HEAT TRANSFER IN POROUS SURFACES OF EVAPORATORS OF HEAT MACHINES AND DEVICES

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Abstract

The results of experimental investigation of propane vaporization heat transfer on horizontal tubes with sintered capillary-porous coating at low and moderate heat fluxes are presented. Experiments were carried out with tested samples placed inside coaxial tube with a circular mini-gap. An intensification of a heat transfer for such case is compared with a heat transfer of the same samples disposed in a liquid pool. At vaporization occurring in mini-channels two-phase flow takes place without additional power supplying (no mechanical pumping). This phenomena stimulates the heat transfer enhancement 2-2.5 times as higher as the heat transfer on the horizontal tube with porous coating disposed in the liquid pool.

KEYWORDS
Heat transfer, phase change, evaporation, porous surface, confined space

INTRODUCTION

Evaporative and boiling heat transfer is widely used in the industry. Modern heat exchangers should be effective and compact. Many investigations have been performed to provide a better understanding of liquid and two-phase heat transfer at microscale, which is very important in the microdevice development and design. Different capillary structures are applied as a heat transfer stimulants on a heat loaded elements. Similar experiments were carried out in the Luikov Heat and Mass Transfer Institute (Minsk, Belarus). Experimental investigation of propane pool boiling and evaporation heat transfer on single horizontal tube (smooth and with porous coating) was performed for the reasons of analysis of its cooling efficiency. The level of working liquid under the porous tube was varied to be sure the capillary forces are responsible for the liquid suction inside the porous coating. A set of experiments on tubes with porous layers obtained by spraying (stainless steel) or sintering of metal powder particles (copper) shows promising results with the point of view of heat transfer enhancement. The data obtained on a flooded and partially flooded horizontal tube with porous coating in liquid pool or in confined space testify the phenomena of micro heat pipe action inside a porous structure. A microscale effect took place inside the porous body and a mini-scale effect was ensured due to flank or circular mini-gaps.

EXPERIMENT

Experiments were carried out on the set-up described in [1, 2]. A cylindrical test samples (D=20 mm, L=100 mm) with copper sintered porous coating (porosity ~50%, particle diameter 63-100 μm, thickness from 0.3 mm up to 0.8 mm) were placed horizontally in a vessel assembled inside the insulated thermal controlled box to prevent heat losses between vessel and environment. A heat was supplied by the electric heater. Copper-constantan thermocouples were used to measure of temperature. The results of measurements were analyzed with help of a personal computer. Propane was chosen as a working fluid. The level of the liquid "h" from an lower generatrix (Fig. 1) was varied from 70 to 0 mm so that on a partially flooded tube two various mechanisms of a liquid supply were available: the lower part of tested sample was in a liquid pool, and on an upper part of a heat exchanging surface a capillary supply of liquid to zones of vaporization was realized.

A series of experiments was conducted when tested tube was placed coaxially inside a glass tube with a circular mini-gap, as is shown in Fig. 1.The transparent glass tube as an outer coaxial cylinder allowed observing a process of two-phase heat transfer in confined space. The circular gaps were varied from 0.5 mm to 3 mm.

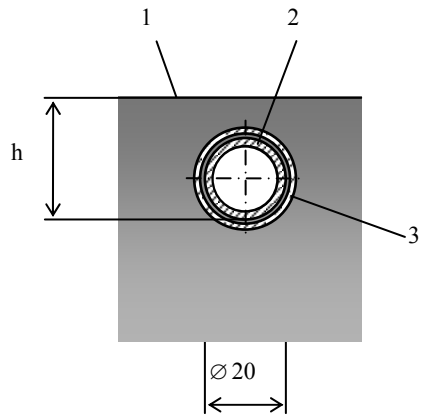


Fig. 1. Cross-section of the operating zone: 1 – liquid-vapor interface, 2 – tested sample, 3 –glass coaxial cylinder

The condenser above the liquid pool ensured the saturation temperature inside the chamber, the temperature inside a temperature-controlled chamber was maintained equal to T_s. An electric heater inside the tube provided the constant heat input. Some auxiliary electric heaters guaranteed the constant saturation pressure, and liquid circuits ensured the level of saturation temperature by regulation of a cooling liquid flow rate through the condenser. A steady state heat transfer regime was necessary to obtain for all the measurements performed during the experiment. In order to verify the reliability of the method chosen, analysis of results obtained and to compare the heat transfer intensity, a series of experiments on plain stainless steel and copper tubes were carried out. Comparison of obtained data with published results of the other authors [3] showed a good correlation.

EXPERIMENTAL RESULTS

The results of boiling and evaporation heat transfer process investigation are published in [4-6]. At first a pool boiling heat transfer on smooth surface was studied. Then the process of liquid boiling on a surface with gas sprayed metal porous coating was considered. The next step was an investigation of heat transfer at evaporation in sintered metal powder porous bodies disposed in a liquid pool or on a partially flooded horizontal cylindrical tube. At last, the experiments with horizontal porous tube placed in confined space were realized. Results of experiments testify that a porous structure of sprayed coating due to closed pores inside is similar to heat transfer on the enhanced surface with microfins, the data of Sokol et al., obtained at propane boiling on tubes with the regular microgeometry of the GEWA-T-x type surface [7]. This kind of a surface represents T-shaped microfins with small depressions between fins to produce additional nucleation centres. Heat transfer intensity at boiling on surfaces with gas-plasma sprayed porous coating like on the GEWA-T-x type surface [7] was 2.5-5 as higher as on a smooth tube [5, 6].

Heat transfer coefficients at vaporization in sintered powder porous bodies with open pores are up 6-8 times as much as at boiling heat transfer on smooth surface [5, 6] in the heat flux range up to $q=100$ kW/m^2. This kind of porous coating is more efficient as compared with gas-sprayed one because of structure differences.

Evaporation heat transfer on partially flooded cylinder

For better understanding of heat transfer mechanism at vaporization in sintered powder open type media the experiments at various levels of liquid were carried out. The porous structure was completely immersed in the liquid pool or partially flooded (Fig. 2).

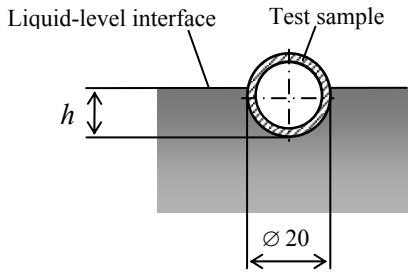


Fig. 2. Cross-section of the partially flooded heat loaded tube with porous coating

In the case of partly flooded sample (h=15 mm - 5mm) the heat transfer coefficients were higher than for the same sample immersed in a liquid pool (h=70 mm,20 mm). At low heat fluxes an influence of the liquid level "h" above the porous coating is important at 'h' less than 2 mm (Fig. 3).

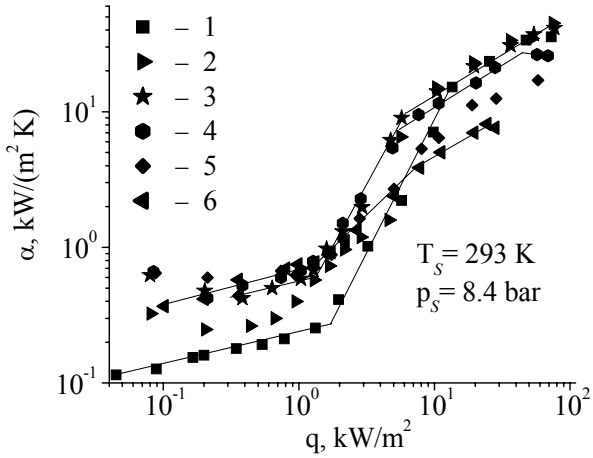


Fig. 3. Heat transfer intensity versus heat flux (thickness of a porous coating is 0.3 mm): 1-6 – h=70, 20, 15, 10, 5 – 5, 0 mm

Decrease of the liquid level above a horizontal porous tube by a quarter of cylinder diameter promotes to increase of the average heat transfer coefficient at low and moderate heat fluxes. The temperature drop between a tube and liquid pool $T_t - T_l$ in various zones of the porous tube surface showed that it goes on due to surface superheat decrease on the unflooded part of a tube, so more intensive heat transfer is available on this part of the sample. It can be explained with the help of following model. There is not boiling but evaporative mechanism of heat transfer in a sintered powder media with the capillary transport of the liquid from the liquid pool to zone of heat release. Hydrodynamic conditions for vapor release through macro pores are better on the unflooded part of a surface.

Micro heat pipe effect in porous media

Sintered powder porous body can be considered as a system with the open micro - and macro-pores (Fig.4). Micro-pores fulfill the function of capillary channels for transport of liquid to zones of vaporization. The macro pores represent the channels for vapor transfer. The vapor is generated on surfaces of meniscuses in orifices of micro-pores. There are a great number of such zones over all porous surfaces, so the total area of evaporation is very large.

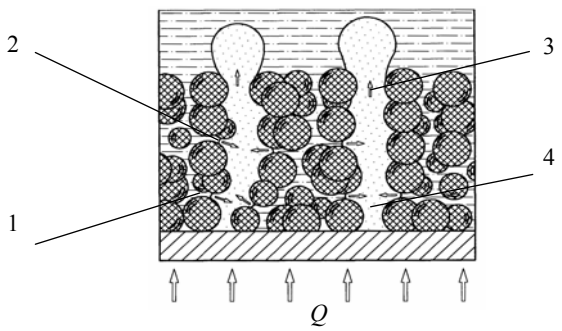


Fig. 4. Cross-section of a powder porous coating: 1 – micro-pore, 2 – meniscus, 3 – vapor, 4 – macro-pore

The process inside a sintered powder porous body is similar to the processes inside micro heat pipes with zone of evaporation and condensation (Fig. 5). If the tested sample is placed in the liquid pool, we have a closed type micro heat pipe (Fig. 5, a), for partially flooded porous cylinder we have a surface with open type of micro heat pipe (Fig. 5, b). A number of active centers of vaporization (meniscus of the evaporation) rise proportionally to the heat flux. At the heat flux interval from 0.1 to 1.5 kW/m^2 the increase of heat transfer intensity up to 1.5 times was noticed, when the liquid covered an upper generatrix of a sample, and 2.5-3 times as high at h=15 mm (Fig. 2) to compare with completely flooded porous tube. Lowering of h down to 10 mm (a middle of tube diameter) decrease the heat transfer intensity at heat flux q>(1.5-2) kW/m^2, due to the insufficient liquid capillary flow to the meniscus of the evaporation.

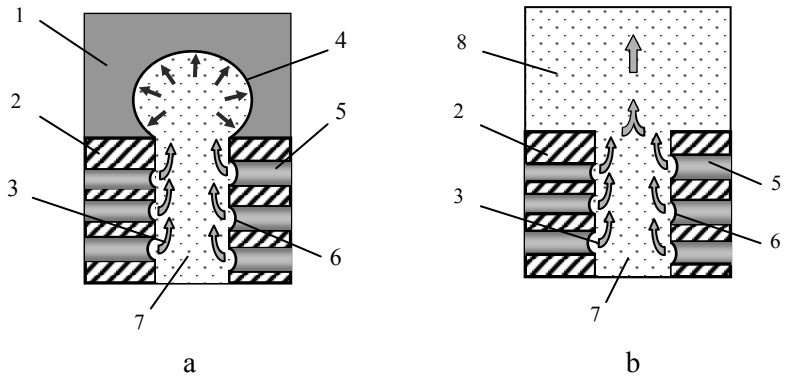


Fig. 5. Micro heat pipe effect in porous coating: a) closed type, b) open type: 1 – liquid pool, 2 – porous body, 3 – rising vapor, 4 – zone of condensation, 5 – liquid filled micro-pore, 6 – meniscus, 7 – macro-pore, 8 – vapor space

There are two limitations for heat transfer intensity: hydrodynamic ability of porous coating to transport liquid and finite number of vaporization centres (curvilinear meniscuses in orifices of micro-pores). The heat transfer intensity depends on the curvature K of meniscuses. While the curvature K doesn't exceed some value K_{max} it is enough of the capillary ability to liquid transport, when curvature rises to $K>K_{max}$ the drainage of heated surface begins. On reaching the certain quantity of heat flux, meniscuses move inside micro pores, the meniscus curvature K increases and exceed K_{max}. Consequently, a heat transfer surface above the liquid-level doesn't get sufficient amount of liquid, "dry spots" appear and then spreads to all over this part of surface. The liquid level is lower; the maximum heat transfer coefficient is decreasing.

Evaporation heat transfer in coaxial mini-gap

To study the influence of space limit on heat transfer a series of experiments were conducted on the tested horizontal cylindrical samples placed inside the coaxial glass tube with circular mini-gap. The porous coating thickness was varied from 0.3 to 0.8 mm. Experimental results show, that such combination is favorable for the enhancement of the evaporation heat transfer at low and moderate heat loads (Fig. 6).

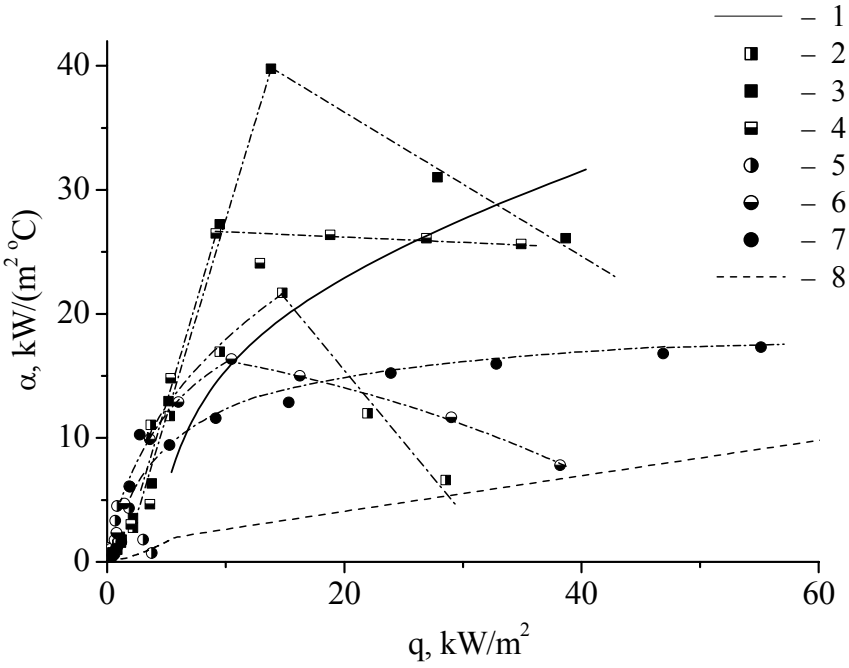
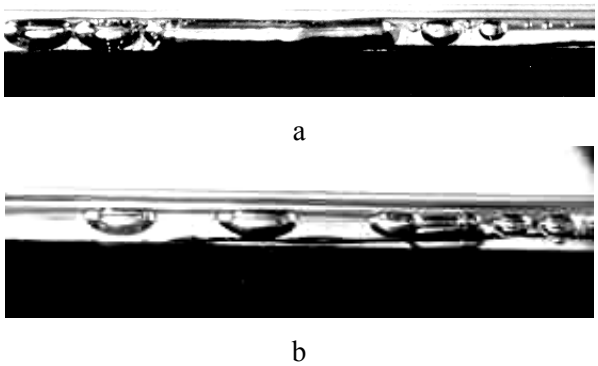


Fig. 6. Heat transfer coefficients at vaporization in horizontal porous cylinders placed inside of coaxial tube: 1 – liquid pool, 2-4 – the sample with porous coating thickness 0.3 mm, circular mini-gaps are 0.8, 1.5 and 2 mm respectively, 5-7 – the sample with porous coating thickness 0.8 mm, circular mini-gaps are 0.2, 1 and 1.5 mm, 8 – plane tube in liquid pool

Visual observing of process of heat transfer with phase changing testifies that vapor bubbles movement in circular mini-channel has a complicated character: bubbles move not only vertically upward but also along a tube axe toward outlets to liquid pool. Thus a two-phase flow through a circular mini-channel took place that was the reason of heat transfer intensification.

The dependences $\alpha(q)$ in Fig. 6 have maximums. At the beginning an increase of heat transfer coefficients were noticed, then it reduction took place. The reason is that a size of mini-gap influenced in two ways on the heat transfer intensity. The mini-gap is narrower; the velocity of two-phase flow is higher. On the other hand, a small throat impedes an evacuation of vapor phase generated inside the porous layer. In Fig. 7 the vapor clusters inside the annular mini-gaps 2 and 2.8 mm at low heat flux ($q=0.3$ kW/m^2) are shown. It's seen that at the first case diametrical size of a vapor clusters above the tested sample were practically equal to the gap size. When the mini-gap size was 2.8 mm (Fig. 7, b) vapor clusters do not fill all space of mini-gap above the sample, they are separated from the heat exchange surface with a water layer. The vapor clusters are not so long as in the more thin gap. Therefore restricted gap is better at low heat fluxes, just as more extensive annular channel is preferable at moderate heat loads when the vaporization process is intense. So, changing the size of annular mini-gap and the parameters of porous coating we can get the optimum conditions for various heat loads. For the sample with porous layer thickness 0.3 mm most intensive heat transfer was observed at the circular mini-gap 1.5 mm, but at heat fluxes $q>15$ kW/m^2 curves $\alpha(q)$ for mini-gaps 1.5 and 2 mm began to approach. The analogous trend took place for the sample with porous coating thickness 0.8 mm; the difference was that the curves profiles were different.



a

b

Fig. 7. Vapor clusters above the cylindrical heat exchange surface inside the circular mini-gaps 2 (a) and 2.8 mm (b) at the heat flux q=0.3 kW/m^2

The heat transfer coefficient for the sample inserted inside the glass tube was higher at heat fluxes up to 40 kW/m^2 to compare with pool conditions and up to 60 kW/m^2 to compare with the pool boiling heat transfer on a plain tube. The explanation is that a cylindrical porous surface disposed inside the transparent coaxial glass tube with circular mini-gap has all particularities of micro-scale and mini-scale effects of the heat transfer.

COCLUSION

Reducing the size of cooling system we increase its efficiency, improve system performance by adding micro scale function (microporous heat pipe effect) to macro scale engineering application.

At vaporization occurring in mini-channels two-phase flow takes place without additional power supplying (no mechanical pumping).

Micro heat pipe effect + two-phase forced convection in the coaxial gap (porous tube inside the glass tube) at low and moderate heat fluxes stimulate the heat transfer enhancement 2-2.5 times as higher as the heat transfer on the horizontal tube with porous coating disposed in the liquid pool.

References

1. Vasiliev L.L., Zhuravlyov A.S., Novikov M.N., Vasiliev L.L. Jr. Experimental investigation of propane boiling in porous structures // *Proceedings of The IV Minsk International Seminar "Heat Pipes, Heat Pumps, Refrigerators", Minsk, Belarus*. 2000. Pp. 245-255.
2. Vasiliev L.L., Zhuravlyov A.S., Novikov M.N., Vasiliev L.L. Jr. Heat transfer with propane evaporation from a porous wick of heat pipe // *Journal of Porous Media*. 2001. No. 4 (2). Pp. 103-111.
3. Gorenflo D., Sokol P., Caplanis S. Pool boiling heat transfer from plain tubes to various hydrocarbons // Int. J. Refrigeration. 1990. Vol. 13. Pp. 286-292.
4. Vasiliev L.L., Khrolenok V.V., Zhuravlyov A.S. Intensification of heat transfer at propane pool boiling on single horizontal tubes // *Revue Générale de Thermique*. 1998. Vol. 37, No. 11. Pp. 962-967.
5. Vasiliev L.L., Zhuravlyov A.S., Shapovalov A. Heat transfer efficiency at vaporization in porous coating of horizontal cylinder // *Proceedings of The 4th International Conference on Heat Transfer and Transport Phenomena in Multiphase Systems (HEAT'2005), Gdańsk, Poland*. 2005. Pp. 511-518.
6. Vasiliev L.L., Zhuravlyov A.S., Novikov M.N., Shapovalov A.V., Litvinenko V.V.. Heat transfer at propane pool boiling and evaporation in capillary-porous evaporators // *Proc. of 4th Baltic Heat Transfer Conf. "Advances in Heat Transfer Engineering", Kaunas, Lithuania*. 2003. Pp. 739-746.
7. Sokol P., Blein P., Gorenflo D., Rott W., Schömann H. Pool boiling heat transfer from plain and finned tubes to propane and propilene // Proc. of 9th Int. Heat Transfer Conf., Jerusalem, Israel. 1990. Vol. 2. Pp. 75-80.