

## **BOILING ENHANCEMENT: RESPONSE TO PROFESSOR A. E. BERGLES**

by

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### 1. INTRODUCTION

I was delighted to accept the invitation to “respond” to the presentation by Professor Bergles (“High-Flux Processes Through Enhanced Heat Transfer”) and thus to participate in this symposium dedicated to Warren Rohsenow. I first met Professor Rohsenow in the early 1960’s and have had continuing contact with him since. I have learnt such a great deal from him, not only technically but also through his enthusiasm, his sense of humour and his caring approach to others!

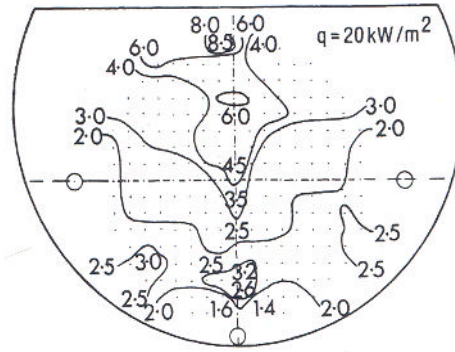
Having gladly accepted the invitation, I then received Art Bergles’ paper from Professor Lienhard and I began to wonder if I had done the right thing! Professor Bergles’ excellent review covers such a wide range of topics that even a cursory “response” would certainly take many times the 10 minutes allocated. I decided, therefore, to concentrate on only three topic areas. There is no logic in the choice of areas, except perhaps that they have been ones of interest to me personally!

The areas I chose were as follows;

- (1) Boiling in tube bundles.
- (2) Enhancement of critical heat flux by twisted tapes.
- (3) Forced convective multicomponent boiling.

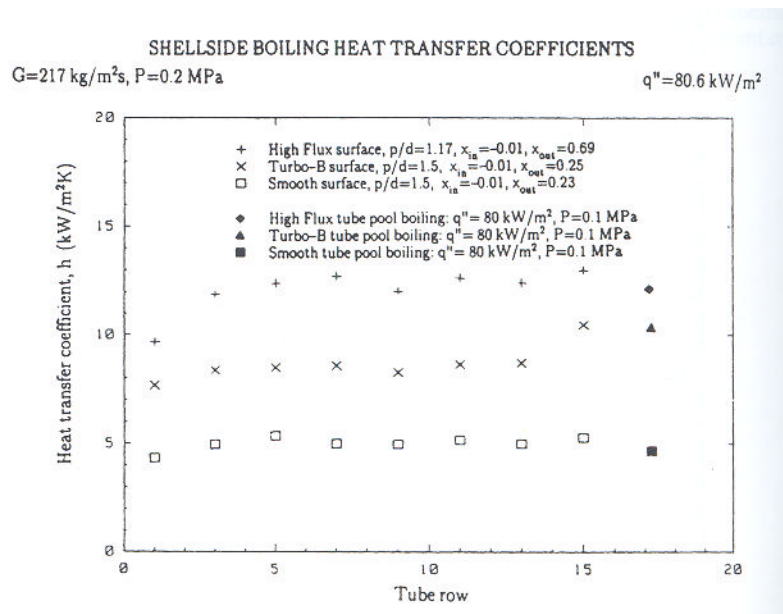
### 2. BOILING IN TUBE BUNDLES

The subject of boiling in tube bundles is discussed in Section 2.5 of Professor Bergles’ paper. Clearly, the application of enhancement technologies to bundles is of great practical importance. However, I fear there are still great uncertainties about prediction of boiling in these conditions. I would like to cite two cases of measurements in bundle systems. The first case (Leong and Cornwell, 1979) concerned measurements of local heat transfer coefficients in a “slice” of a kettle reboiler geometry. The bundle was very short (25.4mm) and, though the liquid (R113) was not pumped, rapid recirculation was observed through the transparent end wall of the system. In this case, the tubes were smooth. Figure 1 shows a contour plot of heat transfer coefficient; this varies in a complex way through the bundle, with the coefficient rising dramatically from tube row to tube row up the bundle with the highest values being observed along the central axis.



**Figure 1: Contours of heat transfer coefficient ( $\text{kW/m}^2 \text{K}$ ) in a simulated kettle reboiler (Leong and Cornwell, 1979).**

In the second case (Jensen et al, 1992), coefficients were measured for forced flow over a rectangular bundle. Again, the fluid used was R113 but both smooth and enhanced surfaces were employed. The results obtained by Jensen et al are illustrated



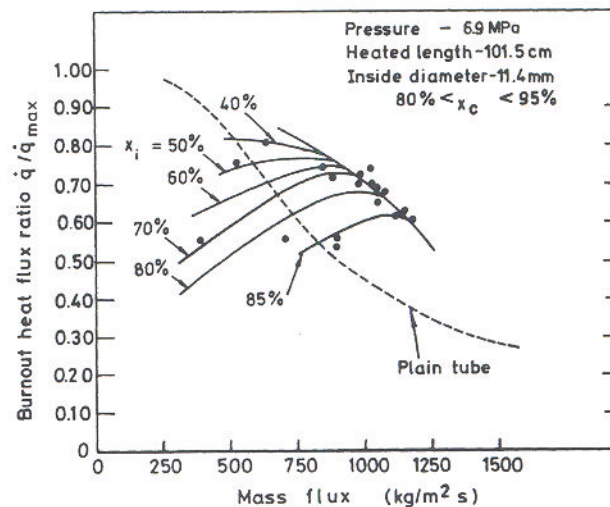
**Figure 2: Comparison of heat transfer coefficient for boiling refrigerant 113 on smooth and enhanced surfaces (**

in Figure 2. Here, the heat transfer coefficients for the enhanced surfaces are higher, as expected, but *the coefficients for both smooth and enhanced tubes are approximately constant up the bundle* (i.e. they do not vary significantly from tube row to tube row). The probable reason for the differences between the results shown in Figures 1 and 2 respectively is that the Jensen et al results (Figure 2) were obtained at around four times the heat flux used by Leong and Cornwell. Thus, the Jensen et al tests could be in fully developed nucleate boiling where the influence of quality might be small. Nevertheless, these two sets of data illustrate the difficulty of making general statements about boiling heat transfer in tube bundles; the nominally static configuration (without *imposed* flow) in the Leong and Cornwell experiments does yield results that are clearly sensitive to flow (i.e. the flow developed by internal

recirculation) and local quality. On the other hand, in the Jensen et al tests, where a flow is superimposed, show no great sensitivity to local quality. The interaction of these various effects in tube bundles is highly complex.

### 3. ENHANCEMENT OF CRITICAL HEAT FLUX BY TWISTED TAPES

In Section 3.2 of Professor Bergles' paper, reference is made to the influence of twisted tape inserts on critical heat flux in evaporation in tubes. Reading his comments on this point led me to recall some work done at AECL, Chalk River in the 1960's (Moeck et al, 1964). The results obtained are illustrated in Figure 3.



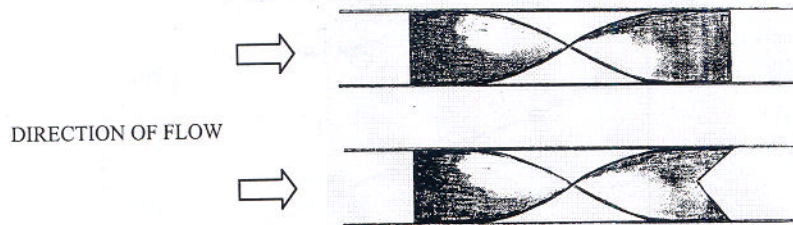
**Figure 3: Critical heat flux for evaporation of water in tubes with twisted tape inserts (Moeck et al, 1964)**

In these experiments, the critical heat flux (CHF) was either decreased or increased relative to the plain tube, depending on the mass flux and the inlet quality. Though the twisted tape may act to redeposit water onto the heated surface, thus increasing CHF, water may also run along the tape itself, denying this water access to the surface and in some cases leading to a *reduction* of CHF.

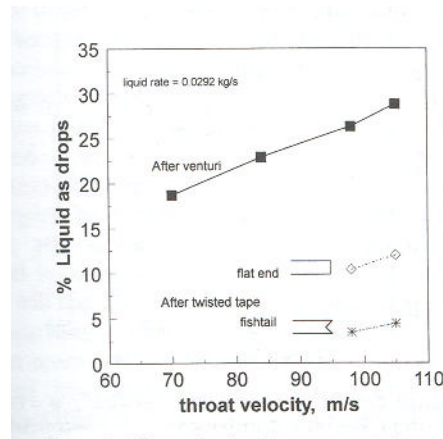
From the point of view of increasing CHF, it may be better to induce swirl using *short lengths of twisted tape*. This leads to downstream deposition of liquid drops onto the heated surface, including some of the water captured by the tape sections but shed at their trailing edges. This concept was investigated in experiments at UKAEA Harwell in the 1960's; a model that describes these experiments and that could be used to optimise such devices is given by Whalley (1979).

Studies of twisted tape devices carried out in a quite different context are described by Hills et al (1996). They used two types of short twisted tapes as illustrated in Figure 4. One was of the conventional form and one had "fishtails" at its trailing edge as shown. For annular air-water flow in a tube, Hills et al measured the entrained droplet flow fraction downstream of the twisted tape devices and upstream of a venturi section. This measurement was achieved by sucking off the liquid film and subtracting the measured film flow rate from the total liquid flow rate. Measurements

were also made downstream of the venturi. Their results are shown in Figure 5. It is clear that the twisted tapes are promoting drop deposition and, interestingly, a significantly better performance is obtained using the tape with fishtails. These results have been confirmed in recent work at Imperial College. As far as I am aware, short twisted tapes with fishtails have not been investigated as a means of increasing CHF. They would appear to offer some potential!



**Figure 4: Twisted tape devices with and without fishtails (Hills et al, 1996)**



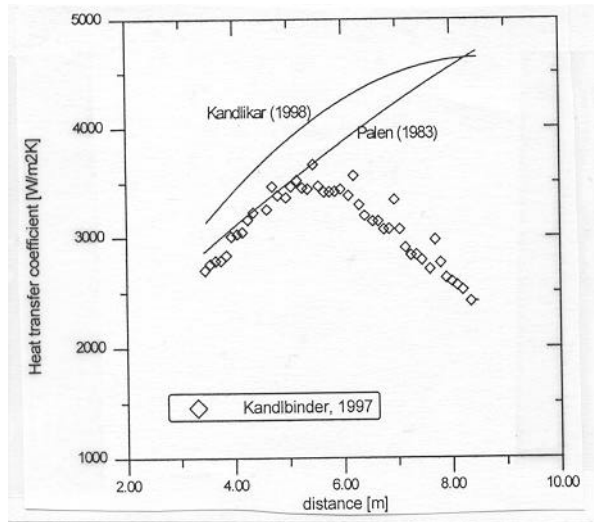
**Figure 5: Effect of twisted tapes on entrained fraction in annular flow (Hills et al, 1996)**

#### 4. FORCED CONVECTIVE MULTICOMPONENT BOILING

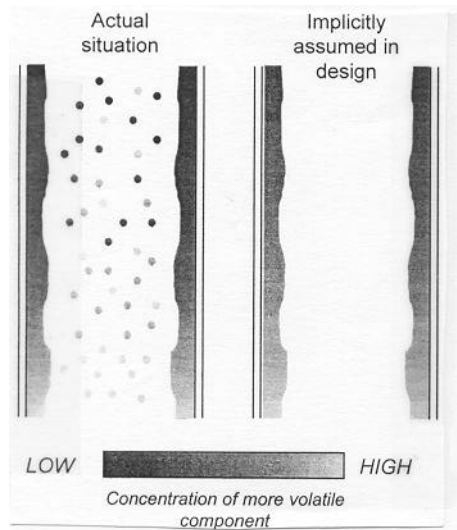
In pool boiling, as referred to in Section 2.6 of Professor Bergles' paper, wall superheat for a multicomponent mixture is higher (and, consequently, heat transfer coefficient lower) than would be expected from a linear interpolation between the single component data points. This effect is probably related to restrictions in bubble growth rate arising from mass transfer limitations. However, for forced convective boiling, where mass transfer is much more rapid, there are reasons to expect that the multicomponent effect would be much less.

It is a commonly accepted view that, in forced convective boiling, and in the absence of nucleate boiling, the heat transfer coefficient should increase with increasing quality. However, in multicomponent boiling, the heat transfer coefficient may *decrease* with increasing quality as shown in Figure 6. This trend is not predicted even by correlations which deal with multi-component mixtures, for example those of

Kandlikar (1998) and Palen (1992), the predictions which are shown on Figure 6. Why does this occur? Well, the explanation seems to lie in the assumptions made in calculating heat transfer coefficients. It is usually implicitly assumed that, at any one cross section, the liquid phase is well mixed and that the interface temperature is the equilibrium temperature between this mixture and the vapour. The difference between this assumption and what actually happens is illustrated in Figure 7.



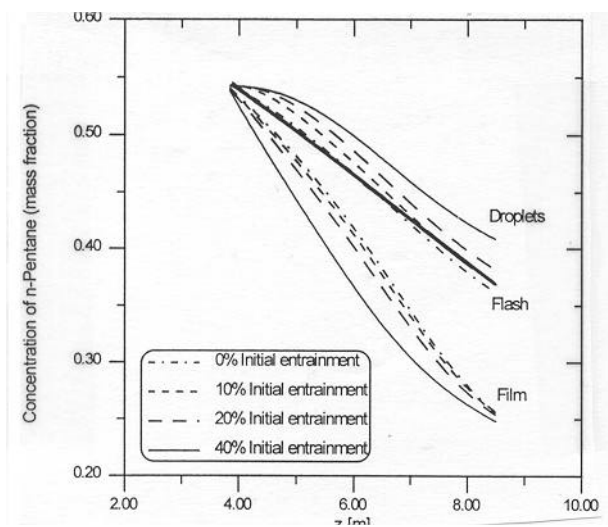
**Figure 6: Data for boiling of a pentane/octane mixture in a vertical tube (Kandlbinder, 1997)**



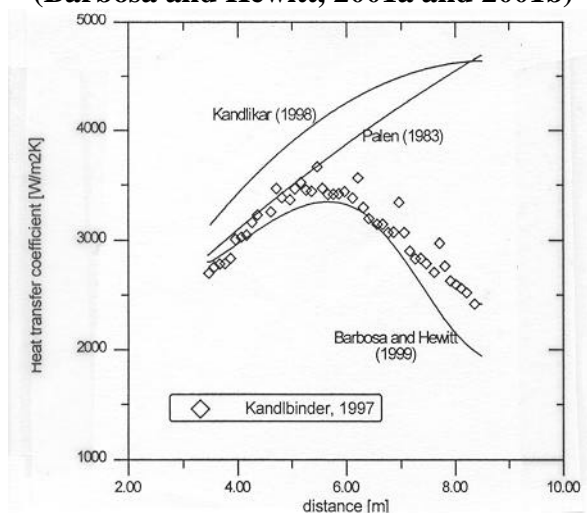
**Figure 7: Differences between actual and assumed processes in multi-component evaporation (Barbosa and Hewitt, 2001a and 2001b)**

In the real system, the liquid flows partly as droplets and partly as a liquid film and differences in mean concentration between the droplets and the film develop with distance along the tube. The droplets have a larger proportion of the more volatile component which means that the interface is hotter and there is an apparent depression of the heat transfer coefficient. These processes can be modelled by adaptation of the single component theory for annular flow to take account of concentration within the film and the droplets (Barbosa and Hewitt, 2001a and 2001b).

Predictions of the developing difference between the concentrations in the droplets in the film are illustrated in Figure 8. These differences lead to changes in the apparent heat transfer coefficient and these changes are in good agreement with those observed in Figure 6 as is illustrated in Figure 9.

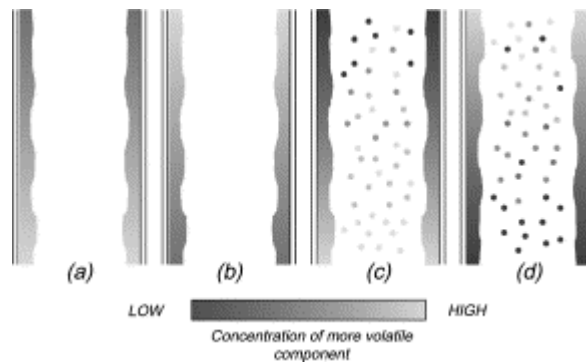


**Figure 8: Differences in concentration between droplet and film in multi-component evaporation (Barbosa and Hewitt, 2001a and 2001b)**

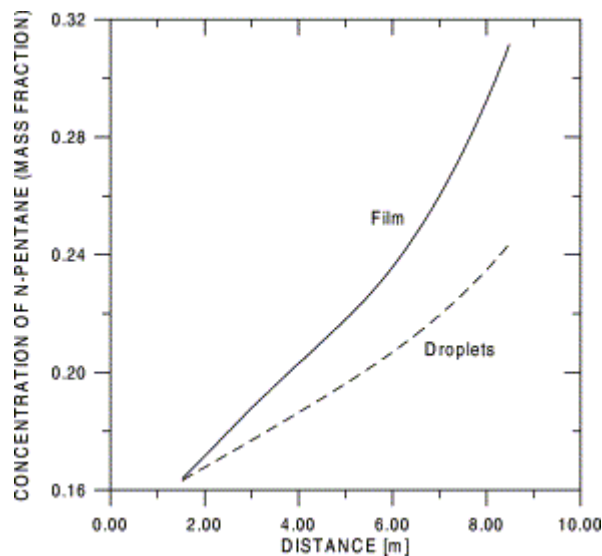


**Figure 9: Prediction of apparent heat transfer coefficient in multi-component boiling using annular flow**

If these droplet interchange processes are occurring in evaporation, then they must also occur in condensation. Figure 10 shows a comparison between evaporation and condensation cases; the droplet interchange processes lead, in condensation, to higher concentrations of the more volatile component in the film than those which would occur if all the liquid were assumed to be well mixed (the normal implicit assumption in design). This would lead, for a given heat flux, to a *reduction* in the interface temperature (relative to that calculated assuming all the liquid was well mixed) and to an *increase* in the apparent heat transfer coefficient, in contrast to the *decrease* observed in evaporation. The calculations shown in Figure 8 were repeated for the hypothetical case of condensation of the same mixture (n-pentane/iso-octane); the results are illustrated in Figure 11 and confirm the expected trends.



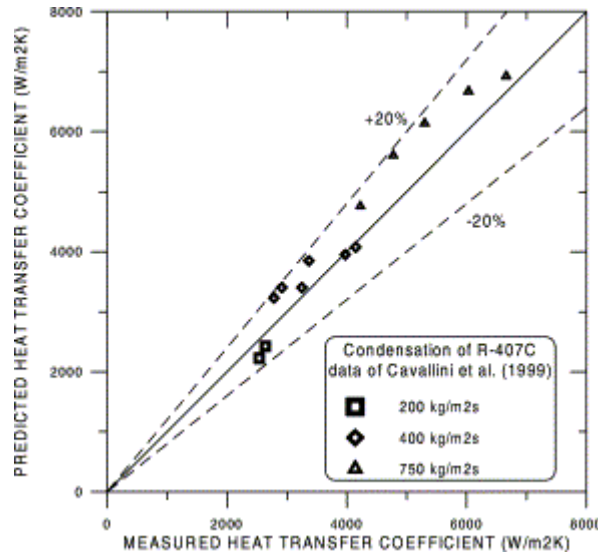
**Figure 10: Comparison of evaporation and condensation. (a) Assumed in design in evaporation, (b) assumed in design in condensation, (c) influence of droplet interchange in evaporation, (d) influence of droplet interchange in condensation. Barbosa et al (2003)**



**Figure 11: Calculations of concentration of n-pentane in liquid film and drops for the hypothetical condensation of the n-pentane/iso-octane mixture (0.7 mole fraction n-pentane) used in the evaporation experiments (Barbosa et al, 2003)**

There is a lack of suitable vertical flow condensation data against which to test these suggestions about condensation. Thus, the calculations were tested against some horizontal flow condensation data kindly supplied by Dr. Luiza Rosetta of the

University of Padua, Italy. This data is described by Cavallini et al (1999) and was for the condensation of R-407C (a mixed refrigerant). For high vapour velocities, the asymmetries introduced by the horizontal flow are less significant. The expected heat transfer coefficient enhancement effects could be discerned in the data and reasonable predictions of the data were obtained with the model as shown in Figure 12 (Barbosa et al, 2003).



**Figure 12. Comparison of predictions with data for condensation of R-407C obtained by Cavallini et al (1999) (Barbosa et al, 2003)**

## 5. CONCLUSION

I think that in all the examples I have discussed here, the common theme is one of unexpected interactions between the hydrodynamic and heat transfer processes. The development of an understanding of these interactions is one of the most important and challenging aspects of our field. It has been a pleasure to share with Warren Rohsenow his fascination with the phenomena associated with flow boiling. The field has always been slow to yield up its secrets – but that has been a good (if sometimes frustrating!) aspect of the subject. One can safely predict that it will be many decades yet before this wonderful goldmine has yielded up all its treasures!

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