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LETTERS TO THE EDITORS

COMMENTS ON 'ON THE EXISTENCE OF TWO "TRANSITION" BOILING CURVES'

IT WAS very interesting to see the recent paper by Witte and Lienhard [1]. Berenson's observation, in his classic work on transition boiling [2], that the heat transfer in the transition regime could be significantly affected by the value of the contact angle the liquid exhibited on the surface, has been insufficiently stressed in much recent comment on transition boiling. To talk of just two transition boiling curves may be an oversimplification though. A recent review of the subject suggested that there might be three distinct types of behaviour, that is three transition boiling curves [3], corresponding to zero, finite (<90°) and non-wetting (>90°) contact angles.

The evidence presented by Witte and Lienhard relates to the first two cases, for zero and small finite contact angles. There is also evidence for a distinctive type of boiling behaviour at very large contact angles. Contact angles of over 90° are unusual, and are normally only encountered either with liquid mercury or, in the case of water, if the solid surface has been treated with a material such as polytetrafluoroethylene or silicone grease. These are in fact the systems for which limited heat transfer information is available.

Lyon, Foust and Katz [4] boiled mercury on the outside of a horizontal steel tube at 1 atm. They concluded that as the power was raised the mercury went straight from natural convection to film boiling (Fig. 1). There was no sign of a critical heat flux. Although no contact angle was measured it is normal to find angles of over 90° with this system. The addition of 0.1% sodium to promote wetting produced a totally different type of boiling, in fact a normal boiling curve with a distinct critical heat flux (Fig. 1). In this power controlled system it was not, of course, possible to obtain transition boiling data. As to the question whether the 'normal' curve shown in Fig. 1 corresponds to finite or zero contact angles, it is difficult to be sure in the absence of contact angle measurements, but measurements were also made on mercury with 0.02% Mg and 0.0001% Ti that showed nucleate boiling heat fluxes well above the value of the critical heat flux with the mercury plus 0.1% Na. This suggests that the results in Fig. 1 do not correspond to a limiting zero contact angle.

Very similar results with water at 1 atm on a horizontal plate were obtained by Gaertner [5]. Artificial non-wetted surfaces were prepared by coating the substrate with thin films of polytetrafluoroethylene or silicone grease. Both surfaces gave contact angles of about 108°. After the first bubbles formed at nucleation sites vapour spread right over the surface. Film boiling began at 1.7×10^4 W m^{-2} at essentially the point of incipient nucleation. Nishikawa *et al.* [6] also studied pool boiling of water under similar conditions. No details were given of the method of preparing the non-wetted surface, but it is likely to have been similar to the method used by Gaertner. In this way film boiling was extended well into the region where with the normal (copper) surface they measured transition boiling (Fig. 1).

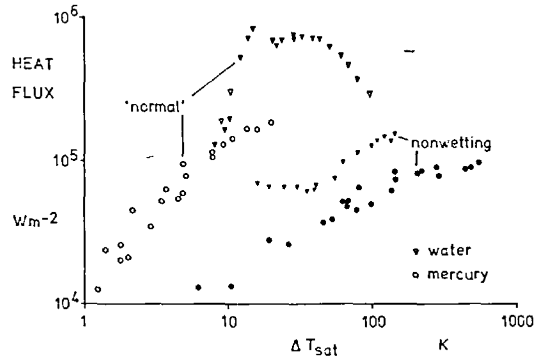

FIG. 1. The effect of changing from a normal to a non-wetted surface in pool boiling. The water results (triangles) are from ref. [6], the mercury results from ref. [4].

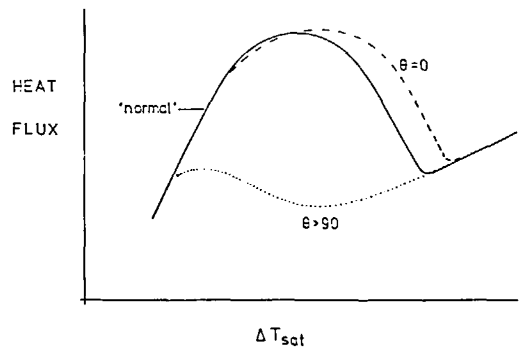

FIG. 2. Postulated effect of contact angle on the boiling curve, for given liquid, flow conditions, subcooling, etc.

While not conclusive, the results of Fig. 1 suggest that there is a profound change in going from a 'normal' (i.e. finite contact angle) surface to a non-wetted (>90°) surface, in addition to the change observed between finite and zero contact angle surfaces. In other words the complete picture would be shown in Fig. 2. Probably a more accurate description still would be to say that the contact angle is one of the parameters that controls boiling heat transfer in this region, and that there is a continuous variation with this parameter. An experimental verification of Fig. 2 in a single system would be of great interest. It is, of course, physically reasonable that improved wetting of the surface should increase the heat transfer rate.

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REPLY TO "COMMENTS ON 'ON THE EXISTENCE OF TWO "TRANSITION" BOILING CURVES'"

WE ARE grateful for R. H. S. Winterton's useful addition to our paper on transition boiling. He has pointed out additional data which show that large contact angle, non-wetting behavior eliminates the nucleate boiling region. On the basis of these observations he suggests Fig. 2 as a proper boiling curve.

Figure 3 is our version of a boiling curve that would correctly reflect this "contact angle > 90°" behavior.* While it differs in some aspects from Fig. 2, we feel that it correctly reflects this phenomenon that we overlooked in our paper.

Such jumps appear never to occur in the data that Mr Winterton has brought to our attention. A film boiling mode is retained as long as there is boiling. This strikes us as a most interesting verification of our suggestion that there exists a film-transition boiling region. The "non-wetting" data of Nishikawa *et al.* [6] seem to fit our notion of a film-transition curve quite well, while their "normal" data appear to fit our "nucleate-transition" curve. Both curves lead to obvious nucleate boiling data points as the surface temperature

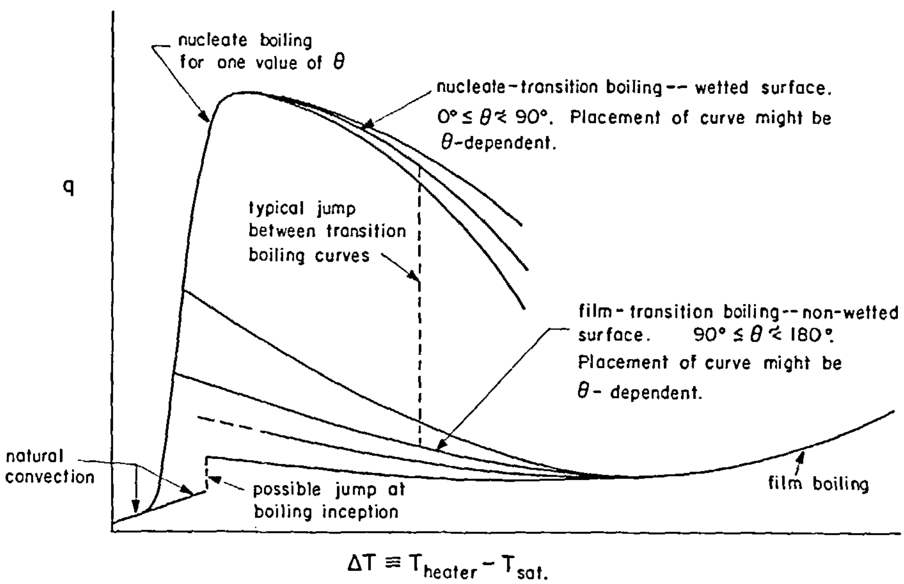

FIG. 3. Boiling curves *for a given liquid* but *for different heating* surfaces.

In our paper we carefully circumscribed our claim that there were two transition boiling curves by saying this would be *for a given heater surface and liquid combination.* Mr Winterton suggests that there might be a great multiplicity of curves for a given liquid as the contact angle, θ, is allowed to vary, and we would tend to agree.

However, for precisely specified heater–liquid combinations, we still believe that there are just two curves and that these are not both reachable under all conditions. Indeed we suspect that "wettability" probably decreases as most heaters become hotter, thus favoring a jump somewhere in the transition region.

decreases, so that some degree of wetting must exist for both cases, however. This appears not to be the case for mercury, which is truly non-wetting.

It is clear that there is a serious need for more data in the transition boiling regimes—data supported by careful surface chemistry control and photographic observations. While we regard Mr Winterton's data as support for our original claims, there is enough speculation embedded in all of this to cry out for more data.

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* We accept the "> 90°" identification as more figurative than literal. The point of departure might be some other angle of the order of 90°.