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Boiling heat transfer from surfaces with porous layers

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Abstract—Heat transfer during the boiling of water, ethyl alcohol and Freon-113 from a 30–70% porous layer at atmospheric pressure was investigated. Bubble boiling on a porous layer commenced at small temperature differences of 1–1.5 K. At high heat fluxes, a vapour film appears at the base of the porous layer, thus a qualitative change in the mechanism of bubble boiling occurs. In relatively thick porous layers, the transition to this new mode of boiling occurs at critical heat flux values two to three times greater than for smooth surfaces. A heat transfer hysteresis was observed in thick porous layers.

INTRODUCTION

If a smooth continuous wall surface is covered with a porous layer, boiling can be intensified. A review of the literature [1] on porous surface boiling heat transfer presents this process as a complex phenomenon dependent on the thickness and the thermophysical and structural properties [2, 5].

METHODOLOGY

Boiling heat transfer on a porous surface was investigated in large volumes of distilled water, Freon-113 and ethyl alcohol at atmospheric pressures and with the natural convection taking place. A horizontal tube with the porous layer was heated by electric current flowing through the tube. The heat flux was calculated from the potential difference and the current through the test section. A K-type thermocouple with the hot junction attached to the inside surface of the tube and on the outer surface of the porous layer was used to measure the respective temperatures.

The sintered metal particle porous layer studied is a capillary-porous structure. Dendrite shaped and spherical 63–100 μm particles were sintered. Porous layer parameters were determined for the polished sample by mercury porosimetry and analysis of photomicrographs. Polished sample photomicrographs are given in Fig. 1. Test samples Nos. 1–5 were Cr–Ni stainless steel on Cr–Ni whereas sample No. 6 was a Cr–Ni stainless steel tube with a titanium porous layer. Sample parameters are given in Table 1.

Intensive bubble boiling at small heat fluxes for 1 h (prior to the experiment) stabilized boiling conditions and removed air from the porous layer. Each change of the heat flux level was followed by a 5–30 min stabilization period. The tube wall temperature was monitored as an indicator of boiling stability.

RESULTS

The heat flux vs the wall temperature–saturation temperature difference is given in Fig. 2 for a 16 mm diameter tube in water. Two heat transfer modes are evident. Initial intensive bubble boiling occurs at relatively small temperature differences of $t_w - t_s = 1$ K (curve I). At a heat flux value of $q = 1.2 \times 10^5$ W m^{-2} which is much smaller than $q_{kr,1'}$ (where $q_{kr} = 10^6$ W m^{-2} for a smooth surface) heat transfer progresses with a practically constant heat transfer coefficient (curve II). Both boiling modes I and II represent different modes of bubble boiling. Visual evidence indicates that the liquid and the outer surface of the porous layer are in contact in mode II. This is borne out by the fact that the heat transfer coefficient in this mode is much higher than for film boiling. The substantial increase of the temperature of the wall during the transition from mode I to mode II indicates that a continuous vapour film layer is formed in the porous layer, whereas the high temperature (of the order of 800°C), Fig. 2, of the tube wall in mode II places the vapour film at the base of the porous layer. The constancy of the heat transfer coefficient ($q \simeq t^{1.05}$) over the wide range of heat flux and temperature differences indicates that the thickness of the film is almost constant.

Boiling condition I differs very slightly from the bubble boiling condition on a smooth surface, and hereafter it shall be referred to as the bubble condition. Intensive bubble boiling develops at temperature differences of only 1 K. The increase in the intensity of

NOMENCLATURE

D	pipe diameter
G	air flow at bubbling
g	acceleration due to gravity
h	sample thickness
K	hydrodynamic stability criterion
P	porosity
Δp	pressure drop
q	heat flux
$q_{\mathrm{kr.k}}$	heat flux corresponding to the capillary crisis
R_{kr}	critical radius
r	latent heat of vapourisation
t	temperature
t_{w}	wall temperature
t_{s}	saturation temperature
Δt	temperature difference, $t_{\mathrm{w}} - t_{\mathrm{s}}$
U''_{kr}	critical vapour velocity.

Greek symbols

α	heat transfer coefficient
δ	thickness of the porous layer
δ_{v}	thickness of the vapour layer
λ_{pl}	heat conduction coefficient of the porous layer
ρ'	liquid density
ρ''	vapour density
σ	surface tension.

heat transfer ($q \simeq t^{1.5}$) indicates that there is an increase in the number of active centres of nucleation with the increase in temperature differences.

Two modes are evident in Fig. 2 for bubble boiling from porous surface. These two modes are differentiated both by their boiling and their heat transfer mechanisms. In mode I, normal bubble boiling takes place. In mode II boiling with a vapour film inside the porous layer occurs.

The transition to mode II with a vapour film in the porous layer occurs in several stages. Segment III on the lowest curve in Fig. 2 corresponds to impeded heat transfer while the temperature increases. For a constant value of the heat flux, the temperature difference increased from 7 to 30 K in 5 h. As the heat flux is increased, a slow transition towards mode II (segment IV) can be observed. The long time interval corresponding to the almost flat segment on the curve can be attributed to the slow growth of the vapour film through the porous layer. And although this is a slow process, the abrupt deterioration of heat transfer at a constant heat flux is marked by criticality. Stable circulation of the liquid through the porous layer occurs for

$$\Delta p_{\mathrm{k}} \geqslant \Delta p_{\mathrm{p}} + \Delta p_{\mathrm{f}} \qquad (1)$$

where: Δp_{k} = liquid capillarity head in the porous structure; Δp_{p} = hydraulic resistance of the vapour flow within the porous layer and Δp_{f} = hydraulic resistance of the liquid flow in the porous layer.

With the increase in heat flux, the vapour flow increases. The pressure drop, which is the driving force both for vapour flow through the porous structure (Δp_{p}) and the liquid flow towards the outer surface of the porous layer (Δp_{f}), also increases. At a certain value of the heat flux, the sum of $\Delta p_{\mathrm{p}} + \Delta p_{\mathrm{f}}$ becomes greater than Δp_{k}, i.e., condition (1) on stable circulation ceases to be satisfied, circulation within the porous layer is disrupted and a film of vapour starts to form at the base of the porous layer. In order to differentiate the heat transfer crisis due to the disturbance in circulation within the porous layer from the hydrodynamic crisis the former will be referred to as the capillary crisis $q_{\mathrm{kr.k}}$.

The transition from normal bubble boiling mode I to mode II (with a vapour film in the porous layer) does not always take the form of an obvious capillary crisis, as can be seen in Fig. 2, q_{kr} is equal to 1.2×10^5 W m^{-2}. It is possible to reach the condition with the vapour film by means of either curves V or VI, where the transition towards condition II is faster, with greater values of the heat fluxes, if for whatever reason the time necessary for stabilization cannot be allowed to elapse.

It can be noted that the boiling mode (II) (with the vapour film at the base of the porous layer) is characterized by high stability and a high value of $q_{\mathrm{kr.1}}$. As shown in Fig. 2, the transition towards film boiling occurs when the heat flux is equal to $q \simeq 1.7 \times 10^6$ W m^{-2}, which is almost double the value for smooth surfaces. The transition in reverse, from mode II towards mode I usually occurs only after a considerable reduction in heat generation.

The porous structure and the thickness of the porous layer have a complex effect on heat transfer. For instance, for sample No. 2 with a thin porous layer of δ = 0.45 mm (Fig. 3), both the bubble boiling mode ($q \simeq \Delta t^{3.6}$) and vapour film boiling ($q \simeq \Delta t^{1}$) were observed. Between the two, there is a region with a small transition boiling gradient. The small thickness of the layer facilitates vapour flow from the porous structure

Table 1.

Sample	Diameter of test tube D (mm)	Thickness of porous layer δ (mm)	Porosity P (%)
1	16	2.2	70
2	3	0.45	30
3	4	1.5	40
4	4	0.53	32
5	4	0.55	75
6	18	0.55	50

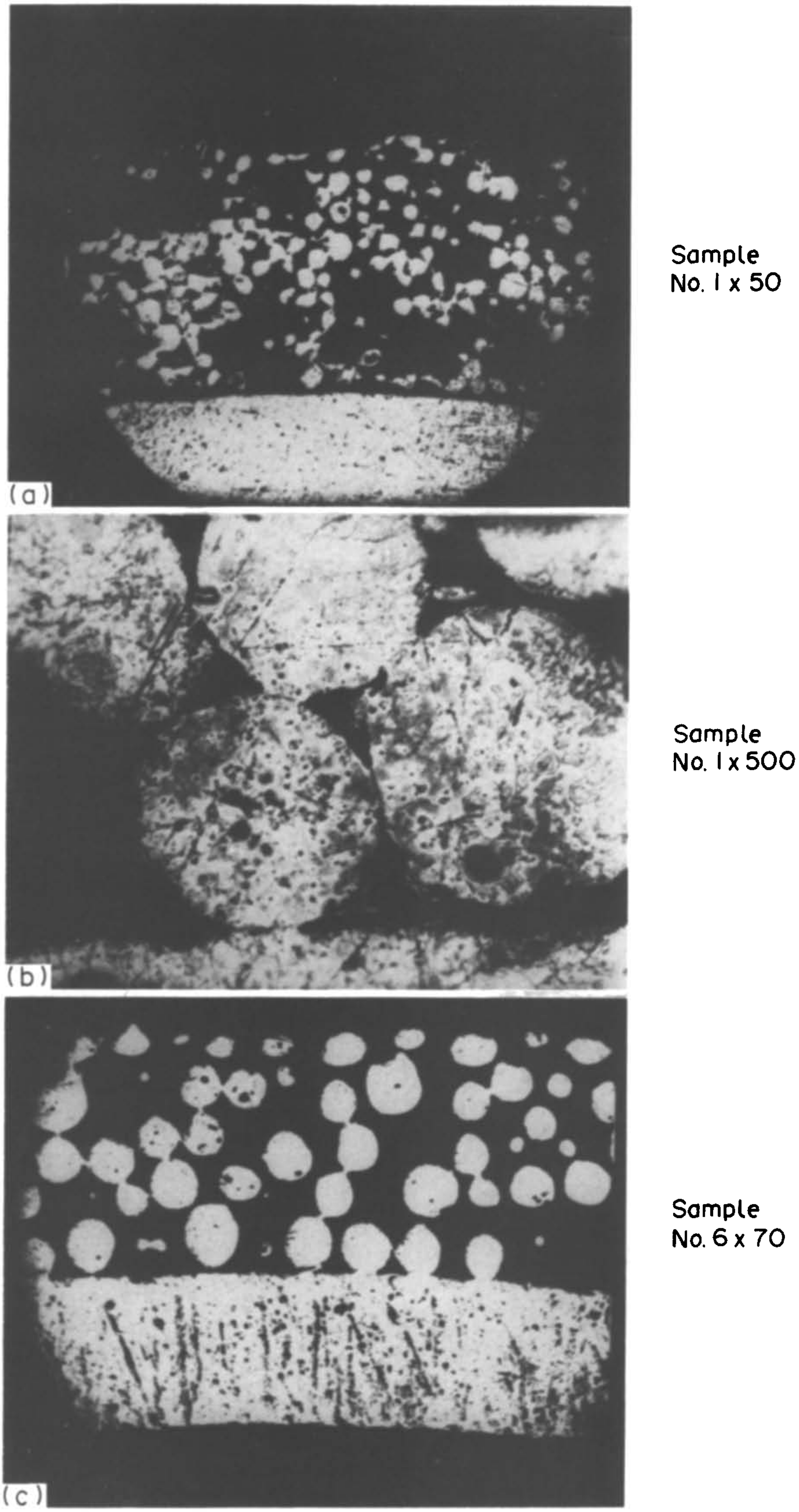

FIG. 1. Polished sample photomicrographs: (a) sample No. 1 × 50; (b) sample No. 1 × 500; (c) sample No. 6 × 70.

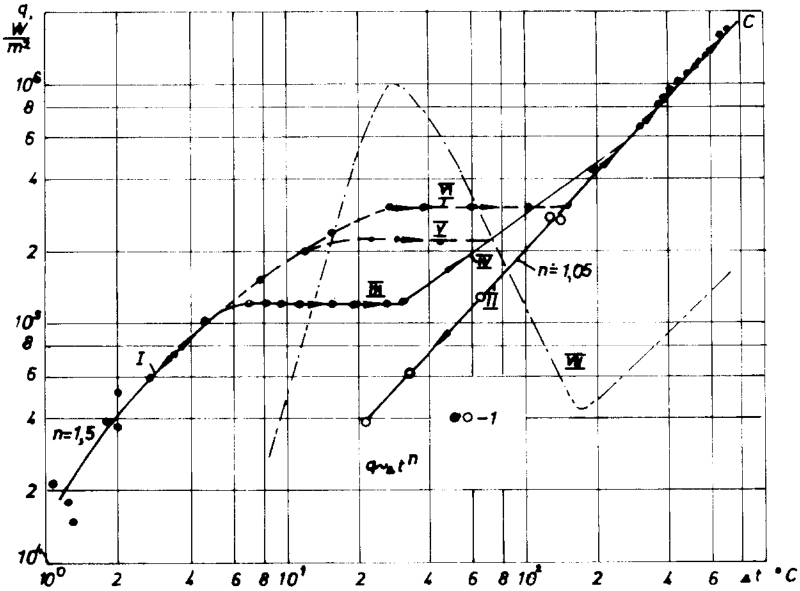

FIG. 2. The boiling of water for sample No. 1 : I—normal bubble boiling, II—boiling with a vapour film in the porous layer, III, IV, V, VI—possible transitional curves to mode II at different heat fluxes. The dashed curve is for a smooth surface; ● are values for an increase in q; ○ are values for the decrease in q; C is the boiling crisis point.

so that there is a complete absence of the heat transfer hysteresis. In the case of sample No. 3 with a mean thickness of $\delta = 1.5$ mm, Fig. 3, both the bubble mode, $q \simeq \Delta t^{3.8}$, and the transitional mode, $q \simeq \Delta t^{0.7}$, were observed. In contrast to sample No. 2 with a thin layer, a heat transfer hysteresis exists here.

The study of the boiling of Freon-113 and ethyl alcohol was conducted on a small diameter tube only. In the case of the boiling of Freon-113 all three modes, bubble boiling (Fig. 4, Curve I), transitional states (Curve II) and bubble boiling with a vapour film in the porous layer (Curve III), as well as the heat transfer hysteresis were observed.

A similar picture is obtained for the boiling of ethyl alcohol, Fig. 5. In the case of a thin porous layer (sample No. 5) only the bubble and transitional modes were observed. For a thicker layer (sample No. 3), the vapour film mode was again present with a heat transfer hysteresis at smaller heat fluxes.

If the heat supplied to sample 5 is reduced, Fig. 5, curve I is slightly shifted towards smaller temperature differences. This is possibly due to the activation of nucleation centres at larger heat flues.

ANALYSIS OF EXPERIMENTAL RESULTS

1. *Boiling on porous surfaces*

The analysis of the factors that effect the onset of intensive boiling on the porous surface at small temperature differences will serve as a basis for the

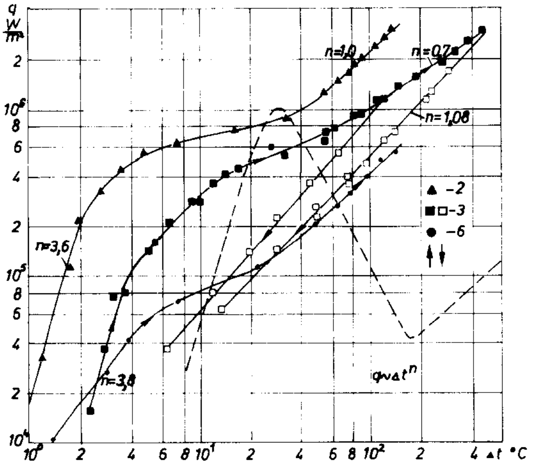

FIG. 3. The boiling of water, samples 2, 3 and 6. The dashed curve is for a smooth surface; ● are values for an increase in q; ○ are values for the decrease in q; C is the boiling crisis point.

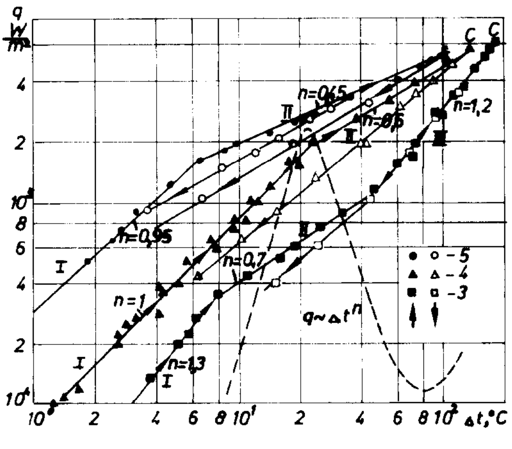

FIG. 4. The boiling of Freon-113 for samples 2, 3 and 6. The dashed curve is for a smooth surface; ● are values for an increase in q; ○ are values for the decrease in q; C is the boiling crisis point.

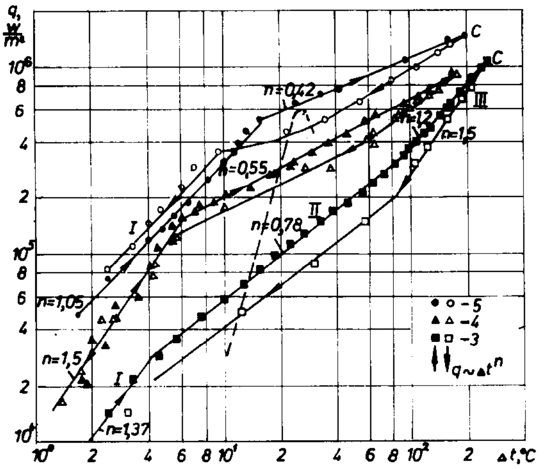

FIG. 5. The boiling of ethanol for samples 3, 4 and 5. The dashed curve is for a smooth surface; ● are values for an increase in q; ○ are values for the decrease in q; C is the boiling crisis point.

analysis of boiling conditions on the porous surface. The porous structure contains more adsorbed gases than a smooth surface while the liquid, in the pores, is uniformly superheated, facilitating the formation of the vapour phase in the porous structure.

In smooth surface boiling, Fig. 6(a), during boiling onset, the separation of bubbles from the superheated boundary layer adjacent to the tube wall into the relatively colder fluid volume is considerably impeded. According to Hsu [7] this is decisive in preventing the activation of nucleation centres. Actually, as soon as the top of the bubble leaves the superheated boundary layer adjacent to the tube wall and touches the cold liquid in the volume, Fig. 6(a), the growth of the bubble ceases or slows down. According to the above mentioned theory, the activation of nucleation centres in greater cavities is only possible with larger superheats and in the presence of a relatively thick superheated liquid boundary layer. This is why so many large pores are filled with steam, although the pore radius is greater than the critical radius

$$R_{\mathrm{kr}} = \frac{2\sigma T_{\mathrm{s}}}{(T_{\mathrm{w}} - T_{\mathrm{s}})\rho'' \cdot r} \tag{2}$$

and cannot be included in the already active nucleation centres.

A completely different picture is obtained for boiling on the porous surface. There is a well-developed channel system in the open pore structure. We shall assume that the centres of nucleation lie at the estuary of large pores, and include a certain volume of the porous structure empty volumes filled with vapour. In Fig. 6(b), a nucleation centre is shown as a cylindrical channel, liquid evaporation taking place on the surface of the meniscus on its boundaries. Intensive evaporation occurs due to the extended evaporation surface and the great liquid superheating inside the porous structure. The vapour flows into the top of the bubble, thus it grows faster.

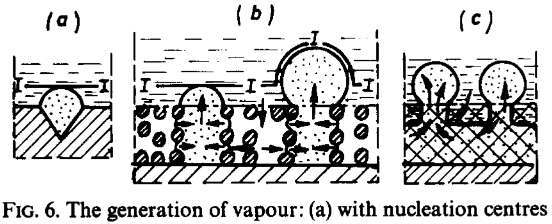

FIG. 6. The generation of vapour: (a) with nucleation centres on the smooth surface, (b) the growth of a bubble with vapour leaving the channels in the porous layer, (c) boiling with a vapour film in the porous layer; I-I is the superheated layer boundary.

When the surface at the top of the bubble breaks through the superheated liquid into the colder liquid, the bubble does not stop growing as would be expected according to Hsu. Although intensive condensation takes place on the inner spherical surface of the bubble, latent heat provided by the constant vapour inflow through the capillary compensates for the heat loss from the bubble to the surrounding liquid. The nucleation centre in fact functions as a small heat pipe, Fig. 6(c). The intensive feeding of the growing bubble with vapour through the channel of the 'heat pipe' will take place until its separation from the wall. That is why the bubble generated on a surface with a porous layer in a relatively cold liquid, grows without the difficulties, which usually accompany boiling on smooth surfaces. Therefore, with an increase in heat flux, larger nucleation centres are the first to be activated, and are the last to be deactivated in the decrease of heat flux. This is completely contrary to the case of smooth surfaces. Thus, equation (2) describes the dimensions of the centres of nucleation for a porous surface rather than for a smooth surface. Due to the stable activity of the larger nucleation centres, intensive bubble boiling on porous surfaces will commence at much lower temperature differences than in the case of smooth surfaces. For example, stable bubble boiling of water on a porous surface can occur at temperature differences $\Delta t = t_{\mathrm{w}} - t_{\mathrm{s}}$ of only 1–1.5°C.

2. *The boiling curve gradient at bubble regime*

It is obvious that the volume of vapour inside the porous layer will increase with the increase in heat flux. In bubble boiling the increase in the volume of vapour in the porous layer is a function of the number of active centres, i.e. it is a function of the number of vapour channels which penetrates through the porous layer. However, independent of the increase of vapour content, the increase in the active centre volume will entail a change in the heat transfer coefficient in accordance with $q = A\Delta t^n$, where n is greater than unity. The formation of elongated vapour volumes at the base of the porous layer and their subsequent merging into a constant vapour film will lower n.

Assuming that heat transfer in bubble boiling with a vapour film is also effected by heat conduction through the metal of the porous structure, the heat transfer coefficient will be determined by the expression $\alpha = \lambda_{\mathrm{pl}}/\delta_{\mathrm{v}}$, where λ_{pl} represents the heat conduction coefficient of the porous layer. If the thickness of the vapour layer remains unchanged with heat flux, the heat conduction coefficient will also remain unchanged. These conditions will be represented by a linear relationship between q and Δt.

If the thickness of the vapour film increases with an increase in the heat flux, its thermal resistance also increases, and n in $q = A\Delta t^n$ will be smaller than unity. Heat pipe experience indicates that the separation of vapour from the porous layer is difficult. Therefore, for a decrease in heat flux q, the decrease in the thickness of the vapour film will take place with a marked time lag, and the heat transfer coefficient will increase slowly. This is confirmed by the nature of the heat transfer hysteresis. For example, for $n > 1$, both in the case of an increase or decrease of the heat flux the experimental points are usually grouped along one curve, while for $n < 1$, for a decreased heat flux, these points are usually below the former, Fig. 4 (the light points). The influence of the permeability of the porous structure on the heat transfer hysteresis should be stressed. For example, for thin layers with a high permeability, samples No. 2, ($\delta = 0.45$) and No. 6 ($\delta = 0.55$ mm) there was no heat transfer hysteresis even for $n = 1.0$ (Fig. 3), while it could be detected for sample No. 3 ($\delta = 1.5$ mm).

3. *The boiling crisis*

In boiling on porous surfaces the transition to film boiling takes place at a much higher heat flux value than in the case of smooth surfaces. The possible mechanism of complete porous surface drying will be analysed.

Tehver [8] assumed that in order to maintain stable bubble boiling on a porous surface, it is sufficient that the liquid be supplied from the surrounding volume as individual drops. An analysis [8] has shown that critical heat fluxes, which are 10 times greater than $q_{\mathrm{kr.1}}$ for smooth surfaces, can be obtained from the stability conditions of the reversed flows of drops and vapour. In our experiments such high critical heat fluxes were not observed. We can, therefore, suppose that the boiling crisis on porous surfaces has the same hydrodynamic characteristics as in smooth surface boiling.

According to Kutateladze [9], the hydrodynamics of the boundary layer for bubble boiling can be modelled by bubbling, the blowing of gas through the porous wall. The critical heat flux for boiling and the separation of liquid from the porous wall surface by means of gas passing through the pores is described by the same equation

$$K = \frac{U''_{\mathrm{kr}}\sqrt{\rho''}}{\sqrt[4]{[g^2\sigma(\rho'-\rho'')]}}. \qquad (3)$$

The possible influence of the porous surface, on the hydrodynamics of the boundary layer, should have an effect on the conditions of bubbling.

Bubbling was investigated for 20 mm diameter and 1.2–5 mm thick porous discs. The disc was horizontal in a water filled cylindrical glass vessel. Compressed air was introduced through the vessel bottom. The gas volume, the pressure drop in the porous structure and the electrical resistance were measured. Electrical resistance was measured by a probe mounted near the sample surface. Various probe shapes (metal needles, cylinders, etc.) at a variety of distances from the surface of the sample were experimented with. Medium size pore (20–200 μm) samples were used.

The results for two samples, Fig. 7, give the pressure gradients in the porous layer for dry and damp samples, as well as the change in electrical resistance of the liquid boundary layer. It is evident that the hydraulic resistance of the damp sample increases monotonously. For large air flows, the curves for the hydraulic resistance of the damp and dry samples converge. The continuous change in the gradient $\mathrm{d}p/\mathrm{d}x = f(G)$ curve for the damp sample indicates an important difference in the mechanism of boiling and bubbling curve, which make the determination of the crisis elaborate. This effect is also presented in the paper.

In the case of the transition to film boiling the critical conditions are not simultaneously met along the entire surface, but only at individual points where there is an increase in wall temperature. The distribution of the vapour film on the whole surface is determined by conductive heat transfer through the structure of the heating wall. The transition to a new boiling regime takes place at a practically constant heat flux. A sudden decrease in heat transfer coefficients and an increase in the temperature of the whole heat transfer surface enables the precise determination of the critical heat flux. In bubbling some parameters which would clearly indicate the change in the boiling regime cannot be

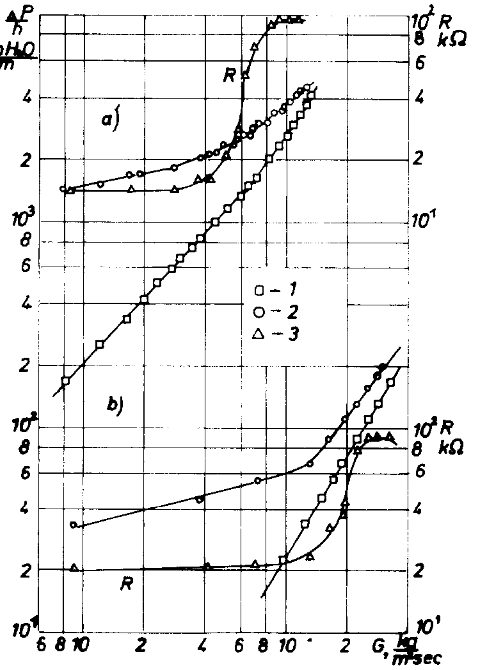

FIG. 7. The investigation of the bubbling crisis: (a) the hydraulic resistance of the dry sample, (b) the hydraulic resistance of a liquid filled porous layer, (c) the electrical resistance of a two-phase layer during bubbling. The average diameter of sample pores is 25 μm for sample 'a' and 200 μm for sample 'b'.

determined because the hydraulic resistance changes monotonously and without clearly defined variations. The change in the electrical resistance of the boundary layer is relatively complex. The increase in the electrical resistance commences practically with the beginning of the gas influx because the electrical resistance in the boundary layer increases with the increase of the gas content. The separation of the liquid from the walls does not occur along the whole surface simultaneoulsy. It rather occurs in the 'weakest' points so that it is possible that an increase in the gas flow is necessary from the moment of the formation of the first dry spots on the wall to the moment of complete separation of the liquid from the entire porous surface. After a continuous gas film has been established, the electrical resistance of the boundary layer stabilized (horizontal part of curve R). If it is assumed that the boiling crisis corresponds to the transition to constant electrical resistance, Fig. 7, the critical flows are $G_{\mathrm{kr}} = 0.9$ and $G_{\mathrm{kr}} = 2.4$ kg m^{-2} s^{-1} for the samples with small and large pores, respectively. The criterion values of $K = 0.24$ and $K = 0.64$ correspond to these values of G_{kr}. It can be seen that the coefficient K and thus the hydrodynamics of the boundary layer are also determined to a great extent by the characteristics of the porous structure. For boiling on a smooth surface, the volume of vapour flows, according to Zuber, is determined by the loss of Taylor stability [10]. On the porous surface incoming flows and their volume are determined to a large extent by the characteristics of the porous structure. The existence of a wide range of values of the criterion K in the porous structures tested proves the assumption that during the boiling on the surface with a porous layer intensive change of the hydrodynamic conditions is possible and that it results in the increase of critical heat fluxes.

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TRANSFERT THERMIQUE PAR EBULLITION A PARTIR DE SURFACES AVEC COUCHES POREUSES

Résumé—On étudie le transfert thermique pendant l'ébullition à pression atmosphérique de l'eau, de l'alcool éthylique et du Freon 113, à partir d'une couche poreuse à 30–70% de porosité. Des bulles apparaissent sur la couche poreuse à de faibles différences de température de l'ordre de 1–1,5 K. Aux flux plus élevés, un film de vapeur apparaît à la base de la couche poreuse, et un changement qualitatif se produit dans le mécanisme de l'ébullition. Dans des couches poreuses relativement épaisses, la transition de ce nouveau mode d'ébullition apparaît à des valeurs critiques de flux thermiques deux à trois fois plus grandes que pour des surfaces lisses. Une hystérèse de transfert thermique est observée dans les couches poreuses épaisses.

DER WÄRMEÜBERGANG BEIM SIEDEN AN OBERFLÄCHEN MIT PORÖSEN SCHICHTEN

Zusammenfassung—Der Wärmeübergang beim Sieden von Wasser, Äthyl-Alkohol und Kältemittel R113 bei Atmosphärendruck an Schichten mit einer Porosität von 30 bis 70% wurde untersucht. Blasensieden an porösen Schichten findet bei kleinen Temperaturdifferenzen von 1 bis 1,5 K statt. Bei höheren Wärmestromdichten bildet sich am Grund der porösen Schicht ein Dampffilm, wodurch eine qualitative Veränderung des Blasensiedemechanismus auftritt. Bei relativ dicken porösen Schichten tritt der Übergang zu dieser neuen Siedeart bei Werten der kritischen Wärmestromdichte auf, die zwei- bis dreimal größer sind als die Werte für glatte Oberflächen. Für dicke poröse Schichten wurde eine Wärmeübergangs-Hysterese beobachtet.

ТЕПЛОПЕРЕНОС С ПОВЕРХНОСТИ ПОРИСТЫХ СЛОЕВ ПРИ КИПЕНИИ

Аннотация—Исследуется теплоперенос при кипении воды, этилового спирта и фреона-113 с поверхности пористых слоев с пористостью от 30 до 70% при атмосферном давлении. Пузырьковое кипение на поверхности пористого слоя начиналось при небольших разностях температур в 1–1,5 К. В случае больших тепловых нагрузок паровая пленка появлялась в нижней части пористого слоя, что свидетельствует о качественном изменении механизма пузырькового кипения. В пористых слоях относительно большой толщины переход к этому новому режиму кипения происходит при критической плотности теплового потока, величина которой в два-три раза превышает значение, характерное для гладких поверхностей. В пористых слоях большой толщины наблюдается гистерезис теплопереноса.