases were considered as incompressible viscous fluids, the heat transfer was described by equations of thermal conductivity. At the phase change boundary, a local thermodynamic equilibrium condition was imposed. In the undisturbed motionless state of the system, the plane interface is at saturation temperature.

All results presented below were obtained by examining a long wave approximation for general neutral stability conditions. When the wall is of zero thickness, considered were two kind of thermal conditions: the wall is at constant heat flux and the wall is at constant temperature. The results will be presented parallel. All groups and characteristic lengths referring to the first thermal condition will be denoted by the subscripts 'q' , while those for the second condition - by the subscript 'T'. If the upper liquid layer has an infinite height, the Rayleigh-Taylor instability is not the dominating mechanism when values of the groups

$$G_q = (\rho-\rho_l)\sigma_0\, g d_l^4/(\rho_l^2 \nu_l^2 k^2)\,, \qquad G_T = (\rho-\rho_l) g d_l^3/(\rho_l \nu_l k) \tag{1}$$

are sufficiently small. The parameter g and σ_0 are the gravity acceleration and the surface tension coefficient at the saturation temperature; ρ , k and ν are respectively the density, the heat and viscose diffusivity coefficients, d_l is a vapor layer thickness. Everywhere in this work. the subscript '1' refers to the vapor phase. The criteria (1) have been derived under the assumptions: $k_l \geq k$ and $16\,\rho\,\nu\, k/(\sigma_0 d_l) << 1$. At the limit $G_q \to 0$, the critical dimensional wave length of perturbation unlimitedly grows. At small values of the group G_T, an absolute (linear) stability takes place if only the transferred heat flux is not very small. The Rayleigh-Taylor instability is replaced due to a stabilizing influence of the phase change occurring at the disturbed interface. The criteria G_q , G_T can be written in the form: $G_q = (d_l/\delta_q)^4$, $G_T = (d_l/\delta_T)^3$ where δ_q , δ_T are the following characteristic lengths

$$\delta_q = (\rho_l \ v_l \ k)^{1/2} [(\rho-\rho_l)\sigma_0 g]^{-1/4}, \qquad \delta_T = (\rho_l \ v_l \ k)^{1/3} [(\rho-\rho_l) g]^{-1/3} .$$

When the assumption $16 \ \rho \ v \ k/(\sigma_0 d_l) \ll 1$ is omitted, the replacement of the Rayleigh-Taylor instability cannot be described in terms of the groups G_q , G_T only; for each kind of the thermal condition at the wall, one more criterion appears which characterizes the liquid viscosity influence. These criteria are ($D = \sigma_0^{1/2} [(\rho-\rho_l) g]^{-1/2}$ is the capillary length):

$$V_q = \rho v \delta_q /(\rho_l v_l D) = \rho v k^{1/2} (\rho_l v_l)^{-1/2} [(\rho-\rho_l) g]^{1/4} \sigma_0^{-3/4}$$

$$V_T = \rho v \delta_T /(\rho_l v_l D) = \rho v k^{1/3} (\rho_l v_l)^{-2/3} [(\rho-\rho_l) g]^{1/6} \sigma_0^{-1/2} .$$

When the bottom wall has non zero thickness, at the solid-vapor interface except of no-slip, the temperature and the heat flux continuities conditions were assumed to be hold. The heat transfer in the wall was described by usual thermal conductivity equation, without any heat sources. At the lower wall boundary, a constant heat flux or a constant temperature were assumed to be sustained; for the first (second) case the replacement of the Rayleigh-Taylor instability is described by the following three groups: G_q , V_q and W_q (G_T , V_T and W_T). The groups W_q and W_T describing an influence of the wall effect are

$$W_q = (\lambda_w/\lambda_l)(\Delta_w/D) = \lambda_w \lambda_l^{-1} \Delta_w [(\rho-\rho_l)g]^{1/2} \sigma_0^{-1/2}$$

$$W_T = (\lambda_l/\lambda_W)(\Delta_w/\delta_T) = \lambda_w^{-1} \lambda_l \Delta_w (\rho_l \ v_l \ k)^{-1/3} [(\rho-\rho_l) g]^{1/3}$$

In case of finite liquid depth, conditions imposed on an upper boundary of the liquid are those as if it were a solid plate kept at a constant temperature, an influence of the liquid depth d has found to be described by the ratio d/D.

The similarity criteria G_q and G_T determine a thickness $d_{l\,q}$ and $d_{l\,T}$ at which the gravity influence on the stability begin to decay. For $d < d_{l\,q}$, correspondingly for $d < d_{l\,T}$, the viscous diffusivity of the vapor and the heat diffusivity of the liquid become dominating effects. It has been shown that the liquid viscosity (assumption that $V_q > 0$, correspondingly, $V_T > 0$) reduces the thickness $d_{l\,q}$, correspondingly $d_{l\,T}$. In the case of non-zero wall thickness where the thermal perturbations penetrate into the wall, the critical thickness $d_{l\,q}$ as well as $d_{l\,T}$ is also reduced with respect to that obtained in the case $W_q = 0$ or $W_T = 0$

respectively. Hence, the critical heights of the vapor layer can be presented as follows: $d_{l\,q} = \delta_q\ F_q\,(V_q\ ,\ W_q,\ \ d/D\ )$ and $d_{l\,T} = \delta_T\ F_T\,(V_T\ ,\ W_T\ ,\ \ d/D\ )$ where F_q is the function of the parameters V_q , W_q , d/D and F_T - of the parameters V_T , W_T , d/D. The function F_q (F_T) decreases with increasing the parameters V_q , W_q $(V_T\ ,\ W_T)$.

The depths $d_{l\,q}$ and $d_{l\,T}$ depend upon the physical parameters of liquid, vapor, the gravity acceleration and in case of non-zero wall thickness upon the material and thickness of wall. We use them correspondingly as the characteristic thickness of a diffusive thermal boundary layer in two different steady state regimes of boiling: developed nucleate (the controlled parameter is the heat flux) and transition boiling (the controlled parameter is the temperature). Presently, it is experimentally proven that all variables (including the wall characteristics) affecting the nucleate boiling affect also transition boiling, and that the transition regime is also characterized by existence of a two phase flow near the wall. Our results show that developed nucleate and transition boiling should be theoretically considered as two regimes that differ each from other by the main similarity criteria.

The nucleate boiling regime exists only if the maintained heat flux is less than a certain critical value at which the heat transfer crisis occurs: a sudden large jump of the surface temperature resulting from a total covering of the surface by a vapor film. A dimensionless criterion $N = q\rho_l^{-1/2}L^{-1}[(\rho\text{-}\rho_l)\sigma_0 g]^{-1/4}$ determining the crisis of boiling heat transfer was first obtained by Kutateladze [1] through correlation of experimental data and similitude analysis of momentum and energy equations for liquid and vapor. In his analysis phases were assumed inviscid fluids and the capillary length was used as characteristic one. We formulate the boiling crisis as suggested by Kutateladze: the crisis of boiling heat transfer occurs in a consequence of a destruction of a hydrodynamic structure of two-phase flow existing close to the heating wall. But we obtain the criterion by Kutateladze with the help of the dimensionless groups revealed from the studied stability problems in which account was made for the viscosity of fluids and for the thermal condition at the wall. For those liquid-vapor systems for which the ratio $\nu_l\,/\,k$ is large, the formula $H_q = (\nu_l\,/\,k)^{1/2}\,d_{l\,q} = (\nu_l\,/\,k)^{1/2}\,\delta_q\ F_q\,(V_q\ ,\ W_q\ ,\ d/D\ )$ defines a thickness of an intermediate region of the two-phase boundary layer, in which the vapor viscosity is still dominating effect, while the liquid thermal diffusivity does dominate only in its sublayer of the thickness $d_{l\,q}$. The intermediate region is affected by both the properties of the heater and by the characteristic of the outer flow. In general, the function F_q should depend more than on the three parameters (revealed here). Assuming evaporation in the viscous boundary layer provides the heat transfer from the wall, a characteristic velocity of vapor rising flow is $V_l = q/(\rho_l L)$ where L is the latent heat of vaporization and q is the transferred heat flux. We introduce the Reynolds number for vapor rising flow $Re_l = V_l H_q / \nu_l$ and find that it is exactly proportional to the criterion N by Kutateladze: $Re_l = q\rho_l^{-1/2} L^{-1} [(\rho - \rho_l)\sigma_0 g]^{-1/4} F_q(V_q, W_q, d/D)$. Assuming that the destruction occurs at $Re = Re_{cr}$ where Re_{cr} is constant ($Re_{cr} = C$) , we obtain for the maximum heat flux q_{cr} on flat plates the formula: $q_{cr} = C\rho_l^{1/2} L[(\rho - \rho_l)\sigma_0 g]^{1/4} F_q^{-1} (V_q, W_q, d/D)$ which extends the formula by Kutateladze to the case of viscous liquids and to the case when the heat flux is maintained not exactly at the solid surface, but inside the heated wall. From existing boiling experiments it is known that the liquid viscosity effect enhances the CHF and that so does also the heater thickness. The enhancement occurs in a consequence of the decrease of the thickness of the intermediate region, predicted here from the analysis of the model problems. Note, that without the wall and the liquid viscosity effects, the described here formulation was made in [2]. Note also, for $\nu_l / k < 1$ the above consideration is impossible. Probably, the formula by Kutateladze is not valid in this case.

Conclusions

The dimensionless groups have been found that determine the influence on the CHF of the viscous effects and of the wall thickness. Distinction of fully developed nucleate boiling from steady state transition boiling is explained through distinction of the main similarity criteria of these two regimes: G_q , G_T ; V_q , V_T and W_q , W_T. All criteria characterizing a state of the near-wall region are gravity dependent. The criteria G_T, W_T for steady state transition boiling are independent of the surface tension.

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