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The effect of heater wall thickness on heat transfer in nucleate pool-boiling at high heat flux

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Abstract—The effect of heater wall thickness, macrolayer thickness, wall superheat and heat flux on nucleate boiling heat transfer has been studied. The equations governing transient conduction in macrolayer and heater wall have been solved analytically. The results show that the heat transfer rate can increase or decrease with increase in thickness of heater wall depending upon the dimensionless parameter $k_1 \Delta T/\delta q_i$.

INTRODUCTION

A DETAILED study of pool-boiling heat transfer reveals that there is no general agreement regarding the mechanism and the extent of the influence of various parameters affecting it. This may be due to the fact that pool-boiling mechanism differs considerably in different regimes of boiling [1] and hence a general model cannot be arrived at, on the basis of experiments conducted or models proposed, for different regimes of boiling.

The presence of a thin layer of liquid known as 'microlayer' between a bubble and heated surface at low heat flux has already been well established. But at high heat flux, the bubbles coalesce and form a vapour mass entrapping a relatively thicker film of liquid between the growing vapour mass and the surface. Yu and Mesler [2] termed this layer as 'macrolayer' to distinguish it from the microlayer.

Various investigations on nucleate pool-boiling have shown that the thermo-physical properties and thickness of heating surface may affect the boiling heat transfer coefficient. Farber and Scorah [3] obtained different boiling curves for different heater materials. Sharp [4] carried out experiments on heater wall of various materials and concluded that a decrease in heat transfer coefficient as a result of decrease of the heater thickness was due to the decrease in the heater thermal capacity. Bliss *et al.* [5] performed experiments on horizontal stainless-steel tubes plated with copper, zinc, tin, nickel, chromium and cadmium to a thickness of 0.005 in. Their experimental results showed that of all platings tested, copper produced the largest increase in the boiling heat transfer coefficient. However, Magrini and Nannie [6] observed a higher heat transfer rate for nickel and tin below certain limiting thickness, whereas no appreciable change was noticed for copper heaters. Chuck and Myers [7] observed only slight influence of the heater thickness on heat transfer coefficient.

There is need for further investigation into the effect of heater wall thickness and other parameters on nucleate pool-boiling. In this paper, the results of the detailed analysis about the influence of the heater thickness and some other parameters like macrolayer thickness, wall superheat, and heat flux on nucleate pool-boiling heat transfer are presented. It is expected that this type of analysis based purely on transient heat conduction through heater and macrolayer should clarify the influence of these parameters under high heat flux conditions when major portion of heat transfer can be assumed to be through conduction [8] across macrolayer.

HEAT TRANSFER MODEL

A macrolayer is formed on the heating surface during the growth period of the vapour mass. The vapour mass above the liquid layer, owing to its greater pressure on the inside, exerts pressure in all directions preventing mixing of the macrolayer with the surrounding liquid. The thickness of the macrolayer is sufficiently thin such that the convective currents in the layer can be neglected and the flow of heat through it can be considered as one-dimensional heat conduction along the axis of the heated surface. The presence of vapour stems in the liquid layer and the change of thickness of the macrolayer due to evaporation is neglected for simplicity.

The heat transfer model for this case is depicted in Fig. 1. This is a case of indirect heating and hence not valid for nucleate boiling experiments using electrically heated wires or strips. Heat is transferred through a composite wall comprising a liquid macrolayer of thickness δ $(0 < y < \delta)$ over a solid heater of thickness a $(-a < y < 0)$. An initial temperature gradient is assumed in the solid. Face $y = \delta$ is maintained at T_{sat} $(\tau > 0)$ and face $y = -a$ has a constant heat input q_i into the solid.

If $T_l(y, \tau)$ and $T_s(y, \tau)$ denote the temperature profiles in the macrolayer and heater respectively, the heat transfer equations can be written as

$$\frac{\partial V_l}{\partial \tau} = \alpha_l \frac{\partial^2 V_l}{\partial y^2}; \quad 0 \leqslant y \leqslant \delta; \ \tau > 0 \tag{1}$$

$$\frac{\partial V_s}{\partial \tau} = \alpha_s \frac{\partial^2 V_s}{\partial y^2}; \quad -a \leqslant y \leqslant 0; \ \tau > 0. \tag{2}$$

NOMENCLATURE

a heater thickness [m]
b constant [m^{-1}]
k thermal conductivity [$\mathrm{W\,m^{-1}\,K^{-1}}$]
q heat flux [$\mathrm{W\,m^{-2}}$]
T temperature [K]
ΔT wall superheat [K]
V dimensionless temperature
y distance from the heating surface [m]
Z dimensionless parameter, $k_l \Delta T/\delta q_i$.

Greek symbols
α thermal diffusivity [$\mathrm{m^2\,s^{-1}}$]
β_m as defined in equation (11A)
δ macrolayer/microlayer thickness [m]
τ time [s].

Subscripts
av average
i input
l liquid
lv liquid–vapour interface
s solid
sat saturation
w initial.

With boundary conditions as:

$$k_s\left(\frac{\partial V_s}{\partial y}\right)_{y=0} = k_l\left(\frac{\partial V_l}{\partial y}\right)_{y=0} \tag{3}$$

$$V_s(0,\tau) = V_l(0,\tau) \tag{4}$$

$$V_l(\delta,\tau) = 0 \tag{5}$$

$$-k_s\left(\frac{\partial V_s}{\partial y}\right)_{y=-a} = \frac{q_i}{T_w - T_{sat}} \tag{6}$$

and initial conditions as

$$V_l(y,0) = 1 \tag{7}$$

$$V_s(y,0) = 1 + by \tag{8}$$

where

$$V = \frac{T - T_{sat}}{T_w - T_{sat}}$$

b is determined so as to satisfy the initial conditions having $(T_w - T_{sat})$ as the super heat of the heated surface and q_i as the heat input rate such that

$$b = -\frac{q_i}{k_s(T_w - T_{sat})}. \tag{9}$$

Solution of equations (1)–(8) gives

$$T_l(y,\tau) = T_{sat} + \Delta T\left[\frac{q_0}{k_l}(\delta - y) - 2\sum_{m=1}^{\infty}\frac{UE}{\beta_m^2 R}(C_a C_{yk} - \sigma S_a S_{yk})\right] \tag{10}$$

$$T_s(y,\tau) = T_{sat} + \Delta T\left[\frac{q_0}{k_s}\left(\frac{k_s}{k_l}\delta - y\right) - 2\sum_{m=1}^{\infty}\frac{UE}{\beta_m^2 R}(C_a C_y - S_a S_y)\right] \tag{11}$$

where β_m is the mth positive root of the equation

$$C_{dk} C_a - \sigma S_{dk} S_a = 0 \tag{11A}$$

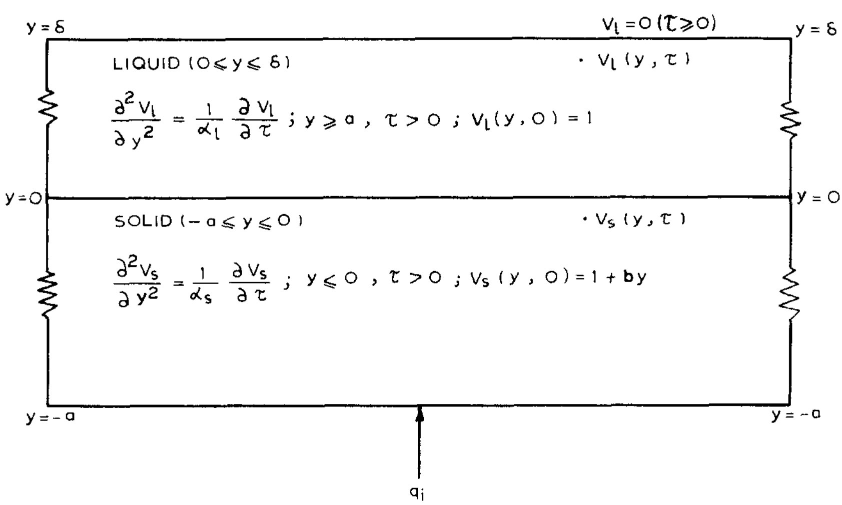

FIG. 1. Heat transfer model.

and

$$C_{dk} = \cos\left(\frac{\beta_m \delta}{K}\right); \quad C_a = \cos(\beta_m a); \quad S_{dk} = \sin\left(\frac{\beta_m \delta}{K}\right).$$

$$S_a = \sin(\beta_m a); \; K = \sqrt{\frac{\alpha_1}{\alpha_s}}; \; \sigma = \frac{k_s}{k_1}K; \; q_0 = \frac{q_i}{\Delta T}$$

$$U = \frac{Q_m C_{dk} - A_m \beta_m S_a + bA_m C_{dk} - \sigma b A_m S_{dk} S_a}{A_m S_a}$$

$$Q_m = \frac{q_0 \alpha_s \beta_m}{k_s}; \; A_m = \alpha_s \beta_m; \; E = \exp(-A_m \beta_m \tau)$$

$$C_{yk} = \cos\left(\frac{\beta_m y}{K}\right); \; S_{yk} = \sin\left(\frac{\beta_m y}{K}\right);$$

$$C_y = \cos(\beta_m y), \; S_y = \sin(\beta_m y)$$

$$R = (a + \sigma D_k) S_a C_{dk} + (D_k + a\sigma) C_a S_{dk};$$

$$D_k = \delta / K.$$

Heat flux at $y = \delta$, q_{lv}, is given by

$$q_{lv} = k_1 \left(\frac{\partial T_1}{\partial y}\right)_{y=\delta}$$

$$= \Delta T \left[q_0 - 2\frac{k_1}{K} \sum_{m=1}^{\infty} \frac{UE}{\beta_m R} (C_a S_{dk} + \sigma S_a C_{dk}) \right]. \quad (12)$$

Heat flux, averaged over time interval τ, may be defined as

$$q_{av} = \frac{1}{\tau} \int_0^\tau q_{lv} \, d\tau$$

$$= \frac{\Delta T}{\tau} \left[q_0 \tau - 2\frac{k_1}{K} \sum_{m=1}^{\infty} \frac{U}{\beta_m R} \times (C_a S_{dk} + \sigma S_a C_{dk}) \left(\frac{E-1}{-A_m \beta_m} \right) \right]. \quad (13)$$

RESULTS

With water as macrolayer liquid and copper as heater material, the numerical results of equations (10)–(13) are obtained for different macrolayer, heater thickness, initial superheat and heat flux values for discussing the influence of each parameter on the heat transfer rate.

1. *Temperature profile*

Figure 2 shows the temperature profiles in the macrolayer, 30 μm thick, formed on copper heaters (a) 75 μm and (b) 0.075 m thick, with initial superheat of 40 K. It can be seen that the slope of the profiles changes faster up to about 1 ms and thereafter the rate of change is slow and becomes linear. Although the time taken for the attainment of linear profile is not influenced, the solid–liquid interface temperature is a definite function of heater thickness. The approach to steady state is faster in thinner heaters because of the lesser penetration time needed. Further it was found that the temperature distribution approaches linearity faster as the macrolayer thickness is reduced. Bhat *et al.* [8] also observed a similar effect of macrolayer thickness on the temperature profile. They have assumed a simple model, with constant wall temperature, and ignored the effect of heater thickness. Hence a comparison with their results may not be strictly valid except for the general observations.

2. *Effect of heater thickness*

Figure 3 shows that the liquid–vapour interface heat transfer rate, q_{lv}, decreases or increases with the increase in heater thickness according to whether $k_1 \Delta T/\delta$ is less than or greater than q_i. In the former case the ratio q_{lv}/q_i decrease to a minimum value below unity and gradually approaches unity while in the latter case, the ratio decreases and becomes unity without attaining values less than unity. In both cases, even though the time taken to attain steady state is the same, the wall superheat changes resulting in either heating (former case) or cooling (latter case) of the solid–liquid interface while tending to attain steady state.

This leads to an important observation regarding the influence of heater thickness on the heat transfer which can be stated as: the heat transfer rate decreases with increase of heater thickness if the boiling conditions are such that the dimensionless parameters $Z(= k_1 \Delta T/\delta q_i)$ < 1, while the heat transfer rate increases with increase of heater thickness if boiling conditions result in $Z > 1$.

In actual boiling conditions as shown in Table 1, in high heat flux region the initial values of Z will always be far below unity. As the heat flux, q_i, increases, ΔT increases, but δ decreases and hence Z increases. Further, evaporation and consequent reduction in macrolayer thickness occurs and hence there is a likelihood of Z attaining values greater than unity during the process of heat transfer. At low heat flux, Z is far above unity and the microlayer formed is very thin and complete evaporation of the microlayer may take place in a few milliseconds. Under these conditions, overall influence will depend upon the net effect taking into account the time periods for which $Z < 1$ or > 1. The present analysis has been restricted to a given constant value of Z for a given situation. The authors could not get sufficient information from many references cited above to evaluate the parameter Z.

Figure 4 shows the effect of heater thickness on the time averaged value of liquid–vapour interface heat

Table 1. Experimental data of nucleate pool boiling heat transfer

$q_i \times 10^{-6}$ (W m^{-2})	ΔT (K)	$\delta \times 10^6$ (m)	Z	Ref.
0.922	19	135	0.104	[11]
1.0	23	95	0.165	[11]
1.295	33.9	80	0.223	[11]
1.401	38.3	70	0.266	[11]
0.6304	12.3	3.81*	34.87	[10]

* Initial microlayer thickness.

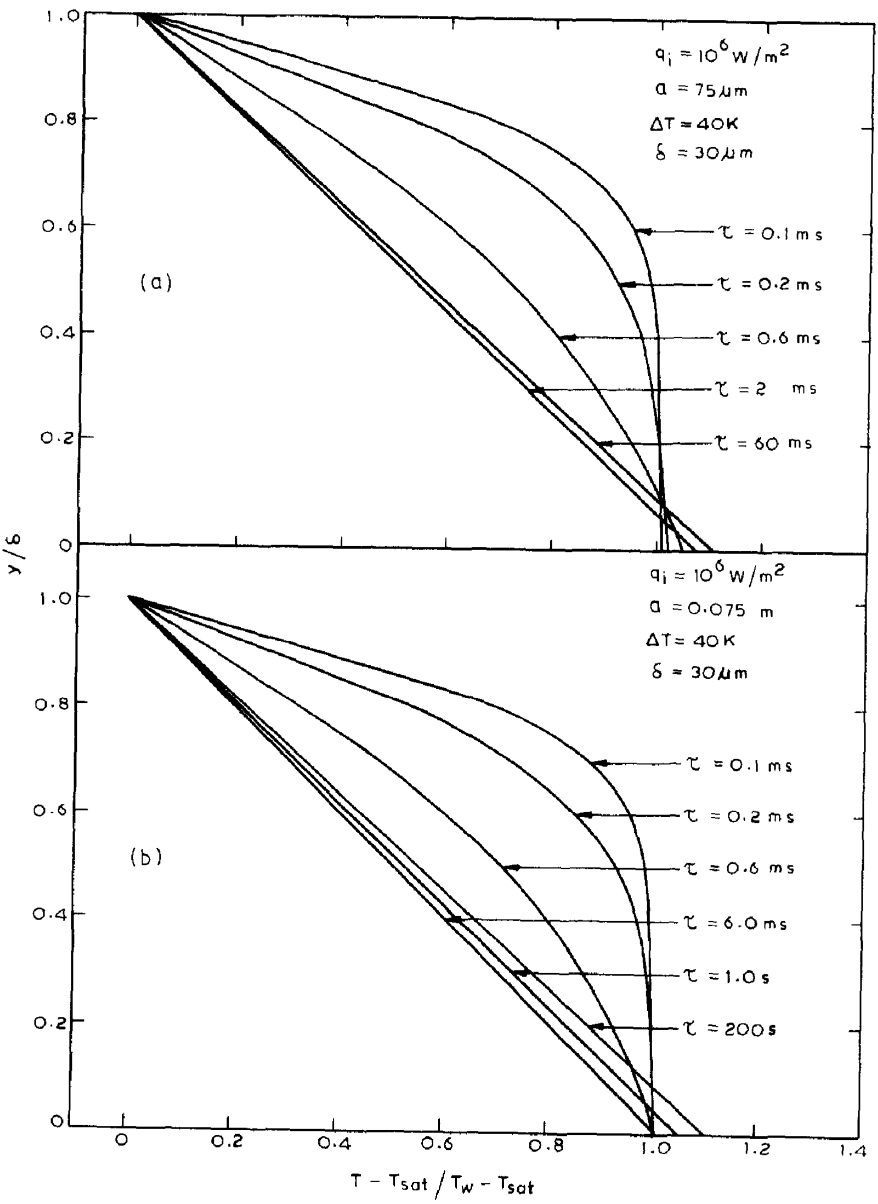

FIG. 2. Temperature profile in the macrolayer.

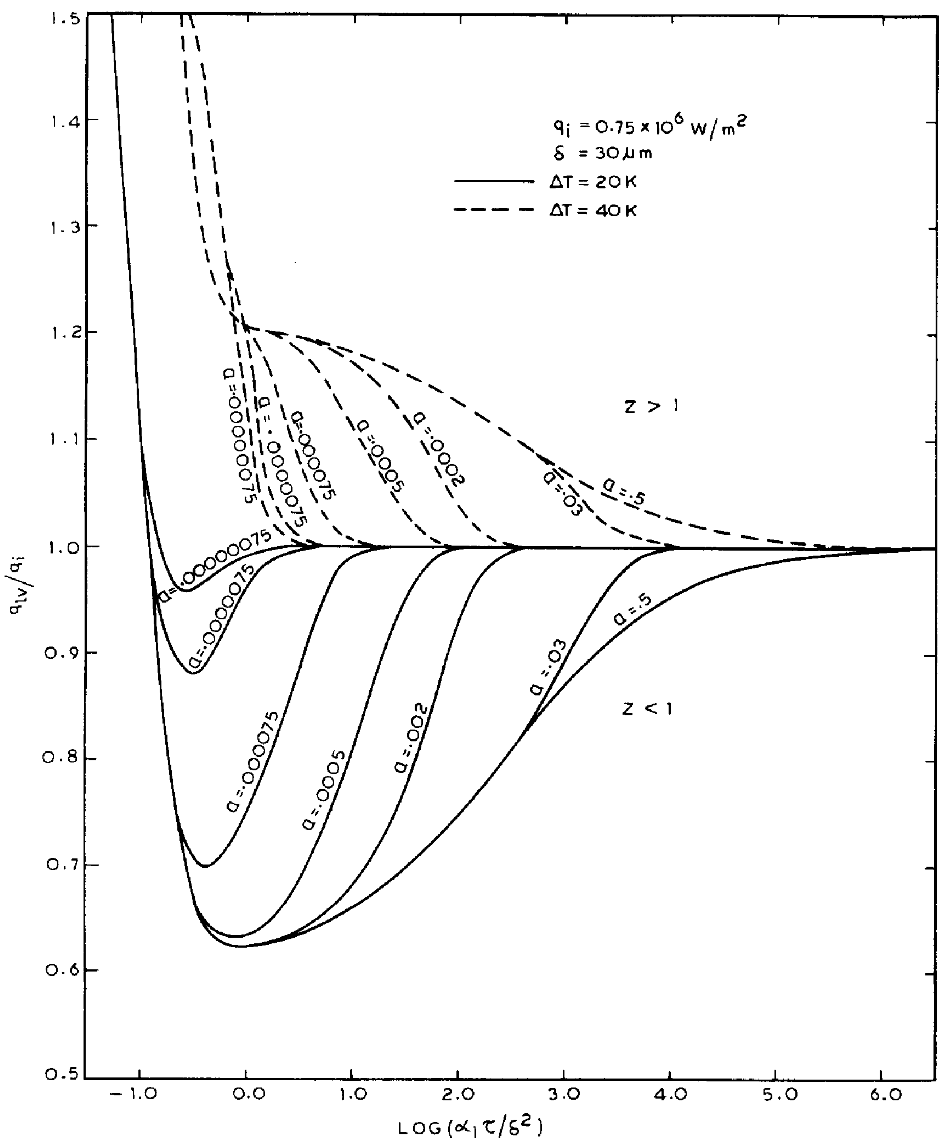

FIG. 3. Liquid–vapour interface heat transfer transients.

transfer rate, q_{av}. The ratio, q_{av}/q_i, approaches unity faster with decrease in heater thickness up to certain limiting value of thickness. The limiting value of heater thickness, above which the ratio (both maximum and minimum) becomes independent of thickness, increases with time. The difference between maximum and minimum values decreases and finally becomes zero as time tends to infinity. However at very small time values, this difference is small because of the sharp non-linearity in the temperature in the macrolayer.

Akiyama [9] obtained the numerical results of accumulated vapour thickness and heat transfer rate for different heater thicknesses at low heat flux values ($Z > 1$). He observed an increase in heat transfer rate and accumulated vapour thickness with increase in heater thickness. Sharp [4] obtained an increase in heat transfer coefficient with increase in heater thickness. Chuck and Myers [7] noticed only a slight effect of the heater thickness. These observations are generally in line with the aforementioned perception, although Magrini and Nannie [6] noticed an increase in heat transfer coefficient with decrease in heater thickness for nickel, tin and zinc (but no appreciable effect was noticed in the case of copper and silver). They hypothesized that such a behaviour, which is contrary to the observations of other investigators, is due to the effect of greater bubble population that may produce greater stirring of liquid near the wall. The transient heat conduction phenomenon discussed in this work does not take into account the change in bubble

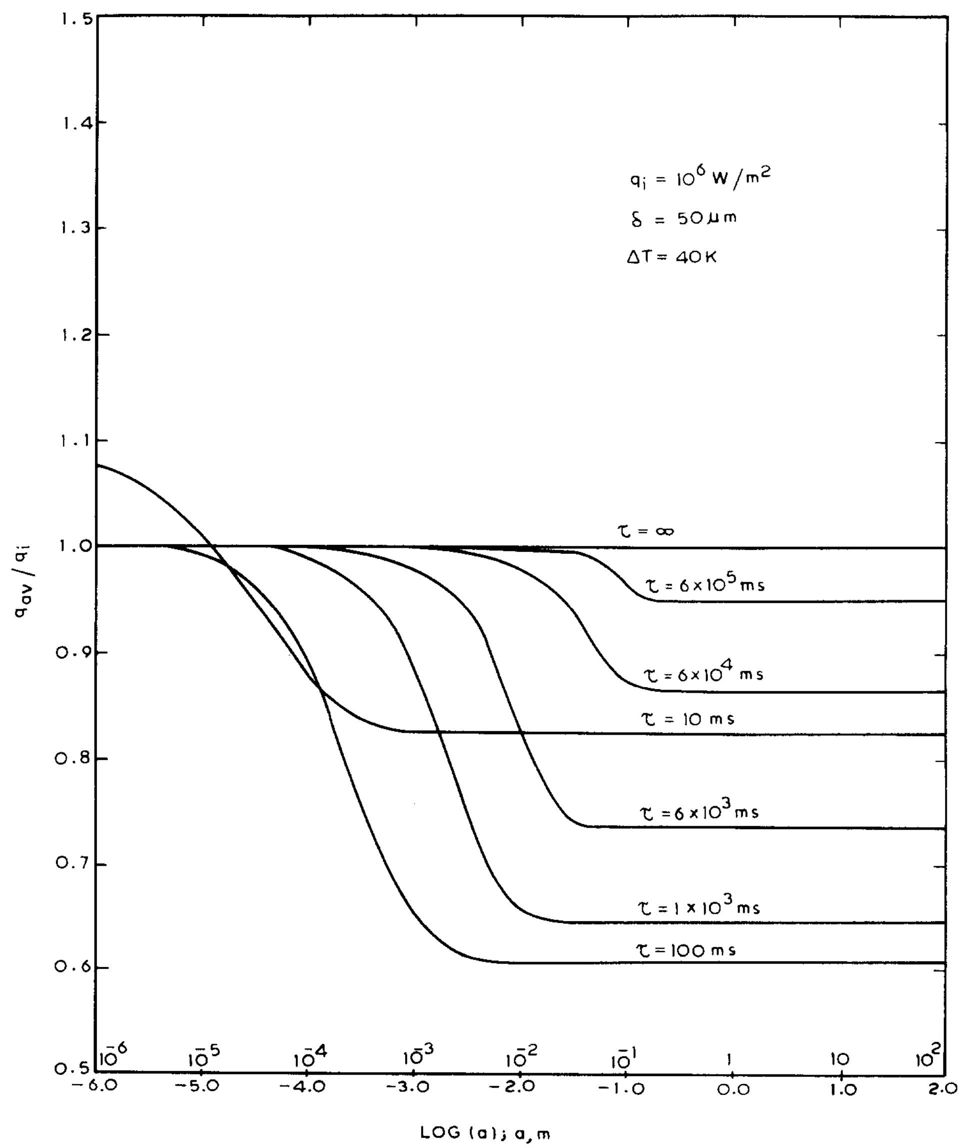

FIG. 4. Variation of average heat transfer rate with heater thickness.

dynamics and hence is unable to predict such a behaviour.

3. *Effect of initial macrolayer thickness, heat flux and wall superheat*

These parameters, i.e. δ, q_i and ΔT are instrumental in determining the value of Z and hence the pattern of influence of heater thickness on heat transfer. The values of δ and ΔT are dependent upon the boiling conditions; both are strong functions of the imposed heat flux q_i. It is well known that the heat transfer rate increases with decrease of macrolayer thickness and with increase of ΔT. Figures 5 and 6 show the effect of variation of macrolayer thickness and heat flux on liquid–vapour interface heat transfer rate. The reversal of heater thickness influence is indicated as the value of Z crosses over from a value less than unity to one greater than unity and vice versa in these figures. The heat transfer rates corresponding to smaller time values do not follow the general pattern because of sharp initial transients of the system as seen in Figs. 5 and 6. Similar effects are noticed in the case of variation of wall superheat also. The values of the physical parameters chosen are arbitrary and have been taken such as to cover wide range of boiling conditions involved, e.g. a very small value of δ combined with lower values of ΔT and q_i may represent a low heat flux boiling case ($Z > 1$) while comparatively larger values of these parameters may combine to represent a situation prevalent in high heat flux boiling near critical value ($Z < 1$). A time

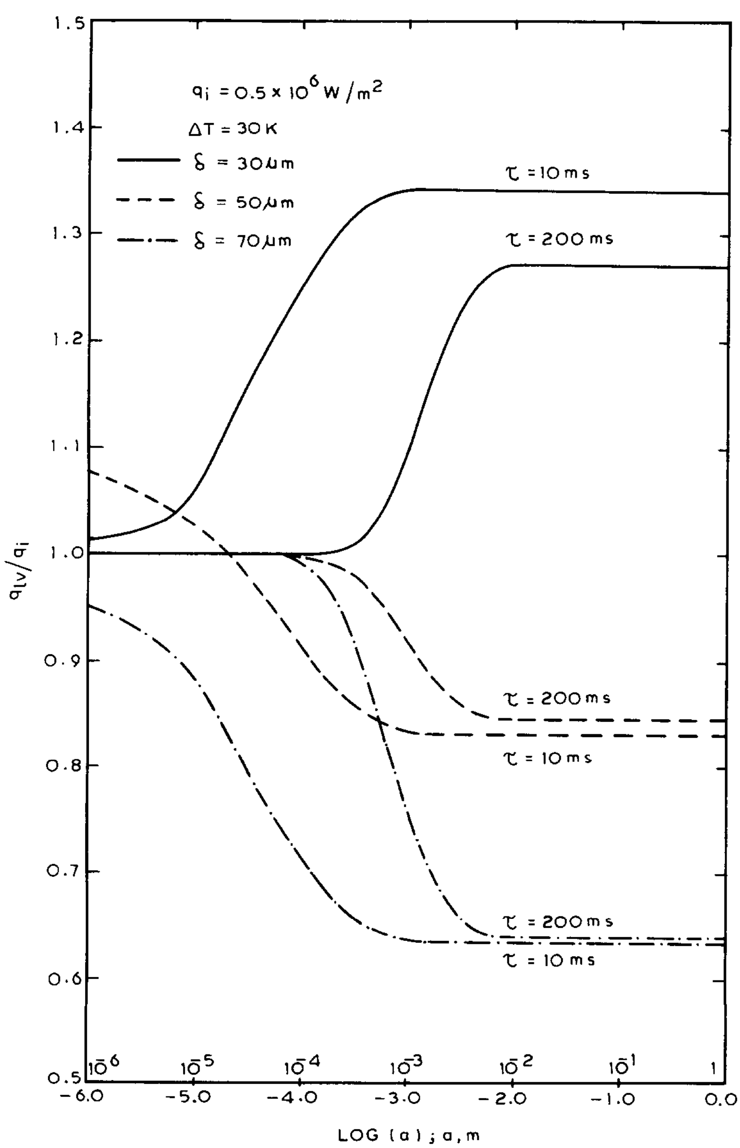

FIG. 5. Effect of macrolayer thickness on heat transfer.

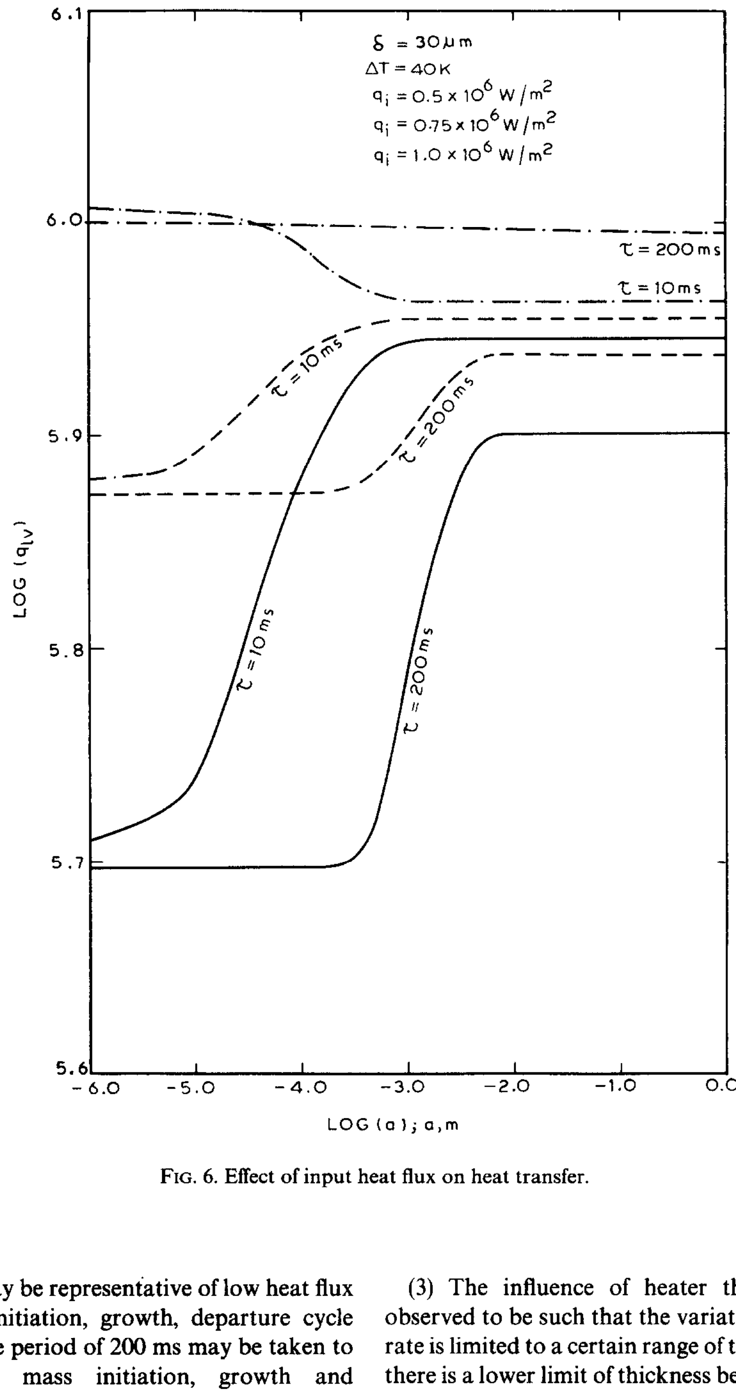

Fig. 6. Effect of input heat flux on heat transfer.

period of 10 ms may be representative of low heat flux nucleate bubble initiation, growth, departure cycle period while a time period of 200 ms may be taken to represent vapour mass initiation, growth and departure cycle period at high heat flux conditions.

CONCLUSION

(1) The influence of parameters like heater thickness, wall superheat, heat input and initial macrolayer thickness on the liquid–vapour interface heat transfer in boiling has been investigated.

(2) The influence of heater thickness on the liquid–vapour interface heat transfer is determined by the value of parametric combination of boiling conditions; the decrease of heater thickness increasing the heat transfer rate if $Z < 1$ and vice versa.

(3) The influence of heater thickness has been observed to be such that the variation of heat transfer rate is limited to a certain range of thickness variation; there is a lower limit of thickness below which the heat transfer does not change as well as there is an upper limit of thickness above which the heat transfer rate does not change. These limits, however, depend upon the boiling conditions as well as the cycle period.

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EFFET DE L'EPAISSEUR DE LA PAROI CHAUFFEE SUR LE TRANSFERT THERMIQUE DANS L'EBULLITION NUCLEEE EN RESERVOIR, AVEC FLUX DE CHALEUR ELEVE

Résumé—On étudie l'effet de l'épaisseur de paroi chauffante, de l'épaisseur de la macro-couche, la surchauffe de la paroi et le flux de chaleur sur le transfert thermique en ébullition nucléée. On résout analytiquement les équations qui gouvernent la conduction transitoire dans la macro-couche et la paroi chauffante. Les résultats montrent que le flux transféré peut augmenter ou diminuer quand l'épaisseur du chauffoir croît, selon la valeur du paramètre sans dimension $k_1\,\Delta T/\delta q_i$.

DER EINFLUSS DER WANDSTÄRKE DES HEIZELEMENTS AUF DEN WÄRMEÜBERGANG BEIM BLASENSIEDEN MIT HOHEN WÄRMESTROMDICHTEN

Zusammenfassung—Der Einfluß der Wandstärke des Heizelements, der Dicke der Makroschicht, der Wandübertemperatur und der Wärmestromdichte auf den Wärmeübergang beim Blasensieden wurde untersucht. Die Gleichungen, welche die instationäre Wärmeleitung in der Makroschicht und der Wand des Heizelements beschreiben, wurden analytisch gelöst. Die Ergebnisse zeigen, daß der Wärmeübergang mit zunehmender Wandstärke des Heizelements, abhängig vom dimensionslosen Parameter $k_1 \cdot \Delta T/(\delta q_i)$, ansteigen oder absinken kann.

ВЛИЯНИЕ ТОЛЩИНЫ СТЕНКИ НАГРЕВАТЕЛЯ НА ТЕПЛООБМЕН ПРИ ПУЗЫРЬКОВОМ КИПЕНИИ В БОЛЬШОМ ОБЪЕМЕ ДЛЯ ВЫСОКИХ ТЕПЛОВЫХ ПОТОКОВ

Аннотация—Изучено влияние толщины стенки нагревателя, толщины макрослоя, перегрева стенки и теплового потока на теплообмен при пузырьковом кипении. Аналитически решаются уравнения, определяющие нестационарную теплопроводность в макрослое и стенке нагревателя. Результаты показывают, что скорость теплообмена увеличивается либо уменьшается с ростом толщины стенки нагревателя в зависимости от безразмерного параметра $K_L\Delta T/\delta q_i$.