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Experimental investigations into intra-layer boiling crisis and hysteresis in metal, fibrous, porous coverings

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Abstract

Capillary-porous structures (CPS) do not only enhance boiling heat transfer, they also may cause the increase in the value of the critical heat flux. Apart from boiling crisis, resulting, as for a smooth surface, in the wall burnout, in CPS there also occurs the so-called "intra-layer boiling crisis". The results of experimental investigations into boiling heat transfer on heating surfaces covered with fibrous, porous layers were presented. The interest area covered the impact of the increase in heating surface temperature on the values of the heat flux and boiling heat transfer coefficient.

Keywords: Boiling crisis; Porous coverings; Hysteresis

Nomenclature

CPS	– capillary porous structure	T	– temperature
q	– heat flux	ΔT	– temperature difference, $T_w - T_s$
p	– pressure	δ	– thickness of the porous layer
Δp	– pressure drop	Π	– porosity

Subscripts

w	– wall	$*$	– for intra-layer crisis
s	– saturation	l	– liquid
kr	– critical	v	– vapour

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1 Introduction

Boiling heat transfer enhancement constitutes one of the important issues in modern technology. Most effective and totally reliable cooling systems are required to cool high integration circuits, nuclear power and space devices. Heat transfer enhancement is also essential in refrigerating engineering and chemical industry, air conditioning equipment, thermal pipes and others. The economic aspect is not to be overlooked, either. The phenomenon contributes to the reduction in weight, dimensions and costs of heat exchangers and lowers energy consumption.

Capillary – porous structures functioning as heating surface coverings offer significant boiling heat transfer enhancement The drawback of CPS applications is the appearance of disadvantageous phenomena accompanying transitions between various boiling stages. The so-called "intra-layer boiling crisis" is one of the most significant phenomena amongst them.

2 Intra-layer boiling crisis

In spite of numerous theoretical and experimental works, the vast literature on the subject does not report a uniform outlook on the process mechanism.

The diversity of structures being manufactured results in a variety of boiling crisis phenomena. Also, the very notion of boiling crisis has been defined in an ambiguous manner. Boiling crisis in porous coverings cannot be understood in the same way as in the case of a smooth surface. The authors studying boiling mechanism quote "intra-layer crisis", "filling a structure with vapour", "vapour layer appearance on the outer porous covering surface", etc. Thus, the definitions of nucleate boiling crisis in porous covering demonstrate significant divergence. Three characteristic ranges of boiling curves can be observed in porous coverings boiling (Fig. 1). In two of them (II and III), heat transfer is thought to be boiling under crisis conditions, thus:

- II, characterised by the decrease in heat transfer coefficient, which according to many authors, is caused by the appearance of a vapour layer inside CPS (see [1,2]).
- III, characterised by the occurrence of a continuous vapour film in the porous layer, (see [1,3]). In this range, the increase in the heat flux leads to the wall burnout.

The transition from range I (nucleate boiling) to range III (boiling with a vapour layer) can take various forms, (Fig.1), possible to register when the heat flux density is determined as the wall temperature function.

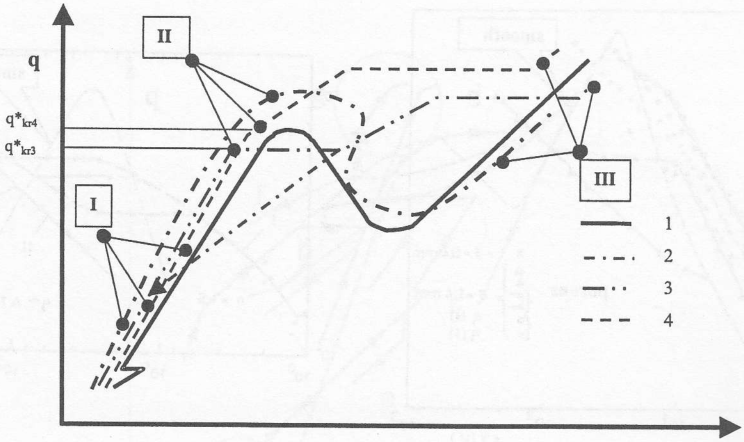

Figure 1. Shapes of boiling curves on a smooth surface (1) and the surface with capillary porous covering (2), (3) and (4) – on the basis of [1].

The decrement of heat transfer coefficient value, accompanying phenomenon II is caused by the occurrence of the so-called "intra-layer crisis". It is a process characteristic to porous coverings, which consists in vapour film formation inside the porous structure. In the diagram, it is manifested as the characteristic change of the boiling curve inclination or in the occurrence of horizontal sectors of q^*_{kr} threshold values, (Fig.2). Transitions are accompanied by high temperature increments.

The disruption of circulation within the porous layer and a vapour film formation at the base of the porous covering are regarded to be [3] the reason for why intra-layer boiling crisis takes place.

Stable circulation of the liquid through the porous layer occurs for:

$$\Delta p_k \geq \Delta p_v + \Delta p_l \,, \tag{1}$$

where: Δp_k is pressure head due to the liquid capillarity in the porous structure; Δp_v pressure drop due to the vapour flow within the porous layer; Δp_l pressure drop due to the liquid flow in the porous layer.

With the increase in heat flux, the vapour flow increases. At a certain value of heat flux, the sum of $\Delta p_v + \Delta p_l$ becomes greater than Δp_k.

A lot of authors assume that the boiling crisis starts only when the entire outer side of the porous layer has been covered with a vapour film (point C, Fig. 2b). The appearance of a vapour film outside the porous covering induces the heating surface burnout in a short period of time [5].

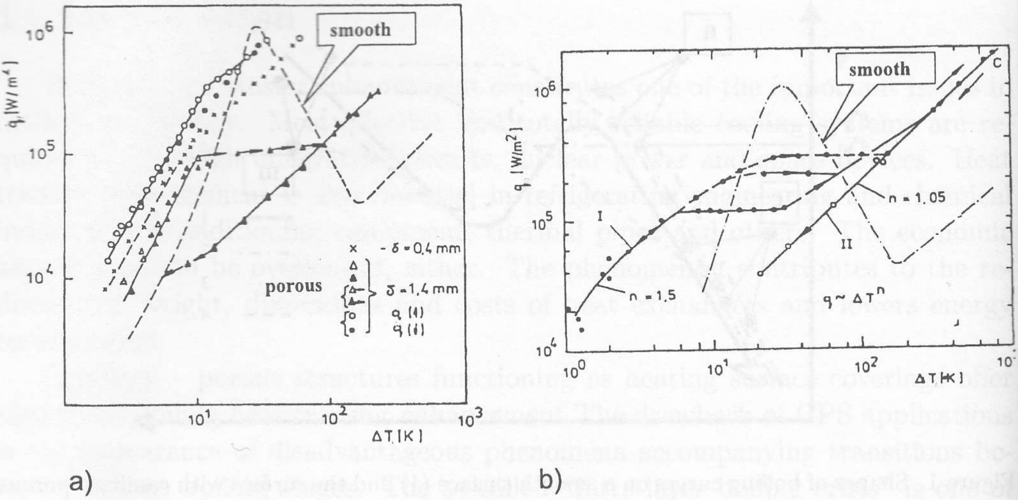

Figure 2. Intra-layer boiling crisis: a) investigations of Adrianov et al [4], structure manufactured with the method of Al_2O_3 plasma spray, δ – thickness of the porous layer b) investigations of Afgan et al [3], sintered metal particle layer, C – the boiling crisis point.

3 I-type hysteresis

While the heat flux supplied to the heating surface covered with CPS diminishes, heat transfer hysteresis is revealed, which prevents the thermal stabilisation of heat emitting systems. Experimental boiling curves demonstrate various courses, depending on the porous covering parameters and the liquid physical properties, Fig. 3.

I-type hysteresis is characterised by decreasing heat transfer coefficient accompanying the heat flux decrease below its critical value, Fig. 3.d.c, [1,3,4,6]. It is assumed that this happens because it is difficult for the vapour film formed inside the porous covering to flow away. Such a mechanism seems to be confirmed by the experiments concerning heat pipes [3].

Earlier experiments carried out at the Kielce University of Technology [7] showed the occurrence of I-kind hysteresis in thick-layered (δ ranging 0.8-2 mm), copper, fibrous CPSs.

Figure 4 presents the characteristic experimental boiling curve for I-type hysteresis [7]. It was determined for water and about 2 mm thick structure of 40 % porosity, at atmospheric pressure. The typical phenomena presented in this figure were also observed for water for other coverings on a various scale.

Boiling on the porous layer begins at lower temperature difference (ΔT below 2K) than on a smooth one. A significant increase in the heat flux, in regard to a smooth surface, is a characteristic feature of boiling for small temperature

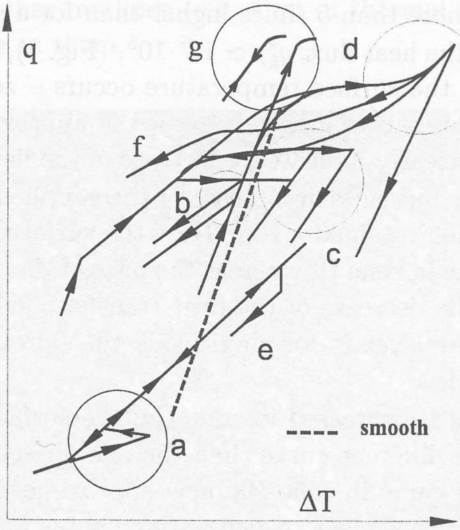

Figure 3. Various kinds of boiling heat transfer hysteresis in capillary, porous structures.

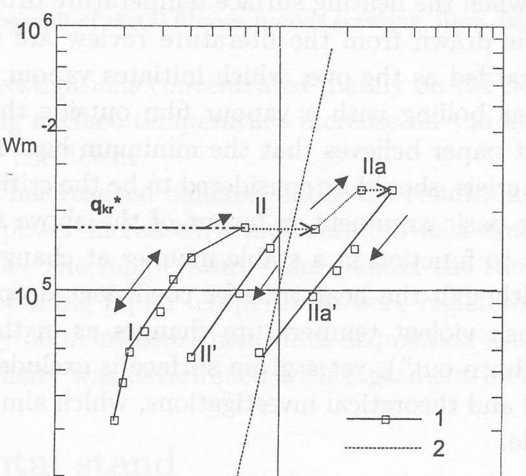

Figure 4. Boiling curve for water at atmospheric pressure [7]: 1 – copper fibrous CPS, $\Pi = 40\%$, $\delta = 2$ mm; 2 – smooth copper surface.

differences (zone I, Fig. 4). The heat transfer coefficient for a low heat flu ($q \simeq 5 \cdot 10^4 \mathrm{Wm}^{-2}$) is more than 5 times higher than for a smooth surface.

When the value of the heat flux, $q^*_{kr} \simeq 1.7 \cdot 10^5$, (Fig. 4), is reached, a consta self-induced growth of the surface temperature occurs – zone II. This is a slo process, where the temperature grows at a pace of approximately 15 K/h. Th flat shape of the curve clearly indicates a decrease of the heat transfer coefficie

If even a very slight but sudden increase of the supplied heat flux takes pla and its new value is then retained – zone IIa – the surface temperature will al grow uncontrollably like in zone II, whereas the pace of the temperature growt is higher than before. The decrease of the heat transfer coefficient in these rang indicates that a vapour layer is forming inside the porous structure, which is called an intra-layer crisis.

When the heat flux is decreased in zone IIa, the surface temperature begi to drop, albeit along a different curve than the one observed when the flux wa increased. The boiling curve in zone IIa′ now approximates the higher values of ΔT. The heat transfer coefficient, which approximates a constant value, poi to constant thermal resistance in this zone of the boiling curve. The same ph nomenon was observed in zone II′ when decreasing the heat flux began in zo II. The heat flux was decreased also in zone I. In this case, the boiling curve di not change shape when the heating surface temperature dropped to lower value

The conclusions drawn from the literature review are that the flux critica value could be regarded as the one, which initiates vapour formation inside th structure as well as boiling with a vapour film outside the covering. The au thor of the present paper believes that the minimum heat flux q^*_{kr}, which star intra-layer boiling crisis, should be considered to be the critical flux at the poro layer boiling. The basic argument in favour of the above thesis is the inabili for the equipment to function in a stable manner at changeable heat flux, aft exceeding q^*_{kr}. Although the heat transfer coefficient drop, which occurs the does not cause such violent temperature changes as in the case of technical smooth surface ("burn-out"), yet a given surface is excluded from work. There fore, experimental and theoretical investigations, which aim at boiling modellin seem indispensable.

4 Aim and scope of the investigations

The aim of the paper was to carry out experimental investigations into intr layer boiling heat transfer crisis in metal, fibrous and porous structures. Th subject of research were copper, fibrous, porous structures widely applied in he pipes. Their elementary structure components were copper wires of 3 mm leng and 50 μm diameter, sintered both with one another and with the copper bas

Fig. 5. The specific feature, which differentiates metal, fibrous CPS from structures obtained with other methods (e.g. that of thermal spray), is the fact that only open pores occur in them.

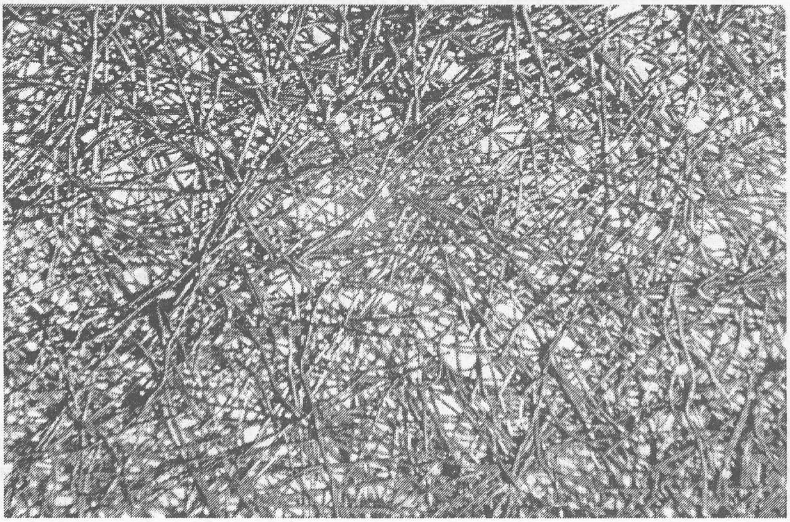

Figure 5. Photograph of metal fibrous porous covering, fibre diameter 50 μm.

Experimental investigations concentrated mainly on the determination of the impact of the heating surface temperature increase on the heat flux values and boiling heat transfer coefficient.

After the system has reached balance, under the conditions of stable nucleate heating, the heater power increased, which resulted in a systematic increase in the wall temperature. The temperature values under the sample, in the copper block as well as the boiling liquid temperature were registered every 0.5 second by means of Keithley 500A measurement data acquisition system.

The heat flux density was determined with a gradient method.

5 Experimental stand

The diagram of an experimental stand [6] as well as of its basic module were presented in Figs. 6 and 7. The experimental stand consists of the following components:

1. basic module;
2. heating module with the measurement of power supplied;
3. temperature measurement module;

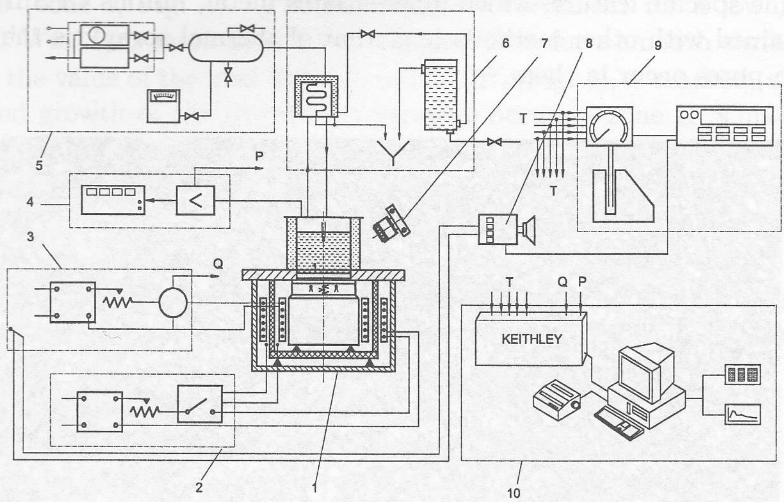

Figure 6. The diagram of the experimental stand with co-operating systems: 1 – basic modu 2 – heat loss compensation system, 3 – heating module with the measurement of power provided, 4 – pressure measurement in the liquid tank, 5 – module produ and measuring low pressures, 6 – vapour cooling and condense recovery modu – boiling digital recording module, 8 – the system signalling the exceeding of preset temperature, 9 – temperature measurement module, 10 – measurement acquisition and processing module.

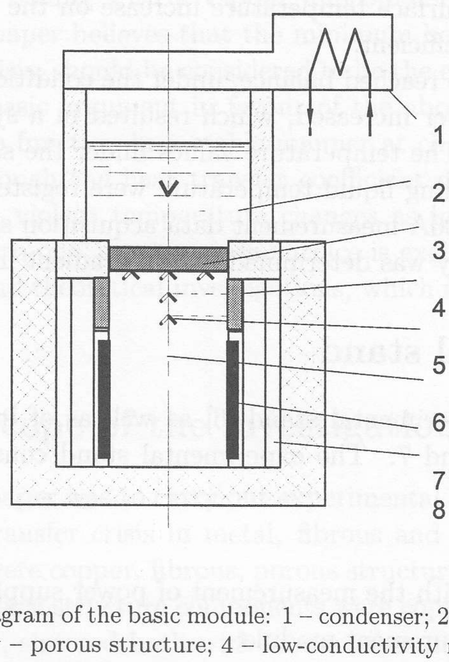

Figure 7. Schematic diagram of the basic module: 1 – condenser; 2 – boiling liquid; 3 – speci with capillary – porous structure; 4 – low-conductivity mineral wool; 5 – thermoc ples; 6 – copper block; 7 – main heater; 8 – ceramic pipe.

4. module generating and measuring pressure;
5. module supplying the stand with liquid fluid and module of vapour cooling and condensate recovery;
6. measurement data acquisition and processing module;
7. module for boiling image digital registration and analysis .
8. The sample (3), (Fig. 7), with porous covering was fixed onto a copper roll (6). The heater (7) wound onto the roll was supplied with alternating current through an autotransformer. Thermocouples (5) were installed under the sample (3), on the roll axis (6) and in the boiling liquid. The temperature of the heating surface was determined by extrapolating it with reference to temperatures measured along the axis of the roll.

6 Investigations results

Figure 8 presents the temperature under the heating surface as a function of time. The surface was covered with a copper CPS of 40 % porosity and 0.8 mm thickness. At the beginning, gentle and then quite fast (aprox. 20 K/min), systematic increase in the heating surface temperature is visible. It should be noted that temperature increases at much slower rate than on a smooth surface. Figure 9 presents the course of changes in the heat flux in refrigerant R-113 boiling. Three characteristic ranges could be differentiated. Initially (range I, Fig. 9), significant heat flux increase is seen, which is connected with the activation of new nucleation centres. With the heat flux density reaching the maximum value $q_{kr}^* = 3.2 \cdot 10^5$ W/m^2, (range I, Fig. 9) inside the porous structure there appear spaces occupied with vapour. The reason for the change in boiling mechanism is the drying up of vapour generating pores, caused by the increase in vapour and liquid resistance and afterwards, the combination of dried sites. The heat transfer coefficient inverse constitutes the qualitative measure of the thickness of the conventional vapour layer inside CPS. In Fig. 10 the course of thickness changes was presented as the function of time. The vapour layer thickness was estimated as:

$$\delta_v = \lambda_v / \alpha \,, \tag{2}$$

where: λ_v is refrigerant R-113 vapour thermal conductivity, α is heat transfer coefficient, determined experimentally for the boiling range under scruting.

7 Conclusions

1. Minimum heat flux q_{kr}^*, which starts intra-layer boiling crisis should be considered to be the critical flux at porous layer boiling,

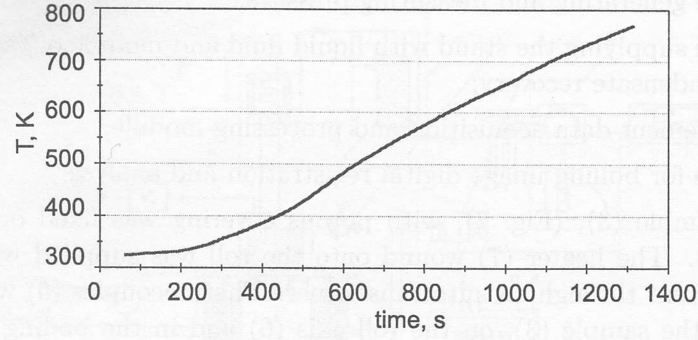

Figure 8. Wall temperature as a function of time; copper CPS, $\Pi = 40\%$, $\delta = 0.8$ mm; refrigerant R-113 boiling at atmospheric pressure.

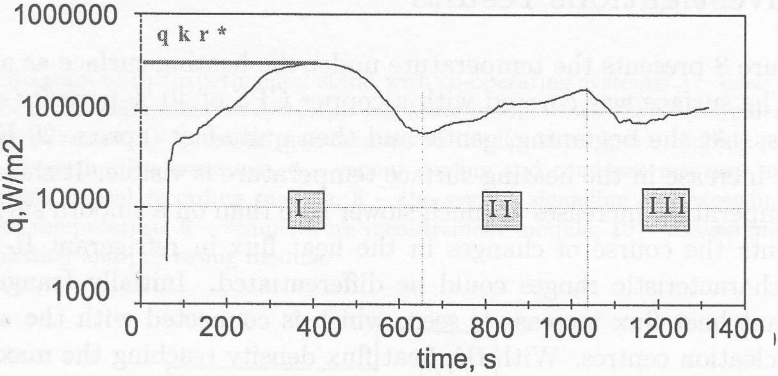

Figure 9. Heat flux in function of time;copper CPS, $\Pi = 40\%$, $\delta = 0.8$ mm; refrigerant R-113 boiling at atmospheric pressure.

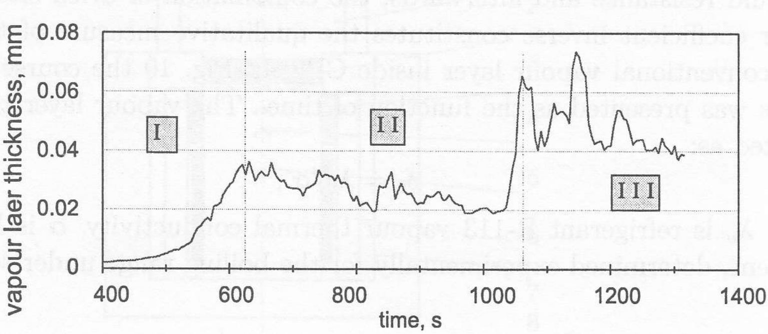

Figure 10. Vapour layer thickness as a function of time; copper CPS, $\Pi = 40\%$, $\delta = 0.8$ mm; refrigerant R-113 boiling at atmospheric pressure.

2. The analysis of temperature changes leads to better understanding of heat transfer mechanisms dominant in intra-layer boiling crisis.
3. Experimental investigations, with the use of gradient method for heat flux determination suggest that q does not have a constant value after it exceeds the value of intra-layer boiling crisis. The reason why it happens is the change in thermal resistance of the porous structure being dried out. The boiling curve resembles the shape (2), Fig. 1.
4. Two zones of conventional thickness of vapour layer can be observed (qualitative measure of volume of vapour spaces inside the structure), with fluctuations caused by bubbles braking away.
5. Investigations into temperature distribution and visualisation experiments should be continued. They will broaden the knowledge of the reasons for thermal resistance of intra-layer boiling crisis.

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