

TED Plaza

Some Remarks on the Nukiyama Curve



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It was about 70 years ago when Shiro Nukiyama published his pioneering paper on “Maximum and Minimum Values of Heat Q Transmitted from Metal to Boiling Water under Atmospheric Pressure” [1]. A milestone at the beginning of a long way towards the “truth” in boiling heat transfer. Numerous researchers discovered a lot on this way but the more we find out the more difficult it becomes to really understand this extremely complex process.

Basically Nukiyama’s boiling curve has never been disputed. Only specific aspects were and are subject of studies or disagreements. The shape of the boiling curve, for instance, is still a subject of discussions in terms of its behavior in the transition region, its change in a transient situation with respect to the steady-state case, its dependence on contaminations on the heating surface etc. The shape of the boiling curve and its change under different system conditions is, of course, a result of different boiling mechanisms and their change. Since pure empiricism can never solve such problems, several physical models for the different boiling modes have been developed. We should trust these models only after experimental verification. Moreover, due to the improvement of our experimental techniques and also of the mathematical tools in recent years, older and relative simple models can now be improved and new ones can be developed.

The present report makes some remarks on the aspects mentioned above. Of course not comprehensive and – subject of excuse – focused mainly on our own work. It is just meant as a small tribute to Nukiyama’s pioneering work. Those who need a sort of survey on new developments may look into the “Proceedings of the 5<sup>th</sup> Int. Boiling Heat Transfer Conf. in Jamaica, May 2003”. A selection of the papers presented there will soon be published in the “International Journal of Heat and Fluid Flow”.

**HYSTERESES ALONG THE NUKIYAMA CURVE**

No contradiction exists about a hysteresis in the region of nucleation incipience (see Fig. 1). In contrast, in transition boiling and for steady-state conditions a hysteresis was postulated [2] consisting of a transitional nucleate boiling–and a film boiling–branch, both overlapping with respect to the heat flux. However, if a precise temperature control system [3] is available and with a clean heating surface, boiling curves even for liquids with large contact angles (water) show no hysteresis regardless in which direction they are measured: stepwise from film to nucleate boiling or vice versa. In contrast, if surface contamination is involved, boiling curves are not reproducible. Each test run, even under carefully established steady- state conditions, results in a shift of the curve already at a minimal change of the deposit [3,4].

The boiling curve behavior changes under transient conditions, even on clean surfaces. Recently it was argued that “how the unsteady process influences the hysteresis is not cleared, yet” [5]. Objection! It is, as shown by systematic experiments in [6]. There, measurements with controlled heating and cooling rates were carried out, of course, by taking into account the “coupling problem

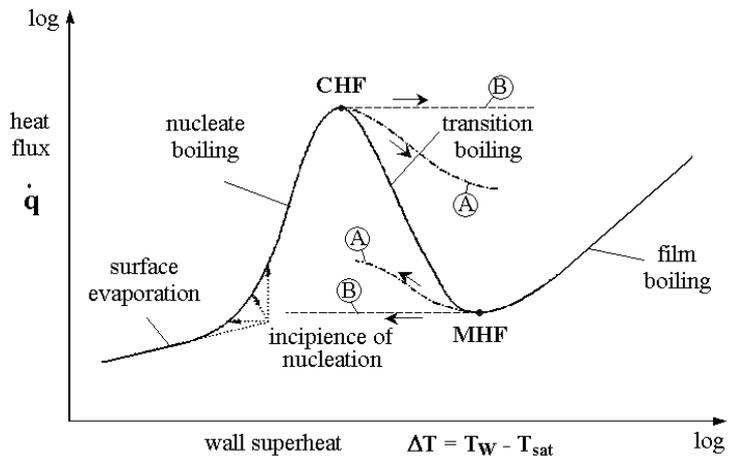


Fig. 1: The Nukiyama curve.

[5]” between heater and fluid which requires the solution of an inverse heat conduction problem. One typical result is shown in Fig. 2: The steady-state curve was measured with stepwise increasing and decreasing temperature without observing a hysteresis. A transient heating rate of e.g. 4 K/s along the entire boiling curve yields significantly higher heat fluxes at a given instantaneous surface temperature and a transient cooling vice versa. The cooling curve in Fig. 2 results from a quenching process (i.e. no heat input from outside and no temperature control) which yields the fastest cooling of the given heater. Hence, the cooling rate (in K/s) along the curve is not constant. In contrast, increasing the heating rate is less limited by the thermal inertia of the heater. At a nominal heating rate of 50 K/s (not exactly constant along the boiling curve, see [6]) we observed a 4 times larger CHF-value than in the steady-state case. These results from systematic experiments are, however, rather the beginning of the story than the end of it. What is the physical explanation for this enormous hysteresis? Here, first, the experimentalists are needed to look into the two-phase layer near the surface where the governing mechanisms take place and to explore as much phenomena as possible in order to initiate the development of mechanistic models, which are useless without experimental support, at least in boiling.

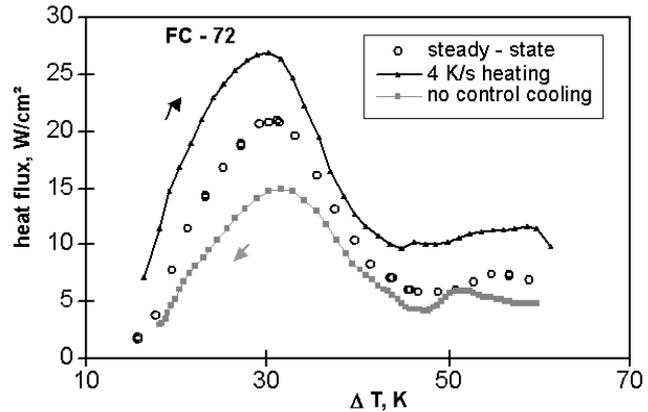


Fig. 2: Boiling curves of FC-72 under steady-state conditions as well as under transient heating and transient cooling conditions.

Incidentally, the transient behavior of a boiling curve in an uncontrolled system is often depicted by horizontal lines (B in Fig. 1) for the heating and the cooling mode. Both are physically impossible. Depending on the thermal inertia of the heater the system always moves along lines according to A in Fig. 1. And if somebody call CHF the “burnout point” we should tell him or her that burnout occurs at a much higher temperature if any.

Many experimentalists are fascinated by the challenge to discover the mechanisms of boiling in each regime under steady-state and/or transient conditions in order to explain global experimental findings as those discussed above. For a good survey of recent efforts in this field again the Jamaica-Conference is mentioned. Here only some own findings are picked out.

### EXPERIMENTS WITH MICROSENSORS

With thick heaters such as used in practical operation, non-intrusive techniques cannot access the most important parameters on both sides of the heating surface. Therefore miniaturized sensors have been developed which do not significantly disturb the processes.

Micro optical probes (tip diameter  $\sim 1.5\mu\text{m}$ , more details in [3]) reveal e.g. a void fraction ( $\alpha_v$ ) distribution as shown in Fig. 3 for isopropanol and the fluorinert FC-3284 (3M-company) in fully developed nucleate boiling. Very near to the surface (smallest distance:  $8\mu\text{m}$  for isopropanol;  $5\mu\text{m}$  for FC-3284)  $\alpha_v$  is small, but it increases with the distance until a maximum is reached. Hence, a liquid rich layer exists near the surface. Its thickness decreases monotonically with increasing wall superheat and it disappears in high heat flux nucleate boiling [3,7]. The distance of the maximum to the surface is linked with some kind of bubble departure diameter  $d_B$  ( $d_B$  isopropanol  $>$   $d_B$  FC-3284). These findings prove the basic idea of the macrolayer theory but the reality is somewhat more sophisticated, the more so as no stationary vapor stems in the liquid rich zone were observed but always single nucleation sites which are not locally fixed for a longer period. A challenge to improve a popular model for the boiling mechanism!

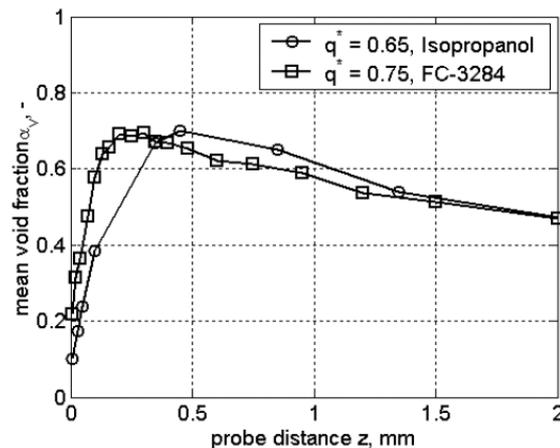


Fig. 3: Mean void fraction for nucleate boiling measured with isopropanol and FC-3284.

$q^* = \dot{q}/\dot{q}_{CHF}$ .  $z$ : distance to the heater surface.

Fig. 4 shows temperature traces from microthermocouples (MTC) in transition boiling. The

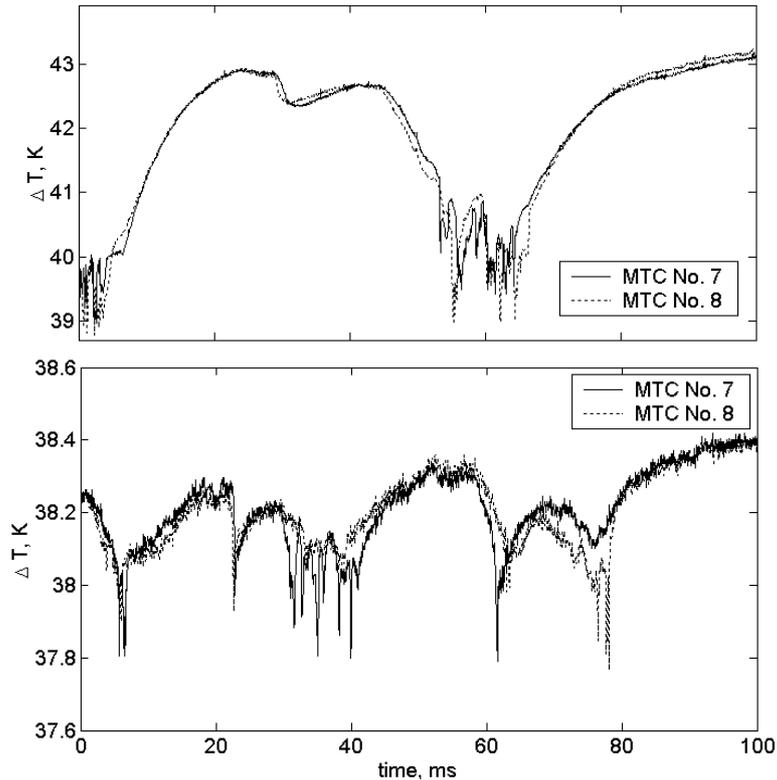


Fig. 4: Temperature beneath the heater surface at microthermocouples No. 7 and 8 in transition boiling; top: isopropanol, bottom: FC-3284. Horizontal distance 7, 8: 211.6 $\mu$ m.

diameter of the MTCs is 38 $\mu$ m. An array of 36 MTCs is implanted in a copper heater within an area of 1 mm<sup>2</sup> (distance between individual MTCs: about 200 $\mu$ m). The sensitive tips of the MTCs are located 3.6 $\mu$ m beneath the surface (more details in [8]). Measurements of this kind were carried out along the entire boiling curve and several conclusions about boiling mechanisms could be drawn [9]. Just a few remarks: In nucleate boiling several sharp temperature drops have been observed which are mostly not correlated even for MTCs with a distance of only 211.6 $\mu$ m. This is another indication of very localized but strong evaporation near the three phase contact line at the bottom of a bubble. In transition boiling (Fig. 4) dry patches with increasing size towards the Leidenfrost point can be quantitatively identified. In between, fast wetting events occur resulting in a local temperature drop of more than -30,000 K/s for isopropanol. Solving an inverse heat conduction problem, heat fluxes within the wetting zone of up to 8 MW/m<sup>2</sup> have been identified [10] at wetting events like those shown in Fig. 4, top. In modeling efforts for transition boiling it is often assumed that it consists of a combination of film and nucleate boiling. This is, at least as far as nucleate boiling is concerned, far from reality. The vapor generation process in a wetting zone is much more effective in terms of heat flux than in nucleate boiling. To assume film boiling heat flux in the dry patch area might be more realistic though sometimes droplets seem to wet the surface within a dry zone which we never observed beyond the Leidenfrost point in film boiling.

Let's finally look at Fig. 5. It shows temperature traces of isopropanol in the two-phase layer above the heater measured with a micro thermocouple probe (MTCP) (diameter: about 16 $\mu$ m) in transition boiling. The non-insulated tip of the wire is covered with a 1 $\mu$ m thick gold layer (more details in [9]). This constant/gold thermocouple exhibits a very short response time. Without going into the details, it is obvious that strong superheats ( $\Delta T_p$ ) are observed in the vapor leaving the surface ( $z = 0.1$ mm,  $\Delta T_p = T_{probe} - T_{sat}$  up to 15K) whereas the surrounding liquid is at saturation temperature. As to be expected, the superheat in the bubbles decreases with increasing distance but at  $z = 9$ mm it is still about 7K. Similar measurements in all boiling regimes show an interesting trend: In low heat flux nucleate boiling the bubbles are slightly superheated but surrounded by strongly superheated liquid of several K (for isopropanol) with a sharp temperature drop near the interface. Towards CHF and via transition to film boiling the liquid approaches saturation already in fully developed nucleate boiling whereas the superheating in the bubbles steadily increases (up to more than 30K at  $z = 0.1$ mm for isopropanol) in film boiling. Even at larger distances (e.g.  $z = 9$ mm) we are far away from thermodynamic equilibrium.

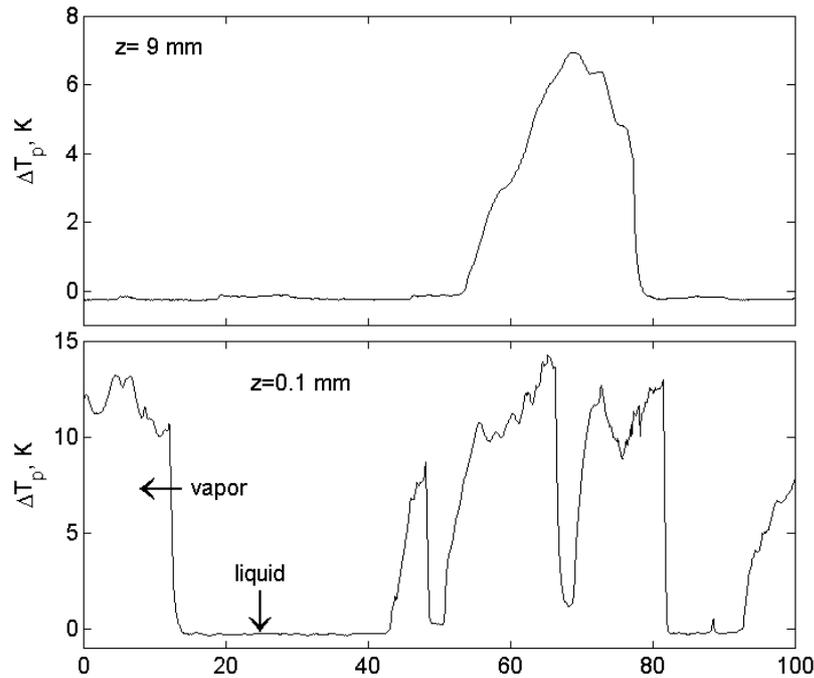


Fig. 5: Measured local fluid temperature in transition boiling ( $\Delta T = 42\text{K}$ ) at 9mm (top) and 0.1mm (bottom) distance (isopropanol);  $\Delta T_p = T_{\text{probe}} - T_{\text{sat}}$ .

### **WHAT'S NEXT**

Shiro Nukiyama would probably say to the boiling community: Continue to carry out experimental and theoretical studies on the fundamentals. In this way it is still possible to better approach the “truth” in boiling. On the next Conference we will see if his opinion was realistic or not.

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