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Boiling crisis and non-equilibrium drying transition

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Abstract. – Boiling crisis is the rapid formation of the quasi-continuous vapor film between the heater and the liquid when the heat supply exceeds a critical value. We propose a mechanism for the boiling crisis that is based on the spreading of the dry spot under a vapor bubble. The spreading is initiated by the vapor recoil force, a force coming from the liquid evaporation into the bubble. Since the evaporation intensity increases sharply near the triple contact line, the influence of the vapor recoil can be described as a change of the apparent contact angle. Therefore, for the most usual case of complete wetting of the heating surface by the liquid, the boiling crisis can be understood as a drying transition from complete to partial wetting.

The state of nucleate boiling, which is boiling in its usual sense, is characterized by a very large rate of heat transfer from the heating surface to the bulk because the superheated liquid is carried away from the heating surface by the departing vapor bubbles. If the heating power is increased, the temperature of the heating surface increases with the heat flux. When the heat flux from the heater reaches a threshold value q_{CHF} (the critical heat flux, CHF), the vapor bubbles suddenly form a film which covers the heating surface and insulates the latter from the bulk of the liquid. The temperature of the heating surface grows so rapidly that the heater can fuse unless its power is controlled. This phenomenon is known under the names of “boiling crisis,” “burnout,” or “Departure from Nucleate Boiling” (DNB) [1]. The final state of this transition is called film boiling.

This problem has become very important since the 1940’s, with the beginning of the industrial exploitation of heat exchangers with large heat fluxes (as with nuclear power stations). Since then a huge amount of research has been done for the various conditions of pool boiling (boiling without imposed external flow) and flow boiling (boiling of the flowing water) [2]. Numerous empirical correlations have been proposed, each describing the dependence of the CHF on the physical parameters of the liquid and of the heater more or less correctly for a particular geometry and particular conditions of boiling [2]. A strong dependence of the threshold on the details of the experimental setup coupled with difficulties in separating the consequences of DNB from its causes is at the origin of a large number of frequently controversial hypotheses [2]. The violence of boiling makes observations quite difficult. Good quality photographic experiments are presented in only a few articles (see e.g. [3] – [6]). Despite an increasing interest in the physical aspect of the problem during recent years [7,8] and numerous empirical approaches, the underlying physics still remains obscure. In this Letter, we propose a model based on a non-equilibrium drying transition.

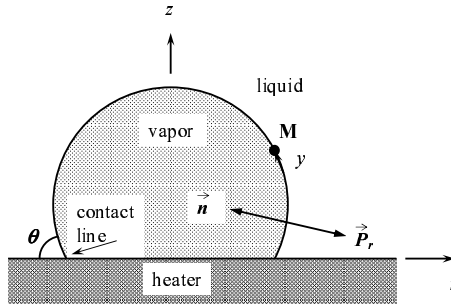


Fig. 1 – Vapor bubble on the heating surface surrounded by liquid. The directions of the vectors \vec{P}_r and \vec{n} are shown as well as the axes for the cylindrical coordinate system.

DNB is a really universal phenomenon which occurs inevitably for pool as well as for flow boiling and for different flow structures, flow velocities, liquid temperatures and pressures. Apparently, the occurrence of the crisis does not induce any change in the flow. The phenomenon is local [9]: it depends strongly only on the local values of the parameters in a very thin layer of liquid adjacent to the heating surface. This layer is nearly quiescent because of the no-slip boundary condition for the fluid velocity at the heating surface. It is thus unreasonable to assume different physical causes for DNB according to the different conditions of pool or flow boiling, and we think that the crisis should be induced by the *same physical phenomenon*. The occurrence of DNB is influenced by the local values of only a few parameters, the most important being the distribution of the local temperature. As a consequence of the local origin of DNB, the threshold depends strongly on the wetting properties of the heating surface. *A priori*, it is quite difficult to extract the dependence of the CHF on the parameters of the heating surface because even a minor modification of its chemical composition can cause a large change in its thermal resistance which controls the temperature distribution and, hence, DNB itself. However, numerous experiments [2,10] show the general tendency: a poor wetting of the heating surface by the liquid favors the DNB and vice-versa.

The experiments [4,6] in visualization of dry spots under the vapor bubbles on the heating surface show that at the CHF a *single* dry spot suddenly begins to spread. However, its size at the CHF remains finite. These experiments show that the bubble coalescence on the heating surface is not the leading process. In [7, 11, 12] the vapor recoil instability [13] is proposed as a reason for DNB. Although it is not clear how an instability can induce the spreading of the dry spots, the authors show that the vapor recoil force can be important at large evaporation rates. The force originates in the uncompensated momentum of vapor which is generated on the liquid-vapor interface during the evaporation. In the reference frame of the bulk liquid, the momentum conservation implies

$$\vec{P}_r + \eta(\vec{v}_V + \vec{v}_i) = 0, \quad (1)$$

where \vec{P}_r is the vapor recoil force per unit interface area, η is the evaporated mass per unit time and unit interface area, \vec{v}_i is the interface velocity, and \vec{v}_V is the vapor velocity with respect to the interface. It is easy to establish that $\vec{v}_i = -\eta/\rho_L \vec{n}$, where \vec{n} is a unit vector normal to the interface directed inside the vapor bubble (Fig. 1). The mass conservation on the interface yields $\vec{v}_V = -\rho_L/\rho_V \vec{v}_i$, where ρ_L and ρ_V are the mass densities of the liquid and the vapor. Therefore, (1) implies [13]

$$\vec{P}_r = -\eta^2(\rho_V^{-1} - \rho_L^{-1})\vec{n}. \quad (2)$$

The surface deformation caused by this force is important whenever the evaporation is strong, e. g. during high-power welding [14] or for evaporation at low pressures [13].

The rate of evaporation η can be related to the local heat flux across the interface q_L by the equality

$$q_L = H\eta, \quad (3)$$

where H is the latent heat of evaporation. Hereafter, we neglect heat conduction in the vapor with respect to the latent heat effect.

Below, we treat only the case of system at high pressure, comparable to the critical pressure for sake of simplicity. Then the growth of the bubble is slow enough to let the surface tension equilibrate its shape, and the forces of hydrodynamic origin can be neglected [1]. This allows the problem to be considered in the quasi-static approximation. However, the vapor recoil remains the leading effect for any pressure.

The spreading of the dry spot looks similar to the spreading of a liquid that wets a solid. But in the case of DNB, it is *vapor* which seems to “wet” the solid. This never happens for a non-metal liquid under equilibrium conditions (zero heat flux) on a perfectly clean and smooth metal surface [15], the finite contact angle being possible due to the surface defects only. We show below that a kind of drying transition occurs due to the vapor recoil force at some heat flux that we associate with the CHF.

Using the quasi-static approximation, the variational approach [16] can be applied to analyze the shape of a vapor bubble just before the boiling crisis. The free energy of the system consists of two parts. The first part is conventional [16]

$$U_1 = \sigma A + \sigma_{VS}A_{VS} + \sigma_{LS}A_{LS} - \lambda V, \quad (4)$$

where σ , σ_{VS} , and σ_{LS} are the surface tensions for vapor-liquid, vapor-solid and liquid-solid interfaces respectively; A_{VS} and A_{LS} are the corresponding interface areas; and A is the area of the vapor-liquid interface (Fig. 1). The last term in (4) reflects the fact that the shape of the bubble should be found for its given volume V , λ being the Lagrange multiplier. The equation $\delta U_1 = 0$ where δU_1 is the energy change due to an infinitesimal displacement $\delta \vec{r}$ of A [16] yields the classical conditions of the bubble equilibrium in the absence of the external forces.

The second part U_2 of the free energy accounts for the virtual work of the external forces:

$$\delta U_2 = - \int_{(A)} \vec{P}_r \cdot \delta \vec{r} \, dA. \quad (5)$$

The minimization $\delta U_1 + \delta U_2 = 0$ of the total energy leads [16] to two equations. The first is the condition for local equilibrium of the interface

$$K\sigma = \lambda + P_r, \quad (6)$$

where K is the local curvature of the bubble and $P_r = |\vec{P}_r|$. The second equation is $\cos \theta = c$, where $c = (\sigma_{VS} - \sigma_{LS})/\sigma$ and θ is the contact angle (Fig. 1). For the case $c > 1$ (as for the case of water on metal surface) the second equation should be substituted by the condition $\theta = 0$.

Let us denote by y the distance along the bubble contour measured from the triple line to a given point M as shown in Fig. 1. To find the bubble shape by solving Eq. (6) we need to know the vapor recoil as a function of y . In the following, we introduce a rough approximation to solve the very complicated problem of the heat exchange around the growing bubble. The case

of saturated boiling is assumed. Thus the vapor-liquid interface is maintained at temperature T_s , the saturation temperature at the system pressure. We also assume for simplicity that the thermal effect of convection can be taken into account by renormalizing the liquid thermal conductivity. To estimate how P_r varies near the contact line (i.e. when $y \rightarrow 0$) we suppose the bubble to be two-dimensional with the contact angle $\theta = \pi/2$. Since we describe the heat exchange in a thin layer adjacent to the heating surface, we can imagine the bubble contour A to be a line Oy perpendicular to the Ox heater line. Then q_L can be obtained from the solution of a simple two-dimensional problem of unsteady heat conduction in a quarter plane $x, y > 0$, the point $O(x = 0, y = 0)$ corresponding to the contact line. The boundary and the initial conditions for this problem can be written in the form

$$T_L|_{x=0} = T_s, \quad -k_L \left. \frac{\partial T_L}{\partial y} \right|_{y=0} = q_S, \quad T_L|_{t=0} = T_s,$$

where $T_L(x, y, t)$ is the liquid temperature, k_L is the liquid thermal conductivity, and q_S is the heat flux from the heating surface which is assumed to be uniform for the case of the thin heating wall. The solution for this problem of heat conduction reads

$$T_L = T_s + \frac{q_S}{k_L} \sqrt{\frac{\alpha_L}{\pi}} \int_0^t \frac{dt}{\sqrt{t}} \operatorname{erf} \left(\frac{x}{2\sqrt{\alpha_L t}} \right) \exp \left(-\frac{y^2}{4\alpha_L t} \right), \quad (7)$$

where α_L is the liquid thermal diffusivity. This solution implies the following expression for $q_L(y)$:

$$q_L = -k_L \left. \frac{\partial T_L}{\partial x} \right|_{x=0} = -\frac{q_S}{\pi} E_1 \left(\frac{y^2}{4\alpha_L t} \right). \quad (8)$$

The exponential integral $E_1(y)$ [18] decreases as $\exp(-y)/y$ as $y \rightarrow \infty$. Therefore P_r (related to q_L via (2) and (3)) is a rapidly decreasing function of y . Note that $E_1(y)$ diverges logarithmically at the point $y = 0$. The divergence demonstrates that the evaporation is strongest in the vicinity of the contact line. Since this singularity is integrable, the heat flux through any finite part of the interface is finite.

In the following we will use for illustration the dependence $P_r(y)$ in the form that retains the main physical features

$$P_r = -C \log(y/L) \exp[-(y/y_r)^2], \quad (9)$$

where L is the length of the half-contour of the 3D axially symmetrical bubble. The coordinate y is measured along the contour from the triple line as shown in Fig. 1. The characteristic length of the vapor recoil decay y_r changes in time and is proportional to $\sqrt{\alpha_L t}$ (cf. (8)). Meanwhile, the bubble grows and its radius is proportional to the same factor [1] during the late stages of its growth. Therefore, y_r is proportional to the bubble size, this fact is taken care of by the expression $y_r = aL$, where a is the non-dimensional fraction of the bubble surface on which the vapor recoil is important. From the physical point of view, y_r characterizes the width of the superheated layer of liquid, which is always less than the bubble size [1], thus $a \ll 1$. This allows the upper limit of integration to be put to infinity in the following expression for the non-dimensional strength of the vapor recoil

$$N_r = \frac{1}{\sigma} \int_0^\infty P_r dy. \quad (10)$$

The integration can be performed analytically yielding the relation between C and N_r : $N_r = CaL/(4\sigma)\sqrt{\pi}[\gamma + \log(4/a^2)]$, where $\gamma = 0.577\dots$ is Euler's number [18].

To estimate N_r at CHF when the radius of the dry spot is of the order of the radius of the drop R we assume that heat is transferred to the fluid only through the belt of the width y_r at the foot of bubbles. Then $q_S \sim 2\pi R y_r n_b q_L$, where n_b is a number of the bubbles per unit interface area of the heater. At CHF a large part of the heater is covered by the bubbles, we assume it to be 50% for the estimation: $n_b \pi R^2 \sim 0.5$. Then we obtain $q_L \sim q_S/a$ using $y_r \sim aR$. Since $N_r \sim q_L^2 y_r / (H^2 \rho_V \sigma) \sim q_S^2 R / (a H^2 \rho_V \sigma)$, the estimate gives $N_r \sim 1$ for $a \sim 0.01$ (usual for large bubbles, see [19]) and for the parameters characteristic for water at high pressures: $R \sim 1\text{mm}$, $q_S = q_{CHF} \sim 1\text{MW/m}^2$, $H \sim 1\text{MJ/kg}$, $\rho_V \sim 10\text{kg/m}^3$, and $\sigma \sim 10^{-2}\text{N/m}$.

Using the cylindrical $r - z$ system of coordinates (see Fig. 1), (6) can be written in parametric form as a system of three ordinary differential equations:

$$dr/dy = \cos u, \quad (11)$$

$$dz/dy = \sin u, \quad (12)$$

$$du/dy = -(\sin u)/r + \lambda + P_r(y) \quad (13)$$

with the boundary conditions

$$z = 0, \quad u = \theta \quad \text{at} \quad y = 0; \quad r = 0, \quad u = \pi \quad \text{at} \quad y = L. \quad (14)$$

The 4th condition is necessary to determine the unknown L . The mathematical problem is completed by the equation, which allows the Lagrange multiplier λ to be determined:

$$V = \pi \int_0^L r^2 \sin u \, dy, \quad (15)$$

where V is the given bubble volume. In the following, the case of the water on metal heater is considered, $\theta = 0$.

The solution of the problem (9 – 15) is presented in Fig. 2. Note that although the actual contact angle is zero for all of the curves (see the insert), the apparent contact angle grows with $N_r \propto q_S^2$. At small values of q_S the dry spot under the bubble corresponds to the size of the vapor bubble nucleation spot (assumed to be zero for the calculations of Fig. 2). The bubble grows with its contact line pinned at the defects on the surface of the heater until bubble departure under action of gravity or external hydrodynamic forces. The departure size of the bubble is small because the adhesion (which is proportional to the contact line length [17]) is small. At some value of q_S the contact line can depin under action of the vapor recoil before the bubble detaches from the heating surface. Fig. 2 shows that the dry spot reaches the size equal to the bubble diameter at $N_r \sim 1$, the value that compares well with our estimation. The adhesion force increases with the increase of the dry spot thus hindering the bubble departure. The departure time (the time interval during which the bubble is attached to the heating surface) grows sharply. We think that this feedback is at the origin of the DNB, with this value of q_S to be associated with q_{CHF} .

There are two additional mechanisms of the dry spot growth. Each of them starts to act when the size of the dry spot attains some critical value. First, when the dry spot becomes larger than the characteristic heat diffusion length of the solid, the temperature of the dry spot increases faster than the temperature of the wetted surface. Second, as the apparent contact angle reaches 90° , the coalescence of bubbles on the heating surface increases rapidly,

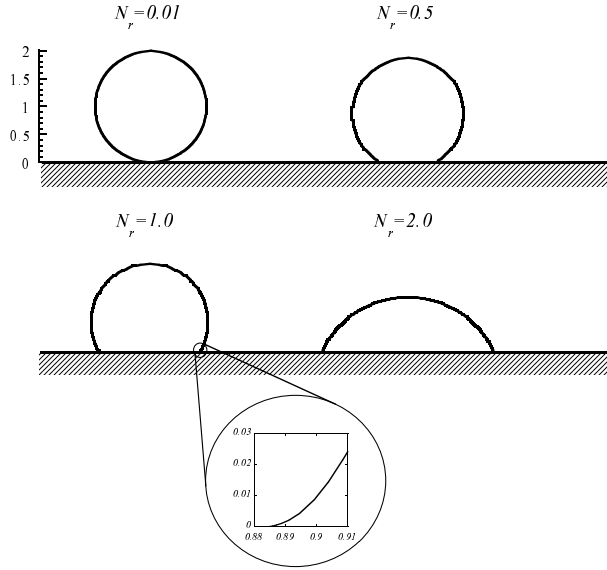


Fig. 2 – Shape of the 3D axisymmetrical vapor bubble on the heating surface under action of the vapor recoil force calculated for $a = 0.01$ (see text). The volume V is the same for all bubbles. The actual contact angle is zero as demonstrated in the insert. The coordinates are scaled by $(3V/4\pi)^{1/3}$.

which causes further spreading of the dry spot. As soon as the critical size of the dry spot is reached due to vapor recoil, these two effects increase the temperature in the vicinity of the bubble thus enhancing vapor recoil and providing a feedback.

For poor wetting conditions the smaller value of the vapor recoil (and q_{CHF}) is needed to create a large dry spot. This explains the decrease of q_{CHF} with the increase of the contact angle and surface roughness [10].

In this Letter we have proposed a mechanism for the boiling crisis based on a transition from complete to partial wetting of the heating surface as due to a vapor recoil force. Unfortunately, it is quite difficult to obtain the analytical form of the DNB criterion only from the above considerations. They can be helpful, however, for future numerical simulations that take into account more realistic temperature distributions, the balance between adhesion and lift-off forces, and the changing bubble shape. This model makes the departure time be the crucial parameter that should increase rapidly near the crisis. Unfortunately, such experimental studies are not available.

It is clear now why vapor recoil can be the triggering phenomenon for the boiling crisis under various conditions of boiling. Providing that the vapor recoil force operates in a very thin belt at the base of the bubble, the change in the bubble shape can be accounted for by a change in an apparent contact angle controlled by the vapor recoil force. Another interesting result is the possibility to change the size of the dry spot under the bubble while the actual contact angle remains zero.

* * *

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