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An explanation for the augmentation of heat transfer during boiling in capillary structures

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Abstract—The heat transfer in pool boiling on surfaces with capillary structures is much better than on plane surfaces. This fact has been observed by many researchers but a reliable physical explanation of the heat transfer process is still missing. In this paper an attempt is made to explain the boiling process in capillary structures. Our consideration is based on a study of the equilibrium of vapour bubbles in capillaries. It could be shown that the liquid superheat for bubbles in capillaries can be considerably reduced in comparison to the superheat needed for the equilibrium of the same bubbles in the liquid with a plane vapour–liquid interface. As a consequence the driving temperature difference with boiling in capillary structures decreases, and therefore the heat transfer increases.

1. INTRODUCTION

CAPILLARY structures have found a wide application in different heat transfer devices for the improvement of heat transfer in boiling [1, 2]. Many experiments have proved that capillary layers can lead to an enormous increase in the boiling heat transfer. Nevertheless, satisfying models for a physical explanation of the obtained results do not exist.

Depending on the level of the liquid above a heating surface, the capillary structure can be fully or partly flooded, Figs. 1(a) and (b). When boiling occurs on a plate or a tube, the capillary structure is fully flooded, whereas in the case of a heat pipe this structure is usually partly flooded. The heat transfer mechanism in the regime of fully-developed boiling is very similar in both cases, whereas the mechanism and the conditions of bubble formation are essentially different. The main difference in the conditions of the bubble formation is due to the concave vapour–liquid interface in the case of the partly-flooded structures, see enlargement in Fig. 1b. At this interface acts the capillary force K_σ which leads to a decrease of the pressure in the liquid. This effect promotes bubble formation and decreases the liquid superheat.

2. EQUILIBRIUM CONDITIONS FOR VAPOUR BUBBLE IN A CAPILLARY TUBE

In order to describe the influence of the capillary forces upon the driving temperature difference with boiling in capillary structures we adopt a physical model schematically given in Fig. 2. Figure 2(a) shows a capillary tube of radius r_c open on both ends. The liquid inside the tube is adjacent to its vapour. The wall of the tube should be completely wetted by the liquid, the pressure in the vapour phase is p_V.

The pressure in the liquid phase p_L is lower than in the vapour phase p_V. Both are related to each other by the equation

$$p_L = p_V - \frac{2\sigma}{r_c}, \qquad (1)$$

where σ is the surface tension and r_c the capillary radius.

Next we assume the liquid in the capillary to be divided by an imaginary wall C into the parts A and B as shown in Fig. 2(b). The part B of the capillary shall be removed and the part A is brought in contact with a heating surface, Fig. 2(c). The capillary tube closed on the one end shall represent a channel of the capillary structure in Fig. 1(b). It contains a vapour bubble in equilibrium with the liquid. We are asking now for the temperature of the bubble interface or for the liquid superheat.

In order to find this temperature and also a relation for the superheating of the liquid we use a method developed by Mitrović and Stephan [3]. As they showed the equilibrium radius r of the bubble in a liquid is related to the superheating ΔT of the liquid according to the equation

$$r = \frac{2\sigma T}{\Delta h \Delta T \rho_V}\left(1 + \frac{\Delta T \omega}{T}\right), \qquad (2a)$$

with

$$\omega = \left(\frac{\Delta h}{RT}\frac{\rho_L}{\Delta \rho} - 1\right)\frac{\rho_V}{\Delta \rho}, \qquad (2b)$$

where T is the saturation temperature at a plane interface, Δh is the enthalpy of evaporation, ρ_V and ρ_L are the densities of vapour and liquid, respectively ($\Delta\rho = \rho_L - \rho_V$) and R is the gas constant.

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NOMENCLATURE

Δh	latent heat
p	pressure
R	gas constant
r	radius
T	temperature
ΔT	temperature difference.

Greek symbols

ρ	density
σ	surface tension.

Subscripts

c	capillary
L	liquid
V	vapour.

Equation (2a) shall be briefly derived in the present paper. It is based on the Clausius–Clapeyron equation

$$\frac{dp_0}{dT} = \frac{\Delta h \rho_L}{T} \frac{\rho_V}{\Delta \rho} \quad (3)$$

and on the Thomson equation for the vapour pressure at a concave vapour–liquid interface

$$p = p_0 - 2\frac{\sigma}{r}\frac{\rho_V}{\Delta \rho}. \quad (4)$$

In equations (3) and (4) p_0 is the saturation pressure at a plane vapour–liquid interface.

If we derive equation (4) with respect to the temperature T with r = constant and replace dp_0/dT by equation (3), we obtain:

$$\frac{dp}{dT} = \frac{\Delta h \rho_L}{T}\frac{\rho_V}{\Delta \rho} - \frac{2}{r}\frac{d}{dT}\left(\sigma \frac{\rho_V}{\Delta \rho}\right). \quad (5)$$

The derivative dp/dT in equation (5) can be approximated by $\Delta p/\Delta T$. Taking into account some simplifications (σ = constant, $\rho_V = p_0/RT$) and the relation

$$\Delta p = 2\frac{\sigma}{r}\frac{\rho_L}{\Delta \rho} \quad (6)$$

for Δp, equation (2a) follows from equation (5). As shown by Stephan [4], equation (5) can be also derived on the base of the chemical potentials. Equation (2a) is only valid for vapour bubbles surrounded by their liquids with plane vapour–liquid interfaces.

In the case considered in the present paper, the vapour–liquid interface is concave. Equation (1) shows that the pressure in the liquid is lower than in the vapour. The difference between these pressures is given by the capillary pressure $p_c = 2\sigma/r_c$. Consequently, the pressure difference Δp due to the curvature of the bubble according to equation (6) is reduced by the same pressure p_c. Hence for a bubble shown in Fig. 2(c) instead of equation (6) we have the relation

$$\Delta p = 2\frac{\sigma}{r}\frac{\rho_L}{\Delta \rho} - 2\frac{\sigma}{r_c}. \quad (7)$$

In a similar manner as described in [3] the following equation for the radius r of the bubble in equilibrium, shown in Fig. 2(c), is derived

$$r = \frac{2\sigma T}{\Delta h \rho_V \Delta T}\left[\left(1+\frac{\Delta T \omega}{T}\right)\Big/\left(1+\frac{2\sigma T}{\Delta h \rho_V \Delta T}\frac{1}{r_c}\frac{\Delta \rho}{\rho_L}\right)\right] \quad (8)$$

where ω is given by equation (2b). If the radius r_c of the capillary reaches infinity, equation (8) reduces to equation (2a).

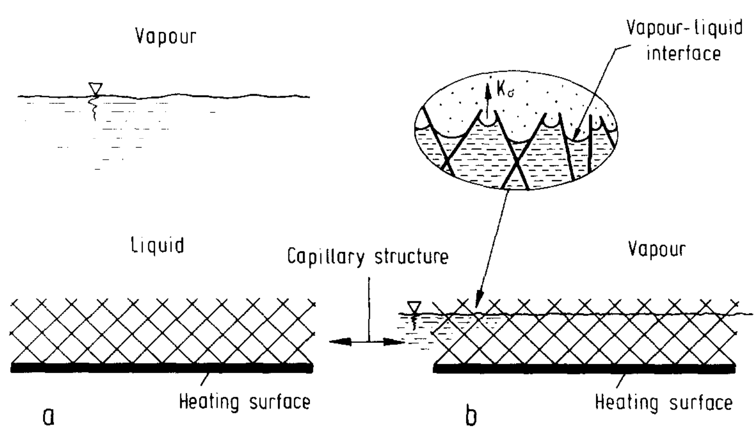

FIG. 1. (a) Fully and (b) partly flowed capillary structure on a heating surface.

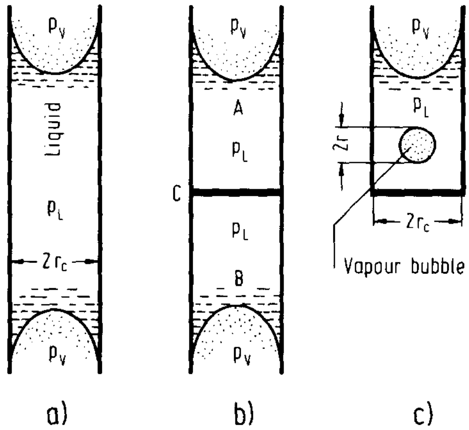

FIG. 2. A model to explain the high boiling heat transfer in capillary structures.

The temperature difference ΔT, which at the same time represents the superheating of the liquid, is important for the analysis of the boiling processes and can be obtained from equation (8) as:

$$\Delta T = \frac{2\sigma T}{\Delta h \rho_V r_c} \left[\left(\frac{r_c}{r} - \frac{\Delta\rho}{\rho_L} \right) \Big/ \left(1 - 2\omega \frac{\sigma}{\Delta h \rho_V r} \right) \right]. \quad (9)$$

This equation can be simplified as shown in [3] because ω is very small and the vapour density ρ_V can be neglected in comparison to the liquid density ρ_L. Hence it follows:

$$\Delta T = \frac{2\sigma T}{\Delta h \rho_V r_c} \left(\frac{r_c}{r} - 1 \right). \quad (10)$$

Equations (9) or (10) are suitable for explaining some of the observed phenomena in boiling on heating surfaces with capillary layers. According to these equations the temperature difference ΔT depends not only on physical properties of the boiling liquid but also on the capillary radius r_c. Using the equation (10) we have calculated ΔT. Some of these calculated values are presented in Fig. 3 for water at 60°C as the boiling liquid. The capillary radius r_c was varied as a parameter. As expected this figure shows that ΔT decreases with increasing bubble radius. The decrease in ΔT is higher for smaller values of r_c. It is noteworthy that ΔT can reach zero for a given value of r_c different from infinity. This is the case when the bubble and the capillary radii become equal. In this case a very low temperature difference is required to transfer an extremely high heat flux, a fact frequently observed when boiling takes place in fine capillary structures.

3. CONCLUSIONS

Our considerations have shown that the temperature difference required for a vapour bubble in equilibrium with the surrounding liquid is reduced when the bubbles are located in capillaries. Concerning the heat transfer this consideration leads to the conclusion that the boiling heat transfer can be enhanced several times by using fine capillary structures.

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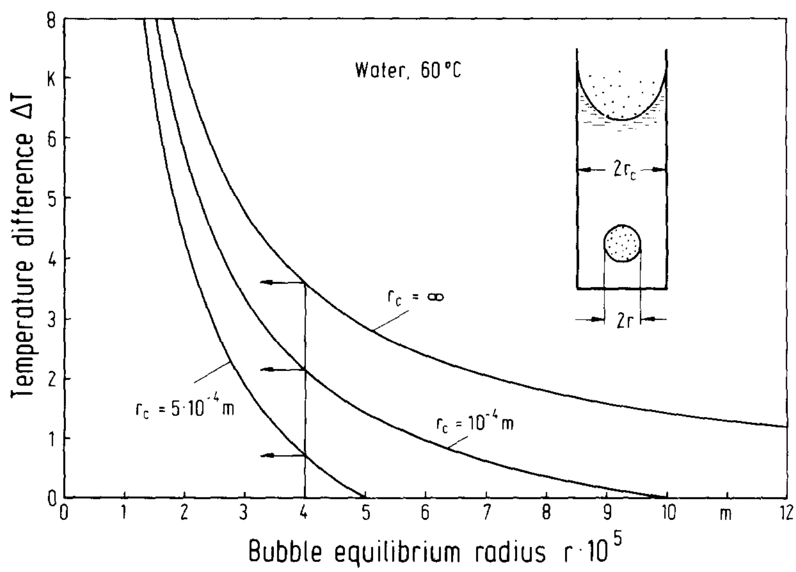

FIG. 3. Temperature difference ΔT as a function of the bubble radius r for some values of the capillary radius r_c.

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L'INTENSITE DU PASSAGE DE LA CHALEUR CHEZ L'EVAPORATION SUR LES SURFACES CHAUFFEES AVEC LES STRUCTURES CAPILLAIRES

Résumé—Le passage de la chaleur chez l'évaporation est beaucoup mieux sur les surfaces chauffées des structures capillaires que sur les surfaces plats. Il y a déjà longtemps qu'on connait ce fait, mais on ne pouvait pas l'éxpliquer sur la base des lois physiques. Dans ce devior, on a essayé de donner une explication d'un bon passage de la chaleur chez l'ébullition bulleux sur les surfaces avec les structures capillaires. On a fondé nos observations sous la condition d'équilibre des bulles à vapeur dans les capillaires. On a prouvé aussi que le réchauffement du liquide dans les capillaires, nécéssaire pour l'équilibre des bulles à vapeurs diminue chez la diminuation du radius capillaire. De conséquence diminue aussi la difference de témperature chez l'ébullition dans les structures capillaires ce qui mène à l'augmentation du passage de la chaleur.

ZUR INTENSIVIERUNG DES WÄRMEÜBERGANGS BEI DER VERDAMPFUNG AN HEIZFLÄCHEN MIT KAPILLARSTRUKTUREN

Zusammenfassung—Der Wärmeübergang bei der Verdampfung an Oberflächen mit Kapillarstrukturen ist erheblich besser als an ebenen Oberflächen. Diese Tatsache ist zwar seit langem bekannt, dennoch konnten die wesentlichen physikalischen Zusammenhänge noch immer nicht befriedigend geklärt werden. In der vorliegenden Mitteilung wird versucht, die Ursache für den guten Wärmeübergang bei der Blasenverdampfung an Heizflächen mit Kapillarstrukturen zu beleuchten. Unsere Betrachtungen beruhen auf den Gleichgewichtsbedingungen von Dampfblasen in Kapillaren. Es wurde gezeigt, daß die für das Gleichgewicht einer Dampfblase in einer Kapillare erforderliche Überhitzung der Flüssigkeit mit abnehmendem Kapillarenradius abnimmt. Als Folge hiervon wird die treibende Temperaturdifferenz bei Verdampfung in Kapillarstrukturen herabgesetzt und der Wärmeübergang entsprechend erhöht.

К ВОПРОСУ О ИНТЕНСИФИКАЦИИ ТЕПЛООБМЕНА ПРИ КИПЕНИИ В КАПИЛЛЯРНЫХ СТРУКТУРАХ

Аннотация—Во многих экспериментальных исследованиях отмечалось, что интенсивность теплопередачи при кипении на поверхностях с капиллярной структурой выше, чем на плоской поверхности. Однако пока отсутствует удовлетворительное физическое объяснение этого эффекта. В данной статье делается попытка объяснить механизм кипения жидкости в капиллярных структурах. Предлагаемый подход основан на рассмотрении равновесия паровых пузырей в капиллярах. Показано, что перегрев жидкости для пузырей в капиллярах может быть значительно уменьшен по сравнению с перегревом, необходимым для равновесия таких же пузырей в жидкости с плоской поверхностью раздела фаз пар-жидкость. Таким образом уменьшение разности температур необходимой для начала кипения в капиллярной структуре является причиной интенсификации теплообмена.