Boiling Crisis as a Non-Equilibrium Drying Transition

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Abstract

The boiling crisis is the formation of a vapor film between the heater and the liquid when the heat supply exceeds a critical value, called the Critical Heat Flux (CHF). 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 uncompensated mechanical momentum of the fluid molecules being evaporated into the bubble. Since the evaporation intensity increases sharply near the triple (gas-liquid-solid) contact line, the influence of the vapor recoil can be interpreted in terms of an increase of the apparent contact angle. As the vapor recoil force is always directed towards the liquid side, it increases the dry spot under a bubble. Therefore, for the usual case of complete wetting of the heating surface by the liquid, the boiling crisis can be understood as an out of equilibrium drying transition from complete to partial wetting. The value of the CHF should be close to that defined by the equality of the contributions of the vapor recoil and the surface tension. We present the results of a 2D numerical simulation of the bubble growth at high system pressure when the bubble is assumed to grow slowly, its shape being defined by the surface tension and the vapor recoil force. The numerical results confirm this physical mechanism of the boiling crisis. Near the gas-liquid critical point for the given fluid, the bubble growth is very slow and we observed experimentally the increase of the apparent contact angle.

Key words: Boiling, bubble growth, CHF, contact angle, recoil force

1 Introduction

Despite the large number of articles related to boiling in the leading research journals each year, the origin of the boiling crisis remains yet to establish. In this article we present our view of this problem.

The boiling curve in the coordinates heat supply – heater temperature is sketched in Fig. 1 for the case of stationary boiling experiment, the so called "pool boiling". When the heat supply to the fluid pool is small, only a fluid convection can be

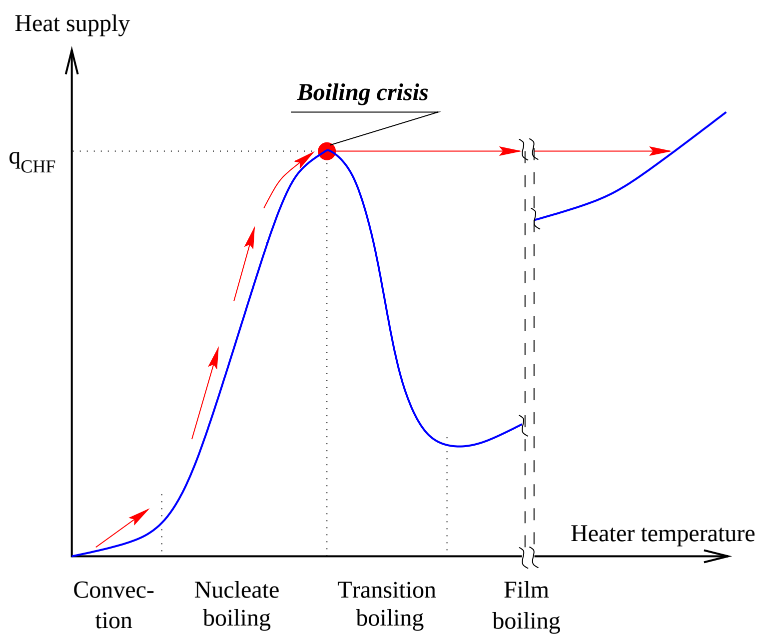

Figure 1: A sketch of the boiling curve.

observed. At a larger heat flux one can observe the well studied regime of the nucleate boiling, boiling in its usual sense. The heat transfer from the heater to the liquid can be characterized by the slope of the boiling curve. In this regime the heat transfer rate is very large due to both the phase change (latent heat of evaporation) and the fact that 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 exceeds a critical value (the Critical Heat Flux, q_{CHF}), the vapor bubbles on the heating surface abruptly form a film that thermally insulates the heater from the liquid. In other words, the heater dries out. The heat transfer is blocked and the temperature of the heater rapidly grows. This phenomenon is known under the names of "boiling crisis," "burnout," or "Departure from Nucleate Boiling" (DNB) [1]. Because the DNB is very rapid under usual conditions, the correct CHF estimation requires a clear understanding of the physical phenomenon that triggers it. Numerous models were proposed, so that completely different mechanisms are assumed to be responsible for the different regimes of boiling (pool or flow boiling, bubble or slug regimes of flow, degree of underheating of the bulk fluid, different system pressures or heater geometries, etc.). The underlying hypotheses for these models are frequently controversial. In addition, many of these hypotheses are hardly justified. An excellent discussion and classification of the existing CHF models can be found in the recent works [2] and [3]. This situation is closely related to the experimental difficulties with the observations of the boiling crisis. For reasons of industrial importance, the most common boiling experiments are carried out in Earth gravity at low (atmospheric) system pressures as compared to the critical pressure of the given fluid. The CHF value is large for these low pressures. The violence of boiling at large heat fluxes makes observations very difficult. However, several important features of the boiling crisis that can help to understand the underlying physics have nevertheless been firmly established. The most important among them is the local nature of DNB. It begins in a thin layer of liquid adjacent to the heating surface at a definite spot. This layer is nearly quiescent because of the no-slip boundary condition for the fluid velocity at the heating surface. We believe it is unnecessary to assume different physical causes for DNB according to the different conditions or regimes of boiling, and that the crisis should be induced by the *same physical phenomenon* [4]. The occurrence of DNB is influenced by the values of only a few parameters of this thin layer, the most important being the wetting conditions [5] and the distribution of temperature. The exact value of q_{CHF}, however, does depend on the particular conditions of boiling because these conditions influence strongly the temperature and other parameters of the thin fluid layer adjacent to the heating surface.

There are two possible scenarios for the beginning of the heater drying. Either the dry spot under a vapor bubble begins to grow or many neighboring bubbles begin to coalesce thus creating a growing dry spot. The second option was analyzed carefully in [4]. It has been shown that this scenario requires repetitive (at least 30 – 40 times) and consecutive formation of aggregates of 2 – 3 coalesced bubbles at the same nucleation spot. This is not a likely event because in order to coalesce, 1) the bubbles should grow close to each other, which is not a likely event itself [6, 7], and 2) their interfaces should be pushed to each other to overcome the strong lubrication forces between them [8]. A fact that of primary importance for the boiling crisis was established by the works [9] and [10] that show that DNB appears as a result of the fast growth of a dry spot under a *single* bubble.

Another important step was the revelation of the strong influence of the bubble residence time (or bubble departure time, the time between bubble nucleation and bubble departure from the heating surface) t_{dep} on the CHF [2]. The residence time depends on the value of lift-off forces that tend to remove the bubble from the heater. These forces can be varied e.g. by inclining the heating surface or by conducting the boiling experiment on board of a spacecraft [11]. A strong decrease of the CHF with the increase of t_{dep} was shown. The long residence time allows the bubble growth to be observed in detail. However, these observations remain difficult at low pressures because of the hindering effect of the fast liquid motion. In the section 4 we discuss the results of our experiment [12] carried out in microgravity environment (Mir space station) with a fluid at high pressure close to its critical point, where the CHF is very small and the bubble growth is very slow when the heat supply approaches the CHF.

The importance of the dry spot growth was recognized in a large number of CHF models (see [4] for a review) that are based on a concept of a microlayer dryout. The microlayer model [13] postulates the existence of a thin liquid film (microlayer) between the heater and the foot of the vapor bubble. This model is based on observations of the bubbles at low system pressures where the fast bubble growth creates a hydrodynamic resistance that makes the bubble almost hemispherical [14].

As proved by direct observations [9, 10] through a transparent heating surface, a dry spot (i.e. the spot of the direct contact between the liquid and the vapor) does exist around the nucleation site while the bubble stays near the heating surface. The origin of this dry spot can be explained as follows. First, it is necessary that the vapor-solid adhesion exists to avert the immediate removal of the bubble from the heater by the lift-off forces. This adhesion only appears when the vapor contacts the solid directly. Second, the strong generation of vapor at the triple contact line around the nucleation site prevents covering of the nucleation site by the liquid. As a consequence, the existence of the dry spot under the bubble is necessary during its residence time.

Because of the hemispheric bubble shape, the apparent bubble foot is much larger than the dry spot at low heat fluxes. This is why the microlayer model works well at low pressures. For high system pressure, comparable to the critical pressure, the picture is different. The bubble growth is much slower so that the hydrodynamic forces are small with respect to the surface tension. Consequently, the bubble resembles a sphere much more than a hemisphere [14]. It is very hard to identify the microlayer as a thin film in this case.

Nothing definite is known about the microlayer behavior at high heat fluxes. The microlayer dryout models of the CHF have a large degree of uncertainty because they use the parameters of the microlayer calculated to fit the low heat flux data on bubble growth rate. In addition, it is not clear from the physical viewpoint how the part of heater between the bubbles becomes covered by vapor while the heater is completely wetted by the liquid and should therefore be always covered by a liquid film. Because of the small size of the microlayer region, its direct experimental study is very difficult. The rigorous numerical modeling of the microlayer heat transfer is unknown to us. We recently suggested a new approach [15] to the boiling crisis problem. It is based on a rigorous calculation [17] of the heat transfer near the triple vapor-liquid-solid contact line and on the concept of the vapor recoil force that we discuss in the next section.

2 Force of vapor recoil and growth of the dry spot under a bubble

In [16] the vapor recoil instability is considered 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.

Let us consider a portion of the liquid-vapor interface with the area A (Fig. 2). The liquid is heated and is thus evaporating. During the time Δt, the liquid mass

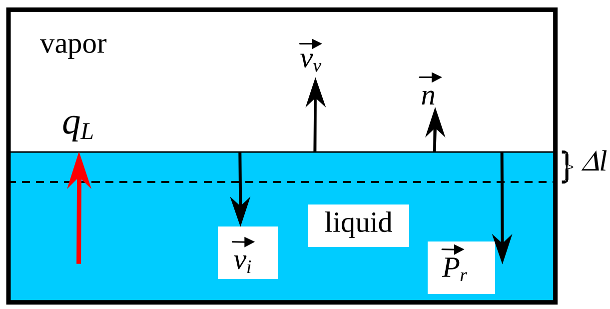

Figure 2: Sketch for the calculation of the expression for the recoil pressure.

Δm (liquid volume ΔV_L) is evaporated. Consequently, the liquid-vapor interface displacement is $\vec{\Delta l} = -\vec{n}\Delta V_L/A$, where $\vec{n}$ is a unit vector normal to the interface directed toward the vapor (Fig. 2). The evaporation results in a vapor volume ΔV_V. According to mass conservation, $\Delta m = \Delta V_L \rho_L = \Delta V_V \rho_V$, where ρ_L (ρ_V) is the mass density of the liquid (vapor). Momentum conservation for this portion of the liquid-vapor interface can be written in the form

$$\Delta m(\vec{v_v} + \vec{v_i}) + \vec{P_r}\Delta t A = 0 \qquad (1)$$

where $\vec{P_r}$ is the vapor recoil force per unit area of the interface (i.e. a recoil pressure), $\vec{v_i} = \vec{\Delta l}/\Delta t$ is the interface velocity, and $\vec{v_v} = \vec{n}\Delta V_V/(A\Delta t)$ is the vapor velocity with respect to the interface. By using the mass conservation, (1) can be rewritten in the form

$$\vec{P_r} = -\eta^2(\rho_V^{-1} - \rho_L^{-1})\vec{n}, \qquad (2)$$

where the rate of evaporation $\eta = \Delta m/(A\Delta t)$ is introduced. It can be related to the local heat flux q_L per unit area across the interface by the equality

$$q_L = H\eta, \tag{3}$$

where H is the latent heat of evaporation.

Let us now consider a growing vapor bubble attached to the heater surface (Fig. 3). While the temperature of the vapor-liquid interface is constant (in fact,

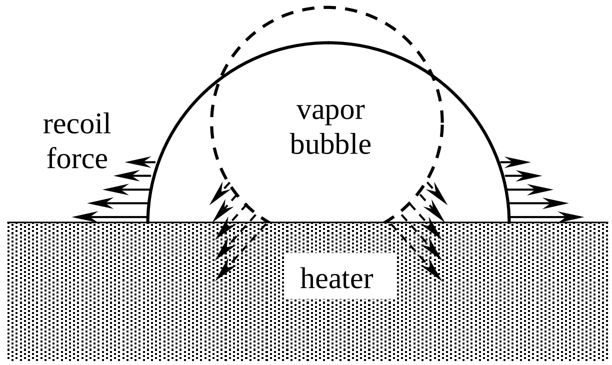

Figure 3: Spreading of the vapor bubble under the action of the vapor recoil force. The thickness l_r of the belt on the bubble surface, in which the vapor recoil force is important, is exaggerated with respect to the bubble radius.

it is the saturation temperature for the given system pressure), a strong temperature gradient forms near the heating surface. The liquid is overheated in a thermal boundary layer of thickness l_r. This means that the flux q_L is elevated in a "belt" of the bubble surface adjacent to the bubble foot. As a matter of fact, most of the evaporation into the vapor bubble is produced in this belt, whose thickness is usually much smaller than the bubble radius R [14]. As follows from (2, 3), the vapor recoil near the contact line is much larger then on the other part of the bubble surface. Consequently, the bubble should deform as if the triple contact line were pulled apart from the bubble center as shown in Fig. 3. This means that under the action of the vapor recoil the dry spot under the vapor bubble should spread covering the heater surface.

In the following subsection, we will show in a simple example that the influence of the vapor recoil can be interpreted in terms of a change of an apparent contact angle.

2.1 Vapor recoil and apparent contact angle.

Let us consider a curvilinear coordinate l measured along the bubble contour, which is perpendicular to the heater plane, as it is shown in Fig. 4. By apparent contact

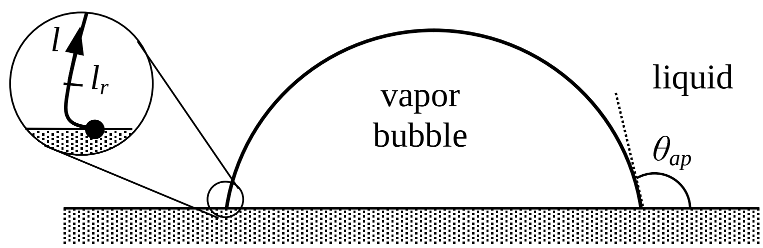

Figure 4: Definition of the apparent contact angle. The insert shows that the actual contact angle is zero while the apparent contact angle can be large. The black point denotes the intersection of the bubble contour with the contact line, i.e. zero for the curvilinear coordinate l.

angle θ_{ap}, we mean the angle between the tangent to this bubble contour and the heater plane measured at the coordinate l_r. Since $l_r \ll R$, θ_{ap} seems to be the actual contact angle to an observer that cannot see the details much smaller than the length-scale R. However, zooming in to the scale l_r would reveal the actual contact angle that can differ strongly from θ_{ap} as it is shown in the insert in Fig. 4. In the following we assume that the motion of the contact line is slow enough so the actual contact angle is given by its equilibrium value θ_{eq}.

Suppose that l_r is so small that the function $P_r(l)$ can be approximated by the Dirac δ-function: $P_r(l) = \sigma_r \delta(l)$. This means that the vapor recoil is localized at the contact line. Note that the constant σ_r has the dimension of a surface tension and can thus be included in the Young balance of the tensions acting on the contact line (Fig. 5). The contact line is stationary when the horizontal component of the vector sum of all the forces is equal to zero. It can be shown from Fig. 5 that this condition is $\cos\theta_{ap} = \cos\theta_{eq} - N_r \sin\theta_{ap}$, where $\cos\theta_{eq} = (\sigma_{VS} - \sigma_{LS})/\sigma$. The parameter $N_r = \sigma_r/\sigma$ characterizes the strength of the vapor recoil. The calculated dependence of θ_{ap} on N_r is presented in Fig. 6. It can be seen that the vapor recoil force increases the apparent contact angle. When the power to heater is kept

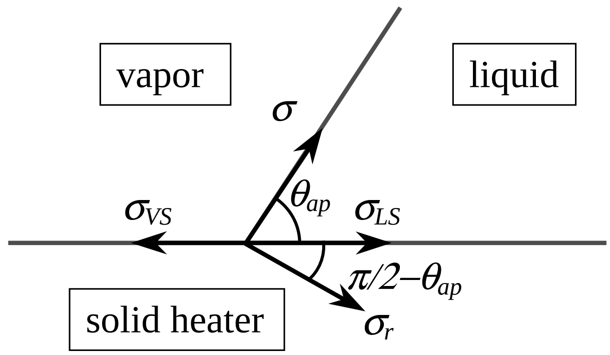

Figure 5: Balance of the forces that act on the triple contact line, where σ, σ_{VS} and σ_{LS} are the surface tensions for vapor-liquid, vapor-solid and liquid-solid interfaces respectively.

constant, the heat flux q_L increases with time, usually by following a square root law. Consequently, P_r and N_r grow with time in accordance with (2, 3). Therefore, the apparent contact angle should grow with time as is sketched in Fig. 3. This increase leads to the spreading of the dry spot. However, the dry spot always remains of finite size (which fits the experimental results [9, 10]) because, according to Fig. 6, $\theta_{ap} < \pi$ even for a large N_r.

2.2 Numerical results on the bubble growth

In reality, the vapor recoil is not localized *exactly* on the contact line as it was assumed in the δ-approximation from the previous subsection. We present here the more general results of a numerical simulation of a growing vapor bubble. Since we do not use any assumptions of the shape of the "microlayer" or of the heat transfer in it, we expect to obtain a realistic picture. A transient thermal conduction problem is solved in the liquid and in the solid heater to describe the time evolution of q_L in 2D. The details of simulation are presented in [17]. We present here the main results calculated for water at 10 MPa in contact with the stainless steel heater.

The time evolution of the bubble shape is shown in Figs. 7. At a low heat flux, the shape of the drop stays nearly spherical (Fig. 7) during the calculation time. Fig. 7b shows that at large heat flux the radius of the dry spot can exceed the bubble height, thus confirming the previous theoretical predictions (cf. Fig. 3). It is easy

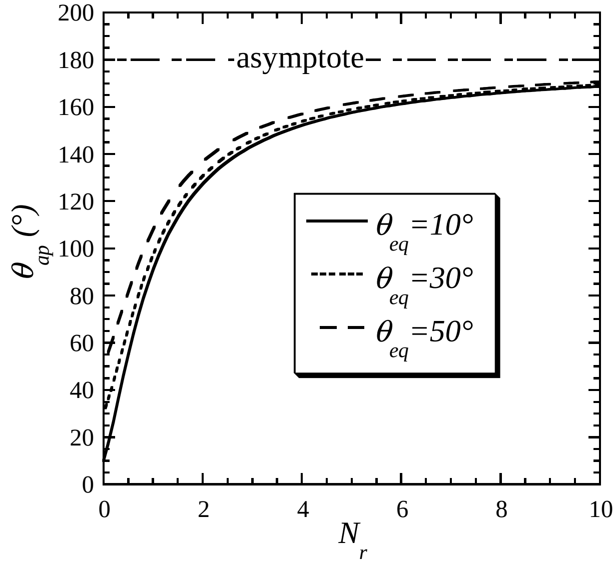

Figure 6: Apparent contact angle versus the strength of the vapor recoil N_r for the different values of the equilibrium contact angle.

to see that the apparent contact angle grows with time, although the *actual* contact angle remains zero during the evolution. The large apparent contact angle is due to the strong change in slope of the bubble contour near the contact line as shown in the insert to Fig. 4.

The temporal evolution of the radius R_d of the dry spot is illustrated in Fig. 8, where the time evolution of R_d/R is shown. R is the drop radius defined as the maximum abscissa for the points of the drop contour, so that $R_d/R \leq 1$. One can see that the dry spot remains small until a transition time t_c, which is an increasing function of q_0. At this point the growth of the dry spot accelerates steeply. The oscillations of the curves in Fig. 8 are not numerical artefacts. They result from an instability, discussion of which is out of the scope of this article.

3 A scenario for DNB

In this section we suggest a possible scenario for the boiling crisis caused by the vapor recoil force. When the heat flux q_0 from the heater is small, the size of the dry spot is very small with respect to the bubble size (see Fig. 7a). The adhesion

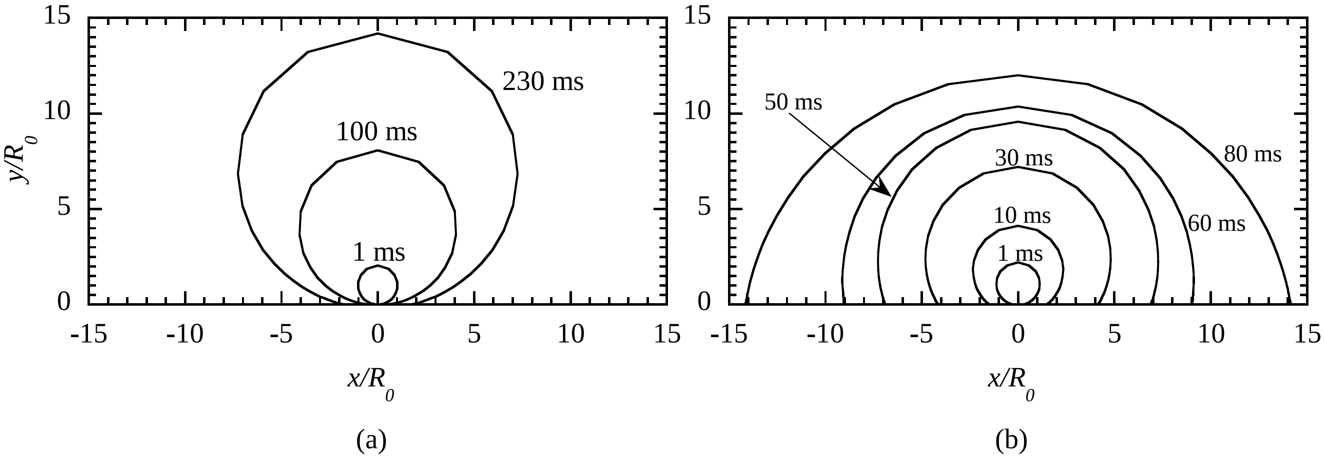

Figure 7: The bubble shape shown for different growth times. The heat fluxes from the heater are a) $q_0 = 0.05$ MW/m^2; b) $q_0 = 0.5$ MW/m^2;

force that keeps the bubble near the heater is proportional to the contact line length [18]. This adhesion force defines the residence time of the bubble t_{dep} that is small in this case, $t_{dep} < t_c$. Therefore, the dry spot remains small until the bubble departure from the heater. Clearly, t_c is a decreasing function of q_0 (see Fig. 8). This means that, at a sufficiently large q_0 the dry spot becomes very large in a short time (see Fig. 7b) and the departure of this bubble is prevented because of a large adhesion to the heater. Therefore, at some value of q_0, which we associate with q_{CHF}, t_{dep} should increase sharply. During the further growth this bubble can either create alone a nucleus for the film boiling or coalesce with another similarly spreading neighboring bubble thus causing the boiling crisis.

The residence time measured even far from DNB can give important information about the CHF. When t_{dep} is large because of the external conditions (as under reduced gravity conditions or when the fluid is heated from above), the CHF should be small because the dry spot has enough time to achieve a sufficiently large value at smaller q_0. Similarly, the decrease of t_{dep} with an increasing flow velocity for flow boiling (the fluid flow facilitates the bubble departure) should increase the CHF. The experimental data confirm this conjecture of our model, see e.g. [11]. The authors of the recent work [2] came to the same conclusion after having analyzed their experimental results on flow boiling. They found $q_{CHF} \propto t_{dep}^{-1}$.

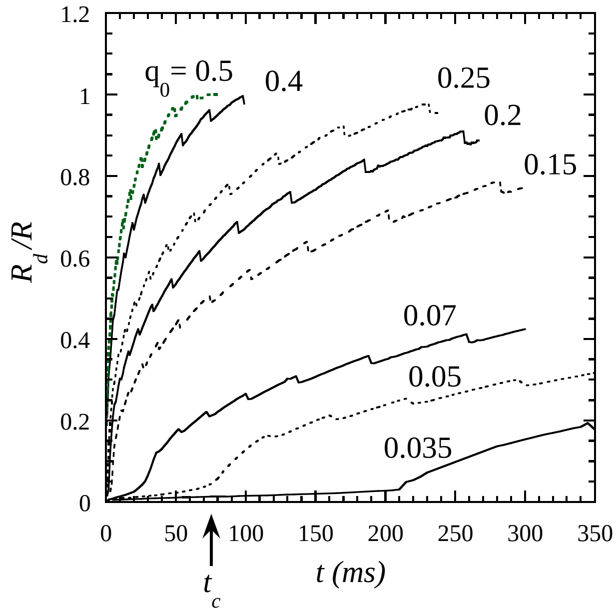

Figure 8: The temporal evolution of the ratio of the dry spot radius R_d and the bubble radius R for different values of the heat flux form the heater q_0 (MW/m^2). The transition time t_c is shown for the curve that corresponds to $q_0 = 0.05$ MW/m^2.

The strong dependence of the CHF on the equilibrium contact angle, that was observed in [5] is a natural consequence of the present model. The dry spot is larger initially for the larger contact angle. A smaller heat flux is thus needed to achieve the spreading of the bubble illustrated by Figs. 3 and 7b.

4 Experimental evidence

Detailed theoretical analysis and experiments [12] confirm that our model of the boiling crisis is valid in the near-critical region, i.e. for the system pressure and temperature that are close to the critical pressure and temperature for the given fluid. Here we simply summarize the findings of [12] relevant to the boiling crisis.

The critical point exhibits many singular properties. In particular, the coefficient of thermal diffusion vanish. The bubble growth thus slows down in the near-critical region. In fact, we could observe the growth of a single bubble during about fifteen minutes. Since the surface tension vanishes at the critical point, the vapor bubbles of the usual convex shape are not observable under Earth's gravity. For this reason our experiment was performed onboard the Mir space station. The CHF value vanishes at the critical point, and a very slow heating rate is expected to produce bubble spreading. Because of the slow evolution, the hydrodynamic effects are suppressed and the bubble shape is not distorted by them in accordance with our initial assumption. The bubble evolution was observed through the transparent bases of the cylindrical cell. The equilibrium value of the contact angle is zero so that the initial bubble shape is nearly circular. The temporal evolution of the bubble is shown in Fig. 9.

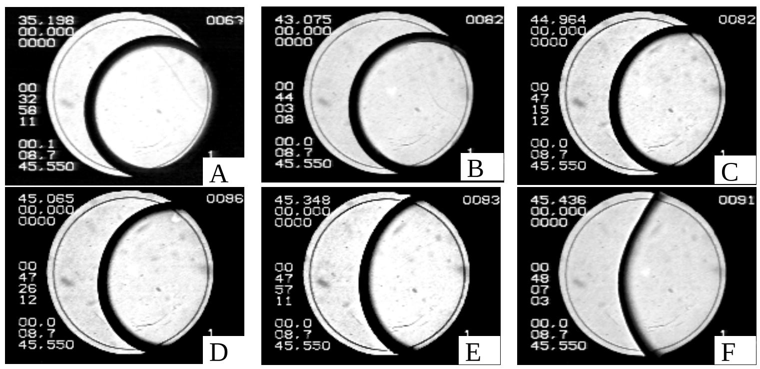

Figure 9: Temporal sequence of images of the vapor bubble in the cylindrical cell with the near-critical SF_6. The images were obtained during continuous heating of the cell. The last image (F) corresponds to the temperature just below the critical temperature. The increase of the apparent contact angle is obvious.

5 Conclusions

We propose a physical explanation for the boiling crisis based on the growth of the dry spot under a vapor bubble caused by the vapor recoil force. The theoretical approach is supported by the numerical simulation of the bubble growth at a large heat flux and by the experimental data on growth of the vapor bubble in near critical fluid performed under microgravity conditions. The proposed criterion for the boiling crisis provides a physical basis for further studies. It explains qualitatively the dependence of the critical heat flux on some key physical parameters.

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