BOILING CRISIS: THEORY, SIMULATION, AND EXPERIMENTS

V. Nikolayev and D. Beysens

Service des Basses Températures
(SBT), DRFMC

Boiling is a very efficient way to transfer heat from a heater to the liquid heat carrier. We discuss the boiling crisis, a sharp decrease in the heat transfer rate, which can cause a major accident in industrial heat exchangers. Numerical simulation of the growth of vapor bubbles has been found to be in very good agreement with experimentally observed results.

L'ébullition est un moyen très efficace de transférer la chaleur d'un élément chauffant à un liquide caloporteur. Nous discutons la crise d'ébullition, une chute brutale du transfert de chaleur, susceptible de causer un accident grave dans des échangeurs de chaleur industriels. La simulation numérique de la croissance des bulles de vapeur s'est révélée en excellent accord avec des résultats observés expérimentalement.

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Boiling is observed commonly in everyday life. This is why it seems well understood. It is true that boiling has been extensively studied from an empirical point of view for the most common fluids and regimes, for instance for water at atmospheric pressure and moderate heat flux supplied to fluid. However, the basic theory of boiling remains *terra incognita*. These difficulties originate from the violence of the fluid motion that on the one hand conceals the mechanisms of bubble growth from detailed observation, and on the other hand hugely complicates direct numerical simulations. Most still unanswered questions concern the close vicinity of the heating surface, down to the scale of bubbles growing at the surface of the heater especially during boiling at high heat fluxes common for industrial heat exchangers, e.g. nuclear power plant steam generators.

Two main boiling regimes can be distinguished: nucleate boiling and film boiling. The former can be commonly observed in a sauce pan. It features separate vapor bubbles that nucleate (i.e. form) and grow at the heater. This regime provides a very efficient heater-liquid heat exchange due to their direct contact. The other regime features a vapor film that separates the liquid from the heater. Film boiling can be also observed in the kitchen by sprinkling water onto a hot frying pan. In spite of the large temperature of the heater (the pan) the water drops survive for a long time precisely due to the thermally insulating vapor film that prevents the liquid from touching the pan. Obviously, the heater-liquid heat transfer is much lower than in the first case.

The subject of our study is the transition from nucleate to film boiling which is called "boiling crisis". During this transition, separate bubbles at the heater are replaced rapidly by a continuous vapor film. This blocks the heater-liquid heat transfer and thus leads to a rapid increase of the heater temperature. If the power is not switched off immediately, the heater can melt down which can cause a major accident if an industrial installation is involved. The boiling crisis occurs at a critical value of the heating flux (fortunately not attainable under "kitchen" conditions).

In spite of its importance, the mechanism of the boiling crisis remains poorly studied. Our purpose is to explain why, how, and when the vapor film begins to form. We have made the fundamental hypothesis that the boiling crisis is triggered by the vapor recoil when liquid transforms into vapor.

Every fluid molecule evaporated from the liquid interface causes a recoil force analogous to that created by the gas emitted by a rocket engine. It pushes the interface towards the liquid side in the normal direction. This force appears because the fluid necessarily expands while transforming from liquid to gas phase. Obviously, the stronger the evaporation rate, the larger the vapor recoil force.

Let us now consider the variation of the evaporation rate along the surface of a bubble growing at the heating surface. Since the fluid is hotter close to the heater than far from it, the evaporation distributed along the bubble surface is strongest in the vicinity of the line of contact of the bubble surface with the

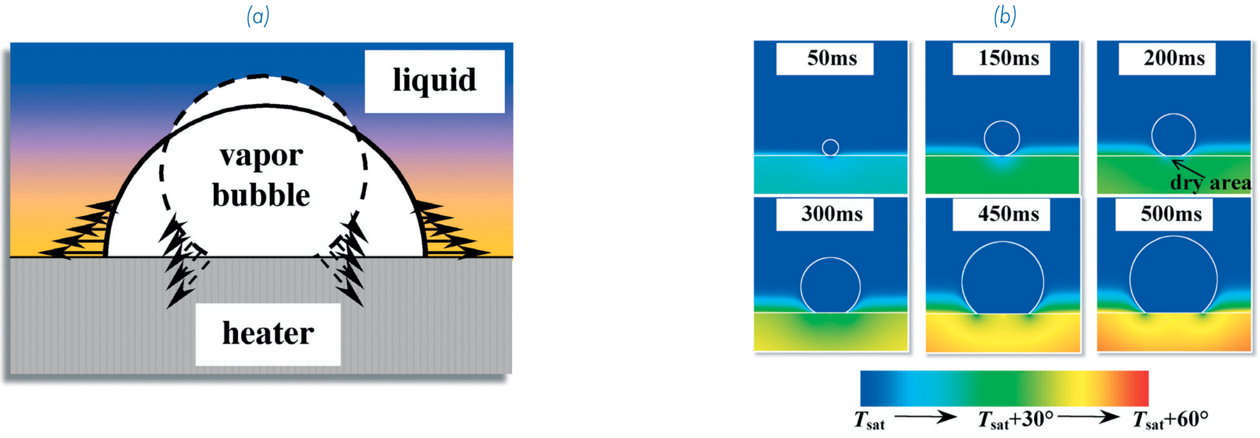

Figure 1. Vapor bubble spreading under the influence of vapor recoil.
(a): Sketch illustrating the vapor recoil effect. The amplitude and direction of the vapor recoil force are shown by arrows.
(b): Simulation results. The color indicates the local temperature with respect to the saturation temperature T_{sat}.

heater. The vapor recoil is also strongest at the contact line and therefore tends to pull the contact line outward, thus spreading the dry area or "dry spot" under the bubble (see Fig. 1a).

A numerical simulation [1] of such a process is presented in Fig. 1b. Such a simulation requires solving of extremely delicate thermal and capillary problems. It can be seen that the dry spot is initially very small and remains so during the initial growth stage. At about 180ms the dry spot begins to grow suddenly, i.e. the bubble spreads. Such a spreading represents the beginning of formation of the vapor film characteristic for the boiling crisis. Figure 1b also shows formation of a hot spot at the heater surface in the middle of the dry area. This temperature rise illustrates the already discussed blocking of the heat transfer by vapor.

This theoretical approach can be compared to an experiment [2] carried out with SF_6 fluid near its critical liquid-gas point. This experiment takes advantage of so-called "critical slowing down" of the bubble growth observed near the critical point. In fact, the growing process of a single vapor bubble could be observed during 45 min thus allowing for a very detailed analysis. The choice of SF_6 was made for practical reasons: the critical point of this fluid is at 45.6°C, 38 bar and requires much less severe conditions for the experiment than for example water (374°C, 220 bar). However, near-critical bubble growth experiments have an important drawback. Since the surface tension becomes very low near the critical point, gravity completely flattens the liquid interface. Weightlessness conditions are thus necessary to preserve the usual convex bubble shape. Some of the results of this experiment performed on board the Mir space station are presented in Fig. 2a. The sequential photos of the growing vapor bubble were taken through the transparent bases of the cylindrical cell, the lateral copper walls of which are being heated. Spreading of the dry spot under the bubble similar to that in Fig. 1b can be seen. The bubble shapes calculated for different values of the vapor recoil strength *N* are presented for comparison in Fig. 2b. The correspondence is striking.

Generally speaking, the comparison between the results presented above shows the complementarity of theory (basic assumptions), experiment (test of the validity of a model) and simulation (access to parameters not attainable by experiments).

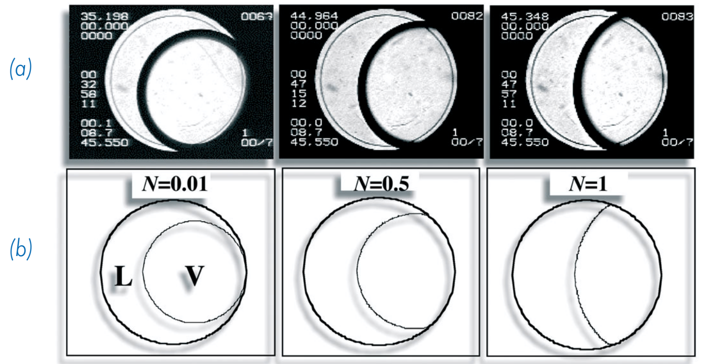

Figure 2. Snapshots of the vapor bubble (V) growing in near critical liquid (L), both experimental (a) and calculated (b) for the given values of the vapor recoil strength N.

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[2] Y. Garrabos, C. Lecoutre-Chabot, J. Hegseth, V. S. Nikolayev, D. Beysens, and J.-P. Delville, Phys. Rev. E **64,** 051602 (2001).

Contact: vnikolayev@cea.fr