Pergamon

Int. J. Heat Mass Transfer. Vol. 39, No. 12, pp. 2495–2504, 1996
Copyright © 1996 Elsevier Science Ltd
Printed in Great Britain. All rights reserved
0017–9310/96 $15.00+0.00

0017–9310(95)00320–7

Nucleate pool boiling heat transfer of pure liquids at low to moderate heat fluxes

R. J. BENJAMIN and A. R. BALAKRISHNAN†
Department of Chemical Engineering, Indian Institute of Technology Madras,
Madras 600 036, India

(*Received* 30 *January* 1995 *and in final form* 14 *August* 1995)

Abstract—A model based on an additive mechanism of heat transfer is proposed for pool boiling of single component systems. The contributing modes of heat transfer are: (i) the heat transferred as latent heat to the evaporating microlayer, (ii) the heat transferred by transient conduction during re-formation of the thermal boundary layer and (iii) the heat transferred by turbulent natural convection from the heating surface not influenced by the bubbles. The heat flux due to the evaporating microlayer is estimated from the instantaneous microlayer thickness during the bubble growth period. An estimate of the nucleation site density is obtained from a literature correlation that includes the boiling surface characteristics. Experimental data from the literature and the present study show very good agreement with the model, validating the postulated mechanism. Copyright © 1996 Elsevier Science Ltd.

INTRODUCTION

Nucleate boiling is characterized by vapour formation owing to heat exchange occurring at preferred sites on a surface that is above the saturation temperature of the liquid being boiled. The present study is concerned with the development of a model based on an additive mechanism of heat transfer comprising of latent heat absorbed by the evaporating microlayer, transient heat conduction during re-formation of the thermal boundary layer and turbulent natural convection in the area outside the influence of the bubbles. The model incorporates the effects of nucleation site density and the rate of bubble growth.

There are a number of empirical correlations to estimate the heat flux during saturated nucleate pool boiling of single component liquids. These are in effect extensions of the single phase forced and free convection correlations to pool boiling. In addition, a number of models are also available. These include mechanistic models, analogy models and hydrodynamic models. Much of this work has been summarized by Van Stralen and Cole [1] and Stephan [2]. The differences between these models lie mainly in the divergent opinions on how the heat energy is transferred from the surface to the fluid and the mode of heat transfer that is dominant. Nucleation and the subsequent vaporisation does not occur at all points on the surface nor at all times. Hence mechanistic models are required to provide an insight of the boiling phenomena.

Han and Griffith [3] subdivided the heating surface into (i) the region of bulk convection (influenced) and (ii) the region of free convection ("not influenced" by the departing bubble). The heat flow from the surface is said to be in two parts: natural convection in the non-influenced region and transient conduction in the influenced region. The area influenced by the bubbles was said to be a circular area having a diameter twice that of the departing bubble. In this region, Han and Griffith postulated the formation of a superheated thermal boundary layer by transient heat conduction which induces bubble formation. The nucleation site density and the dynamic contact angle appear as parameters in the Han and Griffith model. Subsequent studies [1] have shown that as a bubble grows on the surface, a thin liquid film (microlayer) is left under the bubble as a result of very high viscous stresses in the liquid near the wall. The bubble grows by vaporisation of the microlayer. Olander and Watts [4] developed an analytical expression for the microlayer thickness as a function of bubble diameter. Cooper and Lloyd [5] demonstrated the importance of the microlayer thickness in nucleate boiling. However, no analytical expression for the instantaneous thickness of the evaporating microlayer thickness is available. An estimate of this is required to determine the heat absorbed by the growing bubble. This is because as the bubble grows both the microlayer thickness and its area will change and it is this changing volume of liquid that vaporises by absorbing latent heat.

Mikic and Rohsenow [6] modified the Han and Griffith model by including the effects of the heating surface characteristics. But they also assumed that the contribution of the microlayer evaporation is not a predominant factor and the major contribution is the transient conduction mechanism. Judd and Hwang [7] studied the boiling of dichloromethane on a glass surface and proposed a mechanistic model comprising

---

† Author to whom correspondence should be addressed.

NOMENCLATURE

a	area of influence of the bubble on the heating surface [m^2]
A	area of the heating surface [m^2]
Ar	Archimedes number
B	constant in equation (9)
C_p	specific heat [J kg^{-1} K^{-1}]
D	instantaneous bubble diameter [m]
D_d	diameter of dry area under the bubble [m]
D_b	departure diameter of bubble [m]
f	frequency of bubbles [s^{-1}]
Gr	Grashof number
h	heat transfer coefficient W m^{-2} K^{-1}]
Ja	Jacob number
k	thermal conductivity [W m^{-1} K^{-1}]
N	number of active nucleation sites
Pr	Prandtl number
q	heat flux [W m^{-2}]
R_a	roughness [μm]
Re	Reynolds number
t_g	bubble growth time [s]
t_w	waiting time [s]
T	temperature [K]
ΔT	excess temperature ($T_w - T_{sat}$) [K].

Greek symbols

α	thermal diffusivity [m^2 s^{-1}]
β	volumetric coefficient of thermal expansion [K^{-1}]
γ	parameter defined by equation (4)
δ	thickness of the microlayer [m]
λ	latent heat of vaporisation [J kg^{-1}]
μ	viscosity [Pa $\cdot$ s]
ν	kinematic viscosity [m^2 s^{-1}]
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]
ϕ	parameter defined in equation (2).

Subscripts

av	average
B	bubble
l	liquid
ME	microlayer evaporation
NC	natural convection
R	re-formation
sat	saturation
tot	total
v	vapour
w	wall.

of three components: a microlayer evaporation component, a natural convection component and a nucleate boiling component. Bubble frequency, departure diameter and nucleation site density data required for their model was obtained experimentally. The area of influence was obtained by fitting their model to experimental data. Van Stralen [8] envisaged that a part of the growing bubble is surrounded by a superheated liquid layer ('relaxation microlayer') which supplies the vaporisation enthalpy to the bubble and in so doing cools itself. Before bubble initiation occurs again, heat is assumed to be transferred to the liquid by transient heat conduction as hypothesised by Han and Griffith [3]. In the final expression the thickness of the superheated liquid layer appears as a parameter.

The present study focuses on the development of a mechanistic model that takes into account microlayer evaporation, nucleation site density, transient heat conduction, the surface characteristics and the time dependent microlayer thickness.

THE MODEL

The heat removed from the heating surface by the boiling liquid is assumed to be by the following mechanisms:

(i) heat absorbed by the evaporating microlayer (q_{ME});
(ii) heat energy expended in re-formation of the thermal boundary layer (q_R) and
(iii) heat transferred by turbulent natural convection (q_{NC}).

The total boiling heat flux is obtained from the above three fluxes as

$$q_{tot} = \frac{q_{ME} t_g + q_R t_w}{t_g + t_w} + q_{NC} \tag{1}$$

where t_g is the time of bubble growth and t_w is the time for re-formation of the thermal boundary layer. This weighted sum of the first two fluxes is used because the two modes are complementary to each other. The area available for heat transfer is subdivided into (i) active area (or area of influence) over which the first two mechanisms occur alternately and (ii) non-active area over which turbulent natural convection alone occurs. Analytical expressions are developed for each of the above mechanisms.

Microlayer evaporation

A bubble grows by the vaporisation of the thin liquid film left under the bubble. Development of an expression for the instantaneous microlayer thickness is based on the bubble growth description of Unal [9]. Hence all the assumptions made by Unal are assumed here also. If the instantaneous bubble diameter is D and the diameter of the dry area under the bubble is

D_d, then the instantaneous area of the microlayer at the base of the bubble is

$$A_m = \frac{\pi D^2}{4}\left[1-\left(\frac{D_d}{D}\right)^2\right] = \frac{\pi D^2}{4}\phi. \qquad (2)$$

The term within the brackets is assumed to be a constant and is denoted by ϕ. This assumption is justified since the experimental data of Torikai *et al.* [10] indicates that the ratio of "D_d/D" reaches a constant value soon after the bubble starts growing. Sernas and Hooper [11] derived an expression for the heat flux to the bubble from the microlayer as

$$q_B = \frac{(T_w - T_{sat})\gamma k_l}{\sqrt{(\pi\alpha_l t)}} \qquad (3)$$

where

$$\gamma = \sqrt{\left(\frac{k_w\rho_w C_{pw}}{k_l\rho_l C_{pl}}\right)}. \qquad (4)$$

An energy balance on the evaporating microlayer gives (for saturated boiling)

$$-\frac{d}{dt}[m_l C_{pl}(T_w - T_{sat})] = \frac{(T_w - T_{sat})\gamma k_l}{\sqrt{(\pi\alpha_l t)}}\frac{\pi D^2}{4}\phi \qquad (5)$$

where m_l is the instantaneous mass of the evaporating microlayer

$$m_l = A_m(t)\delta\rho_l \qquad (6)$$

where δ is the instantaneous microlayer thickness. Substituting equations (3) and (6) in equation (5) gives

$$\frac{d\delta}{dt} + \frac{2\delta}{D}\frac{dD}{dt} = -\frac{\gamma\alpha_l}{\sqrt{(\pi\alpha_l t)}}. \qquad (7)$$

Using the data of Zmola [12] and Siegel and Keshock [13], the instantaneous diameter of the growing bubble has been correlated and is given by

$$D(t) = B\cdot Ar^{0.135}[Ja\cdot\alpha_l t]^{1/2} \qquad (8)$$

where

Ja: Jacob number = $(\rho_l C_{pl}\Delta T)/\rho_v\lambda$

Ar: Archimedes number = $(g/\nu_l^2)\cdot(\sigma/\rho_l g)^{3/2}$

B: constant = 1.55 for water, CCl_4 and n-hexane
1/1.55 for n-pentane and acetone.

While water, carbon tetrachloride and n-hexane are high density, high boiling point liquids the opposite is true for the other two. The performance of the correlation is shown in Fig. 1.

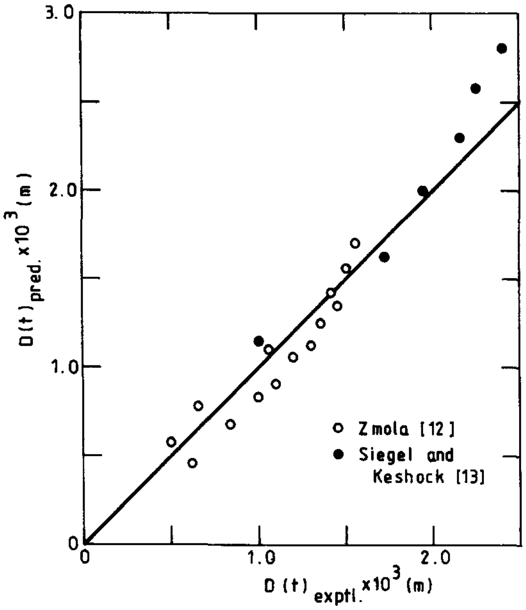

Fig. 1. Performance of correlation for bubble growth rate.

Differentiating equation (8) gives

$$\frac{dD}{dt} = \frac{D}{2t}. \qquad (9)$$

Substituting the above in equation (7) gives

$$\frac{d\delta}{dt} + \frac{\delta}{t} = -\frac{\gamma\alpha_l}{\sqrt{(\pi\alpha_l t)}}. \qquad (10)$$

The above ordinary differential equation can be solved with integrating factor t and the solution is

$$\delta = \frac{2\gamma}{3}\sqrt{\left(\frac{\alpha_l t}{\pi}\right)} - \frac{C}{\sqrt{t}}. \qquad (11)$$

It is postulated that the microlayer vaporises almost completely by the time the bubble is fully developed so that the microlayer thickness δ is almost zero. This gives a boundary condition to evaluate the constant C in equation (11), i.e.

$$\textit{when } t = t_g \textit{ (growth-time)}, \delta = 0. \qquad (12)$$

Therefore,

$$C = \frac{2\gamma\alpha_l}{3\cdot\sqrt{(\pi\alpha_l)}}t_g^{3/2}. \qquad (13)$$

Using this in equation (11) gives the instantaneous thickness of the microlayer as

$$\delta(t) = \frac{2\gamma}{3t}\sqrt{\left(\frac{\alpha_l}{\pi}\right)}(t_g\sqrt{t_g} - t\sqrt{t}). \qquad (14)$$

The volume of the microlayer evaporated (V_{ME}) is given by

$$V_{\mathrm{ME}} = \frac{\int_0^{t_g} A_m(t)\cdot\delta(t)\,\mathrm{d}t}{\int_0^{t_g} \mathrm{d}t}. \tag{15}$$

Substituting for $A_m(t)$ and $\delta(t)$ from equations (2) and (14) in the above, gives

$$V_{\mathrm{ME}} = \frac{\gamma\phi\sqrt{\pi}}{10}B^2 Ar^{0.27}(\alpha_l t_g)^{3/2}\cdot Ja. \tag{16}$$

This volume of liquid evaporates during time t_g. Hence, the heat flux associated with it is given by

$$q_{\mathrm{ME}} = \frac{\gamma\phi\sqrt{\pi}}{10}B^2 Ar^{0.27} Ja(\alpha_l)^{3/2}\cdot\sqrt{t_g}\rho_l\lambda\left(\frac{N}{A}\right) \tag{17}$$

where N/A is the nucleation site density.

Thermal boundary layer re-formation

Once a bubble departs from a nucleation site, fresh liquid comes into contact with the heating surface. This occurs during the "waiting time" (t_w) at the end of which nucleation occurs at the same site once again. During this waiting time the liquid receives heat by transient conduction. At low heat fluxes Roemer [14] observed that this re-formation of the thermal boundary layer is complementary to the microlayer evaporation mechanism. Each bubble cycle, therefore, consists of a growth period and a waiting period.

Assuming only pure conduction to the liquid in the active area during the waiting period, this mechanism may be modelled as transient conduction to a semi-infinite medium (the liquid in this case) with a step change in temperature $(T_w - T_{\mathrm{sat}})$ at the surface. The instantaneous heat flux for such a case is given by Carslaw and Jaeger [15] as

$$q_{\mathrm{cond}} = \frac{k_l(T_w - T_{\mathrm{sat}})}{\sqrt{(\pi\alpha_l t)}}. \tag{18}$$

The average heat flux during the waiting period will be

$$(q)_{\mathrm{avg}} = \frac{\int_0^{t_w} q\,\mathrm{d}t}{\int_0^{t_w}\mathrm{d}t} \tag{19}$$

$$= \frac{2k_l(T_w - T_{\mathrm{sat}})}{\sqrt{(\pi\alpha_l t_w)}}. \tag{20}$$

As each bubble departs, it carries along with it a portion of the super heated thermal boundary layer. Han and Griffith [3] have shown that this portion is four times the projected area of the bubble at departure. This area is the area of influence 'a'. That is

$$a = 4\frac{\pi D_b^2}{4} = \pi D_b^2. \tag{21}$$

The bubble departure diameter is obtained from the equation due to Stephan [2], which is

$$D_b = 0.25\sqrt{\left(\frac{\sigma}{g(\rho_l - \rho_v)}\right)}\cdot\left[1 + \left(\frac{Ja}{Pr}\right)^2\cdot\frac{1}{Ar}\right]^{1/2}. \tag{22}$$

Equation (20) is valid for a single nucleation site. Hence, for all the nucleation sites on the surface

$$q_R = 2\sqrt{\left(\frac{k_l\rho_l C_{pl}}{\pi t_w}\right)}\cdot\left(\frac{N}{A}\cdot a\right)(T_w - T_{\mathrm{sat}}). \tag{23}$$

The assumption here is that the areas of influence of neighbouring bubbles do not interfere with each other, which is true only in the low heat flux regime. The average heat flux during the entire bubble cycle is

$$q_{\mathrm{cycle}} = \frac{q_{\mathrm{ME}}\cdot t_g + q_R\cdot t_w}{t_g + t_w} \tag{24}$$

where t_g and t_w are related to the bubble frequency 'f' by

$$f = \frac{1}{t_g + t_w} \tag{25}$$

and 'f' can be estimated from a correlation by Malenkov (reported by Stephan [2]). Van Stralen *et al.* [16] assumed that the waiting time is three times the growth time

$$t_w = 3t_g. \tag{26}$$

Using equations (17), (23), (25) and (26) in equation (24) gives q_{cycle}.

Turbulent natural convection

The fraction of the total area of the heating surface not influenced by bubbles is $[1 - (N/A)\cdot a]$. McAdams [17] estimated the heat transfer coefficient in turbulent natural convection using

$$h = \frac{0.14k_l}{L}(Gr\cdot Pr)^{1/3}. \tag{27}$$

Using this, the heat flux due to natural convection can be estimated from

$$q_{\mathrm{NC}} = h\left[1 - \left(\frac{N}{A}\right)\cdot a\right]\cdot(T_w - T_{\mathrm{sat}}). \tag{28}$$

RESULTS

The total boiling heat flux is estimated from equation (1). In a parallel study, Benjamin and Balakrishnan [18] proposed a correlation based on their own and literature data for the nucleation site density for a variety of liquids, surfaces and surface finishes

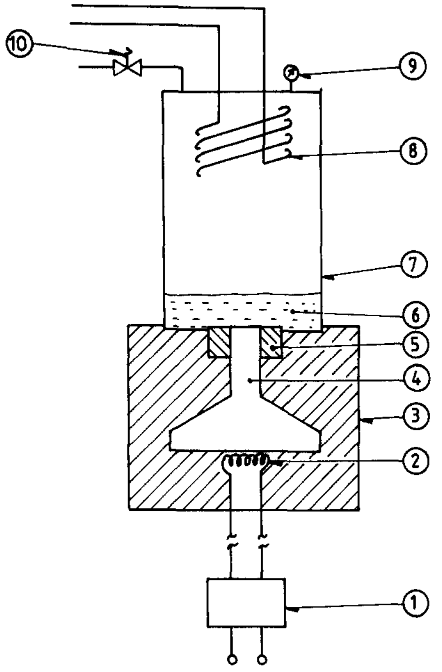

Fig. 2. Sketch of the experimental set-up.

as

$$\left(\frac{N}{A}\right) = 218.8(\theta)^{-0.4}(Pr)^{1.63}\left(\frac{1}{\gamma}\right)(\Delta T)^{3} \qquad (29)$$

where

$$\theta = 14.4-4.5\left(\frac{R_{\mathrm{A}}P}{\sigma}\right)+0.4\left(\frac{R_{\mathrm{A}}P}{\sigma}\right)^{2}. \qquad (30)$$

The physical properties of the heating surfaces and the boiling liquids were obtained from *Perry's Chemical Engineer's Handbook* [19], Piret and Isbin [20] and Gallant [21]. R_a is the surface roughness. Once a surface is polished with a particular grade of emery paper, the R_a value is measured using an instrument called the "Perth-o-meter". R_a is the average value of the ordinates from the mean line (see Fig. 3). The coordinates are summed up without considering their algebraic signs

$$R_{\mathrm{a}} = \frac{1}{l}\int_{0}^{l} |y|\,\mathrm{d}x \qquad (31)$$

and R_a is expressed in μm (i.e. 10^{-6} m). The correlation shown in equation (29) is a dimensional equation and care should be observed while using it.

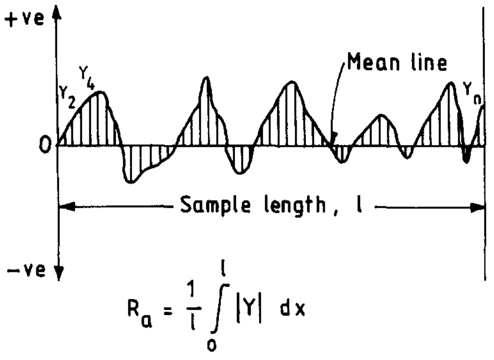

Fig. 3. Definition of surface roughness: the R_a value.

A sketch of the experimental set-up used to obtain pool boiling data is shown in Fig. 2. It consisted of a double wall glass column of height 25 cm with vacuum in the annular space. The inner diameter was 93 mm. The column is held by tie-rods between circular grooves fitted with oil seals on two square stainless steel slabs of side 150 mm and thickness 10 mm. A hollow cylinder made of Teflon is screwed onto the bottom plate. A heating block is screwed on to the inside of this cylinder thus avoiding direct contact with the bottom plate. The bottom of the plate is electrically heated. Temperatures are measured at four points along the axis of the block using resistance thermometers and the heat flux and surface temperature are thereby measured accurately. The liquid temperature is also measured using a resistance thermometer. For a given liquid, surface material and surface finishes, boiling experiments were conducted at different excess temperatures. The process was repeated for different surface materials, surface finishes and other liquids. The range of surface materials, surface finishes and liquids used in this study are summarized in Table 1.

Figure 4(A) shows the comparison of the model with the experimental data of Kurihara and Myers [22] for water boiling on a copper surface finished with a 4/0 grade emery paper. Since the R_a value was not explicitly stated by Kurihara and Myers, a copper block was polished with 4/0 emery paper and the R_a value measured using the Perth-o-meter. The R_a value of 0.07 μm so obtained was used to evaluate the nucleation site density from equation (29) and used in the present model to estimate the heat flux. Similarly Figs 4(B)–(D) show the comparison of the model with the experimental data on the same surface for CCl_4, acetone and n-hexane. Figure 5 shows the comparison of the present model with the data of Zuber [23] obtained on a Nickel surface finished with a 4/0 emery paper. Here the R_a value was obtained by polishing a nickel block with a 4/0 emery paper. The liquid used for boiling was n-pentane. Figures 6 to 9 show the comparison of the model with the data obtained in the present study. The heating surfaces were stainless steel and aluminum finished with 2/0, 3/0 and 4/0 grade emery paper. The liquids were again water, CCl_4, acetone and n-hexane. Figures 4–9 clearly

Table 1. Summary of range of variables used in the present study

Surfaces	Surface finish	Boiling liquid	Figure number where data is shown	Source of data
Copper	4/0 emery paper $R_a = 0.07\ \mu m$	water CCl_4 acetone n-hexane	Fig. 4	Kurihara and Myers [22]
Nickel	4/0 emery paper $R_a = 0.045\ \mu m$	n-pentane	Fig. 5	Zuber [23]
Aluminum	2/0 emery paper $R_a = 1.17\ \mu m$	water CCl_4 acetone n-hexane	Fig. 6	Present study
Aluminum	3/0 emery paper $R_a = 0.89\ \mu m$	water CCl_4 acetone n-hexane	Fig. 7	Present study
Aluminum	4/0 emery paper $R_a = 0.52\ \mu m$	water CCl_4 acetone n-hexane	Fig. 8	Present study
Stainless steel	2/0 emery paper $R_a = 0.19\ \mu m$	CCl_4 acetone n-hexane	Fig. 9	Present study
Stainless steel	3/0 emery paper $R_a = 0.18\ \mu m$	CCl_4 acetone n-hexane	Fig. 9	Present study
Stainless steel	4/0 emery paper $R_a = 0.16\ \mu m$	CCl_4 acetone n-hexane	Fig. 9	Present study

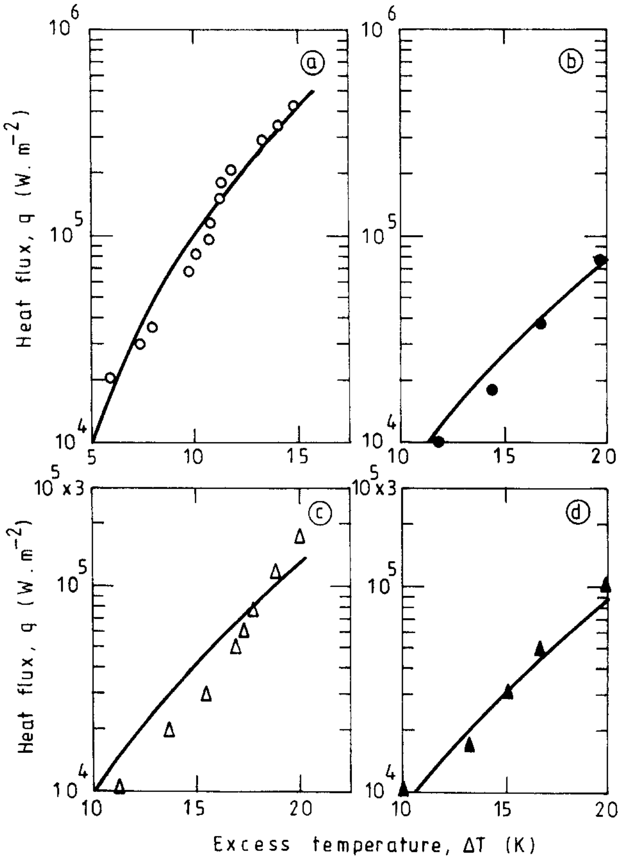

Fig. 4. Comparison of the model with the data of Kurihara and Myers [22]; boiling surface: copper finished with 4/0 emery paper ($R_a = 0.07\ \mu m$); liquids used for boiling: (a) water, (b) CCl_4, (c) acetone and (d) n-hexane.

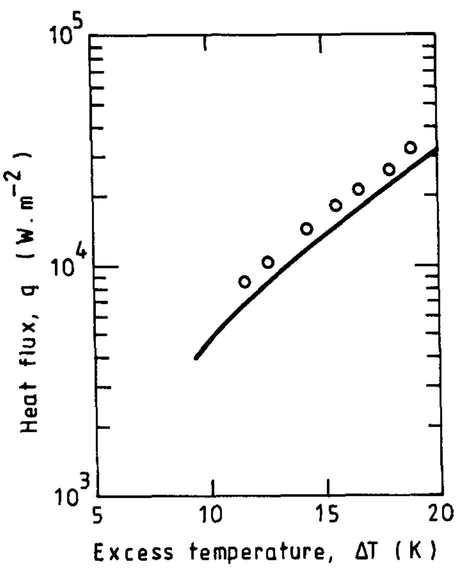

Fig. 5. Comparison of the model with the data of Zuber [23]; boiling surface: nickel finished with 4/0 emery paper (R_a = 0.045 μm); liquid used for boiling: n-pentane.

show that the agreement between the model and the experimental data, both from the literature as well as from the present study are very good.

DISCUSSION

In Fig. 8, the data shown was obtained with aluminum finished with 4/0 grade paper. This is the same grade of emery paper used by Kurihara and Myers [22], but with copper. Aluminum being a softer material than copper, however, gives a R_a value of 0.52 μm as opposed to 0.07 μm obtained for copper for the same grade of emery paper. Since the nucleation site density is inversely proportional to the R_a value, at very small values of R_a, for the same grade of emery paper the nucleation site density obtained on aluminum is lower than for copper. Hence, for a given excess temperature the heat flux obtained on a copper surface is higher for a liquid. This appears somewhat contradictory to conventional wisdom. That is a rough surface should give a higher heat flux. However, here micro-roughness is being investigated and the smoother the surface, the nucleation cavities

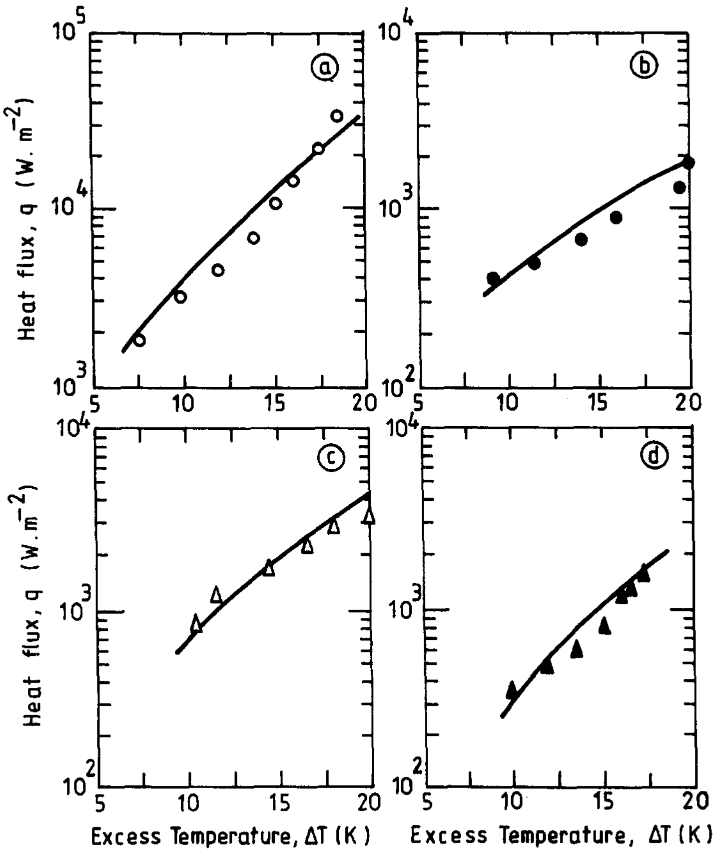

Fig. 6. Comparison of the model with present data; boiling surface: aluminum finished with 2/0 emery paper (R_a = 1.17 μm); liquids used for boiling: (a) water, (b) CCl_4, (c) acetone and (d) n-hexane.

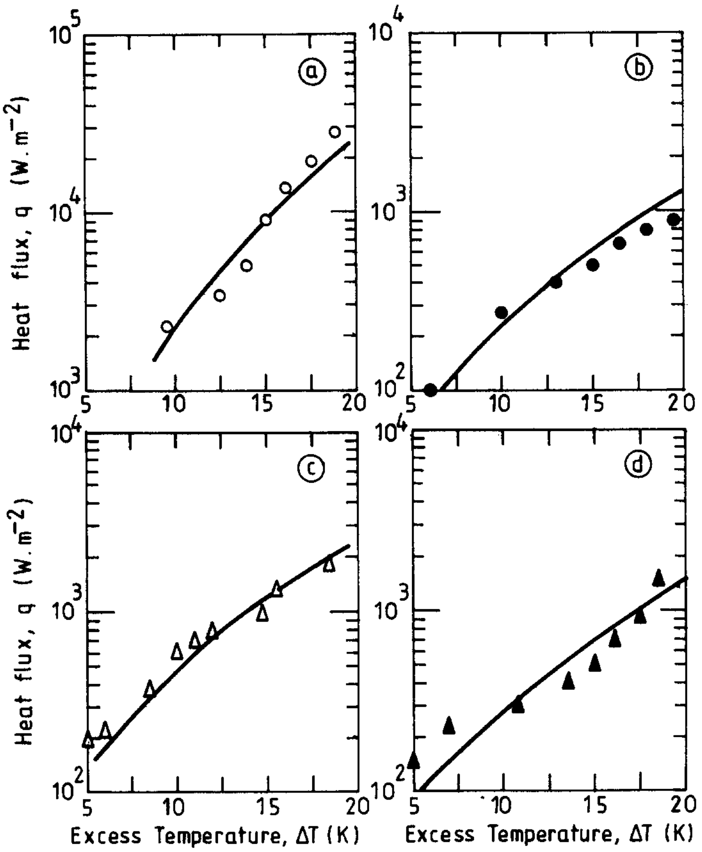

Fig. 7. Comparison of the model with present data; boiling surface: aluminum finished with 3/0 emery paper (R_a = 0.89 μm); liquids used for boiling: (a) water, (b) CCl_4, (c) acetone and (d) n-hexane.

will be smaller leading to smaller bubbles and higher bubble frequencies leading to larger fluxes. Benjamin and Balakrishnan [18] have discussed the limits in their correlation for the nucleation site density, and explained why rougher surfaces do not yield smaller (N/A) values.

It can also be seen from the figures that the boiling curve is much more steep for water in comparison to the other three organic liquids. This is because the latent heat of water is much higher than for the other liquids. Hence for a given excess temperature, the heat flux is almost an order of magnitude greater for water than for the organic liquids. The boiling behaviour of water and the other organic liquids seem to be segregated in another way also. q_{cycle} contributes nearly 90% of the total flux in the case of water and about 75–80% for the organic liquids, while the turbulent natural convection is very small. This can also be explained by the large difference in latent heats between water and the organic liquids. Furthermore, even though the boiling points between the organic liquids is quite large, their behaviour is quite similar, mainly because their latent heats and densities are quite close.

Moreover, the flux due to microlayer evaporation alone amounts to about 50% for water and about 45% for the organic liquids. This is the contribution averaged over a cycle. This shows that the present approach is in contrast with the approach of Mikic and Rohsenow [6], who assumed that although microlayer evaporation exists, its contribution to the total is negligible. The model developed in the present study is closer in approach to that of Judd and Hwang [7]; but their model does not take into account surface finish and the 'area of influence' is obtained only by fitting the model to the experimental data. The present model is general and only requires information on physical properties of the liquid and surface roughness characteristics.

The model developed and the nucleation site density correlation used are valid only in the low to moderate heat flux regime. At higher fluxes, the frequency of the departing bubbles becomes very high leading to the breakdown of the evaporation–replenishment cycle. Furthermore, bubbles interact and coalesce with each other and so the terms 'area of influence' and 'nucleation site density' are no longer meaningful.

CONCLUSIONS

A model has been proposed for the heat flux in pool boiling in the low to moderate heat flux regime. The model has been validated with experimental data, both from the literature as well as from the present

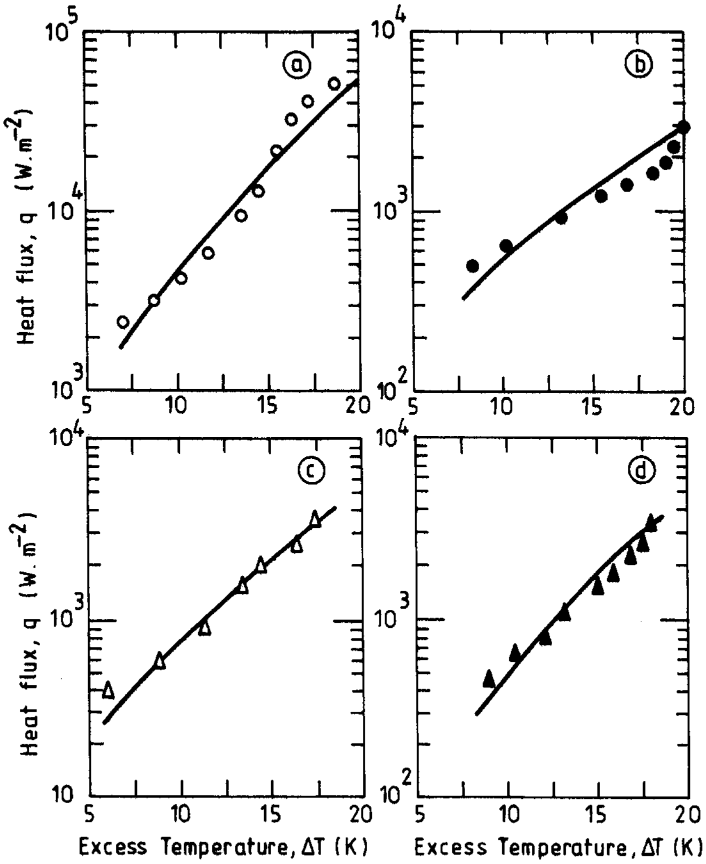

Fig. 8. Comparison of the model with present data; boiling surface: aluminum finished with 4/0 emery paper ($R_a = 0.52$ μm); liquids used for boiling: (a) water, (b) CCl_4, (c) acetone and (d) n-hexane.

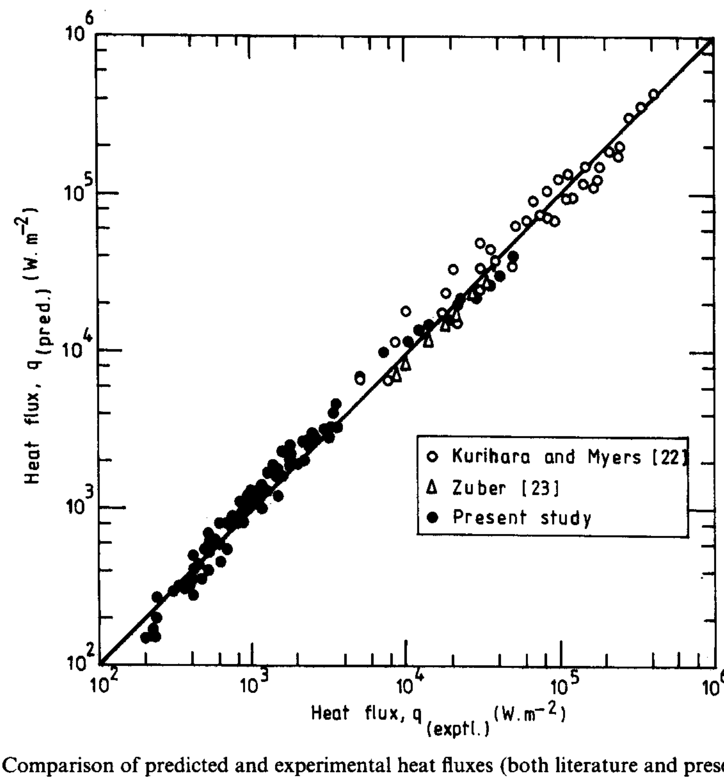

Fig. 9. Comparison of predicted and experimental heat fluxes (both literature and present data).

study. The contributing modes of heat transfer are the heat flux due to microlayer evaporation, the transient heat conduction during re-formation of the thermal boundary layer and the turbulent natural convection. The contribution of the heat flux to microlayer evaporation is as high as 45–50%. The surface roughness is an important parameter and can be obtained from a literature correlation in the micro-roughness range.

Acknowledgements—This study was funded by a research grant from the Department of Atomic Energy, Government of India through the Board of Research in Nuclear Sciences, Bhabha Atomic Research Centre, Bombay, India.

REFERENCES

1. S. J. D. Van Stralen and R. Cole, *Boiling Phenomena*, Vol. 1. Hemisphere, New York (1979).
2. K. Stephan, *Heat Transfer in Condensation and Boiling*, pp. 135–136; 145–149. Springer, New York (1992).
3. C. Y. Han and P. Griffith, The mechanism of heat transfer in nucleate pool boiling—I and II, *Int. J. Heat Mass Transfer*, **8**, 887–914 (1965).
4. R. R. Olander and R. G. Watts, An analytical expression for microlayer thickness in nucleate boiling, *Trans. ASME J. Heat Transfer* **91**, 178–180 (1969).
5. M. G. Cooper and A. J. P. Lloyd, The microlayer in nucleate boiling, *Int. J. Heat Mass. Transfer* **12**, 895–913 (1969).
6. B. B. Mikic and W. M. Rohsenow, A new correlation of pool boiling data including the effect of heating surface characteristics, *Trans. ASME J. Heat Transfer* **91**, 245–250 (1969).
7. R. L. Judd and K. S. Hwang, A comprehensive model for nucleate pool boiling heat transfer including microlayer evaporation, *Trans. ASME J. Heat Transfer* **98**, 623–629 (1976).
8. S. J. D. Van Stralen, The mechanism of nucleate pool boiling in pure liquids and in binary mixtures—II, *Int. J. Heat Mass Transfer* **9**, 1021–1046 (1966).
9. H. C. Unal, Maximum bubble diameter, maximum bubble growth time and bubble growth rate during subcooled nucleate flow boiling of water up to 17.7 MN m^{-2}, *Int. J. Heat Transfer* **19**, 643–649 (1976).
10. K. Torikai, M. Hori, M. Akiyama, T. Kobori and H. Adachi, Boiling heat transfer and burn out mechanism in boiling water cooled reactor, *Third United Nations International Conference on the Peaceful Uses of Atomic Energy*, Paper No. 28/P/580 (1964).
11. V. Sernas and F. C. Hooper, The initial vapour bubble growth on a heated wall during nucleate boiling, *Int. J. Heat Mass Transfer* **12**, 1627–1639 (1969).
12. P. Zmola, Investigation of the mechanism of boiling in liquids, Ph.D. Thesis, Purdue University, W. Lafayette, IN (1950).
13. R. Siegel and E. G. Keshock, Effects of reduced gravity on nucleate boiling bubble dynamics in water, *A.I.Ch.E.J.* **20**, 509–517 (1964).
14. R. B. Roemer, Surface temperature fluctuations during steady state boiling, *Int. J. Heat Mass Transfer* **13**, 985–996 (1970).
15. H. S. Carslaw and J. C. Jaeger, *Conduction of Heat in Solids* (2nd Edn). Oxford University Press, London (1959).
16. S. J. D. Van Stralen, M. S. Sohal, R. Cole and W. M. Sluyter, Bubble growth rates in pure and binary systems: combined effect of relaxation and evaporation microlayers, *Int. J. Heat Mass Transfer* **18**, 453–467 (1975).
17. W. H. McAdams, *Heat Transmission* (3rd Edn), p. 180, McGraw-Hill, New York (1945).
18. R. J. Benjamin and A. R. Balakrishnan, Effect of surface micro-roughness and liquid properties on nucleation site density in pool boiling, personal communication.
19. *Perry's Chemical Engineer's Handbook* (6th Edn), (Edited by R. H. Perry, D. W. Green and J. O. Maloney). McGraw-Hill, New York (1984).
20. E. L. Piret and H. S. Isbin, Natural circulation evaporation two phase heat transfer, *Chem. Engng Prog.* **50**, 305–311 (1954).
21. R. W. Gallant, Physical properties of hydrocarbons, *Hydrocarbon Process.* **46**, 121–129 (1967).
22. H. M. Kurihara and J. E. Myers, The effects of superheat and surface roughness on boiling coefficients, *A.I.Ch.E.J.* **6**, 83–91 (1960).
23. N. Zuber, Nucleate boiling: the region of isolated bubbles and the similarity with natural convection, *Int. J. Heat Mass Transfer* **6**, 53–78 (1963).