УДК 66.045

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TO ENGINEERING CALCULATION OF THE INFLUENCE OF POROUS STRUCTURE-COATING CHARACTERISTICS ON THE BEGINNING OF WATER BOILING

The article presents the results of experimental studies of impact of basic characteristics and parameters of porous metal fiber structures on two-phase heat transfer intensity during water boiling on porous surfaces. The simplified empirical formulas were obtained. The formulas are necessary for engineering calculations of heat transfer coefficients under conditions typical for heating zones of heat pipes and termosyphones, operating in low temperature range of chemical-energy and heat-recovery equipment.

Key Words: *heat pipe, thermosyphon, metal-porous materials, capillary structure, porosity, intensity of two-phase heat transfer, beginning of boiling, heat transfer, heat exchange.*

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ДО ІНЖЕНЕРНИХ РОЗРАХУНКІВ ВПЛИВУ ХАРАКТЕРИСТИК ПОРИСТИХ СТРУКТУР-ПОКРИТТІВ НА ПРОЦЕСИ ЗАКИПАННЯ ВОДИ

Представлено результати експериментальних досліджень впливу основних характеристик і параметрів пористих металевих волокнистих структур на інтенсивність двофазного теплообміну при кипінні води на пористих поверхнях. Отримано спрощені емпіричні формули, необхідні для інженерних розрахунків коефіцієнтів тепловіддачі в умовах, типових для зон нагрівання теплових труб і термосифонів, функціонуючих у низькотемпературних діапазонах роботи хіміко-енергетичного та теплоутилізуючого обладнання.

Ключові слова: *теплова труба, термосифон, метало-пористі матеріали, капілярна структура, пористість, інтенсивність дво-фазного теплообміну, початок кипіння, теплопередача, теплообмін.*

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К ИНЖЕНЕРНЫМ РАСЧЁТАМ ВЛИЯНИЯ ХАРАКТЕРИСТИК ПОРИСТЫХ СТРУКТУР-ПОКРЫТИЙ НА ПРОЦЕССЫ ЗАКИПАНИЯ ВОДЫ

Представлены результаты экспериментальных исследований влияния основных характеристик и параметров пористых металлических волокнистых структур на интенсивность двухфазного теплообмена при кипении воды на пористых поверхностях. Получены упрощенные эмпирические формулы, необходимые для инженерных расчетов коэффициентов теплоотдачи в условиях, типичных для зон нагрева тепловых труб и термосифонов, функционирующих в низкотемпературных диапазонах работы химико-энергетического и теплоутилизационного оборудования.

Ключевые слова: *тепловая труба, термосифон, метало-пористые материалы, капиллярная структура, пористость, интенсивность двух-фазного теплообмена, начало кипения, теплопередача, теплообмен.*

Two-phase heat-transfer devices – heat pipes (HP) and their variations – thermosyphons (TS) have been lately rapidly developing and getting implemented in many industries [1,2]. The most promising and effective designs of HP are the heat-pipe heat exchangers-recovery (HPHE), the basic elements of which are heat pipes. Important advantages of HPHE are the following: 1) for complex thermo-physical and operational parameters and characteristics HPHE dominate by classic recuperative heat exchangers (considering equal sizes) [3,4]; 2) design of HPHE is simple, and their mass production can be quickly adjusted (given that HP are supplied by specialized companies); 3) the problem of thermal expansions compensation of heat-tension surfaces, which are essential for classic heat exchangers, is almost absent in HPHE; 4) the reliability rate of HPHE functioning is quite high.

Quality and thermal characteristics of HP and TS directly depend on the types, characteristics and parameters of metal-porous materials (MPM) [5], which are important structural elements of HP. MPM serve as capillary structures in HP (transporting working fluids inside HP) and, simultaneously, two-phase heat transfer intensifiers in the areas of heating (boiling) and cooling (condensation) zones in HP [6].

Among defining characteristics of MPM are: 1) porosity $\mathbf{\Theta_{мfм}}$; 2) effective pore diameter $\mathbf{D}_{ef}$ (sometimes known as average diameter); 3) size fractions (for fiber MPM — fiber length $\mathbf{L_v}$ and fiber diameter $\mathbf{d_v}$); 4) thermal conductivity of metal fibers $\mathbf{\lambda_{мет}}$ and thermal conductivity of porous structure $\mathbf{\lambda_{ks}}$. The values of porosity $\mathbf{\Theta_{мfм}}$ and frame heat conductivity $\mathbf{\lambda_{ks}}$ significantly affect the parameters of heat exchange inside the HP. If $\mathbf{\lambda_{ks}}$ increases, the intensity of two-phase heat transfer also significantly increases, while the values of thermal resistance of heat pipes ($\mathbf{R_{hp}}$) reduce. Therefore, the calculations of

MPM characteristics quantitative impact on heat transfer coefficient α is an important task in engineering practice, development and production of effective heat pipes.

Experimental equipment and methods. The aim of the work was to investigate the influence of porosity $\Theta_{мfм}$ values of porous metal structures-coatings cauterized to smooth metal heating surface on the intensity of two-phase heat transfer process in modes, that are typical for HP and TS working. A scheme of experimental setup is given in [7]. Figure 1 shows the scheme-design of two working stations required for the research of heat transfer intensity of water and acetone boiling in conditions typical for heat pipes (Figure 1, II) and termosyphones (Fig. 1, I) working. A number of MPM prototypes was created with different characteristics of porosity, thermal conductivity and thickness. The main characteristics of MFM changed in the following ranges: $\Theta_{мfм}$ = 35-95 (%); λ_{ks} = 0,2-60 W/(m·K); MPM thickness $\delta_{мfм}$ = 0,2-4 mm; L_v = 3-12 mm; $d_в$ = 20-70 microns; MPM materials — copper and stainless steel (9H18N10T). Porous materials (structures) made previously were sintered to copper substrates. Parameters of researched MPM provided enough wide range of fiber sizes and porosity.

During the experiments MPM prototypes 6 (cylindrical form) with previously sintered to copper substrate porous fibrous structure was sintered to the butt end of copper cylindrical heater 3. Six copper-constantan thermocouples were previously sintered to inner butt end of substrates. Values of them were averaged. Heat flow generated by the wire heater 2 (or 3) was regulated via autotransformer and through a cylindrical rod heater 1 rose to the prototype 6 of porous structure. The values of heat flow [W] reaching certain values of stationary thermal modes were measured with a precision Wattmeter, temperatures - with digital microvoltmeter. Non-working surfaces of the cylinders were insulated with glass and basalt fiber 20. The calibration experiments during water boiling on technically smooth copper surfaces showed high reliability of the obtained results. The results of calibration were compared with known literature data of Tolubinskiy, Labuntsov as well as with boiling curves calculated by Kutateladze and Rozenow formulas. The errors of determined heat transfer coefficients did not exceed 7-12%, depending on the density values of summed heat flows q. The values of heat flow density **q** were in the range of $(0\text{-}250)\cdot 10^4$ W/m^2.

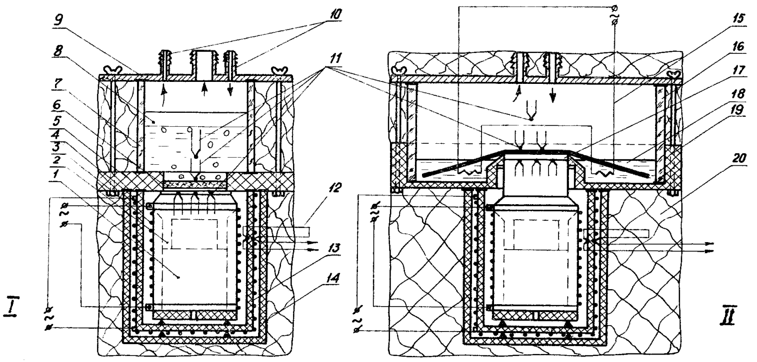

Fig. 1. **Scheme of work stations of experimental setup for investigations of heat exchange during beginning of boiling and boiling of water on surfaces with porous capillary structures**

1 - the power supply to the sample of porous structure; 2 - "small" heater; 3 - main ("big") heater; 4 - guard heater; 5 - fluoroplastic flange; 6 - sample of porous material; 7 - glass cylinder; 8, 18 - liquid; 9 - lid; 10 - connections; 11 - thermocouples; 12 - differential thermocouple; 13 - alundum casing; 14 - ceramic casing; 15 - auxiliary heater; 16 - cylinder; 17 - sample of metal-fiber capillary structure; 19 - flange; 20 – insulation.

Research results. The results of experiments conducted in boiling water on the surfaces with metal porous materials in condition of free fluid motion and in condition of capillary transport are shown in Fig. 2. The results showed that copper fibrous structures with average porosity (40-50%) in the range of thicknesses from 0.5 to 1.0 mm provide the highest heat transfer coefficients α. A significant increase in the intensity of heat transfer during boiling on porous surfaces compared to the smooth technical surfaces can be justified by applying proposed in [8] semi-empirical model of two-phase heat transfer. The essence of the model is the hypothesis about significant effect of thermal properties of capillary structure-coverage (in particular - its thermal conductivity λ_{ks}) on boundary conditions during bubbles formation in pores and during the porous channels formation in structures. The experimental data for boiling conditions at the free flow of water is summarized satisfactorily with empirical formula (1).

α, Вт/(м^2·К)

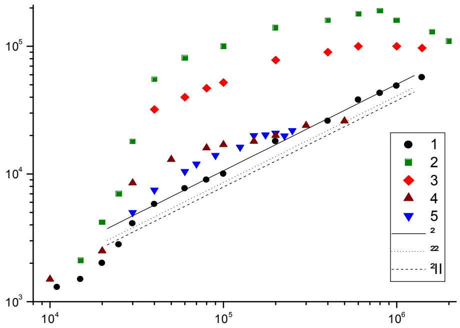

Fig. 2. **The intensity of heat exchange of water boiling on surfaces with metal-fiber capillary structures in free movement of fluid at atmospheric pressure**

Heat flow density q, W/m^2

1 - technical smooth surface; copper fibrous capillary structures (Θ = 40% δ = 0.8 mm): 2 - sintered capillary structure; 3 - pressed capillary structure; corrosion-resistant capillary structures (steel): 4 sintered capillary structure: Θ = 88%, d = 0,8 mm; 5- pressed capillary structure: Θ = 84%, d = 0,4 mm; curves I-III - water boiling on a smooth technical surface (published data of various authors)

The proposed formula takes into account the degree of such influence on the intensity of heat transfer characteristics and main parameters of MPM, namely, porosity, thickness of the structure, its thermal conductivity, effective pore size and physical characteristics of liquids. The impact of the latter is illustrated by known in boiling complex Labuntsova. The formula is:

$$\alpha = c \cdot q^n \cdot \delta_{MfM} \cdot \lambda_{ks}^{0.6} \cdot \Theta^m \cdot D_{ef}^{0,15} \cdot [\lambda_{fl}^2 / (\nu_{fl} \cdot \sigma_{fl} \cdot T_s)]^{0,33}. \quad (1)$$

The coefficient of proportionality c = $2 \cdot 10^4$; $\boldsymbol{n} = 0{,}15 \cdot \delta_{MfM}^{-0,14}$ at $1 \cdot 10^{-3}$ m $\le \delta_{MfM} < 0{,}8 \cdot 10^{-3}$ m; $\boldsymbol{n} = 0{,}0535 \cdot \delta_{MfM}^{-0,28}$ at $0{,}8 \cdot 10^{-3}$ m $\le \delta_{MfM} \le 10 \cdot 10^{-3}$ m; $\boldsymbol{m} = 2{,}4 \cdot \Theta$. The values of physical quantities and parameters are necessary to substitute in formula (1) in the SI system.

The feature of the studies of water boiling on the surfaces with MPM was the following: the experiments in free movement of water (mode of termosyphones operation) were performed by following conditions: 1) the existence of certain "underheating" of water to the boiling point; 2) heating water to such values of temperature, which were only a few tenths of a Celsius degree lower than tabulated values of boiling point, typical for atmospheric pressure (during the measurement).

The start of water boiling was recorded visually at the moment of appearance and isolation of the first steam bubbles (steam jets), which were formed in the pores-channels. Accordingly, the temperature pressures ΔT_{bb} were measured (for each experimental sample of MPM). Such temperature pressures are considered the defining for boiling beginning characteristics on porous surfaces.

The results of experiments conducted with water boiling on the surface of fiber MPM in free movement of fluid are shown in Fig. 2 in the form of dependence ΔT_{bb} = f (Θ_{MfM}) by changing of thermal conductivity values of MPM and average (effective) pore diameter Def.

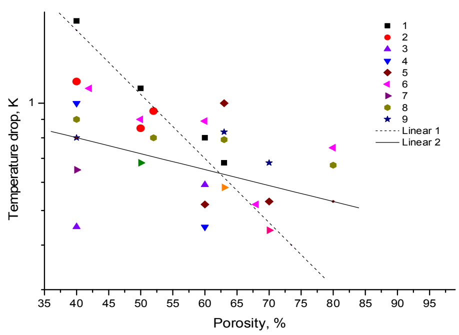

Fig. 3. **The impact of the characteristics of porous metal fiber materials on thermal pressures at the beginning of water boiling on porous surfaces**

The thickness of porous fibrous structures-coverages: 1- 0.1 mm; 2 - 0.2; 3 - 0.4; 4 - 0.6; 5 - 0.8; 6 - 1.0; 7- 2.0; 8-4.0; 9-10.0. Curves: I - for the authors of [6]; II - for authors of the article.

It is known, that during boiling of extra-heated water on smooth surfaces in conditions of free convection the temperature pressures ($\Delta\mathbf{T} = \mathbf{T}_{surface} - \mathbf{T}_{saturation}$) necessary for boiling, are in the range of 7-10 ^{0}C [6-8]. The results of authors [6] summarized in a curve II (Fig. 3) show, that porosity increasing of fibrous MPM makes the temperature pressures of boiling beginning to decrease. The relatively large number of "big" pores is present for highly porous MPM. Such structures have lower Laplace capillary forces, than structures with "shallow" pores. Capillary forces are essential for the growth and movement of bubbles through steam channels. It should also be noted, that thermal characteristics of MPM affect the processes of evaporation and steam movement through the channels (or "trunks"), besides capillary forces and hydraulic resistance of "channels". Foremost thermal conductivity of MPM affects $\Delta\mathbf{T}_{bb}$.

Experimental data obtained in our study indicates that the impact of MPM porosity Θ on temperature pressure of boiling $\Delta\mathbf{T}_{bb}$ is (to some extent) the same compared to the results obtained by the authors [6]. Curve II in Fig. 3 was calculated by the formula proposed in [6]. Our results (curve I in Fig. 3) show that the degree of influence of MPM porosity Θ is significantly smaller (weaker) compared to the results of calculations performed by the respective authors formula [6].

As a result of generalization of the experimental data the following formula was suggested. It allows to determine the temperature pressures of boiling water at free convection (working in termosyphones conditions) on the surface of the fiber MPM, for the conditions of atmospheric air pressure:

$$\Delta\mathbf{T}_{bb} = \mathbf{c} \cdot \mathbf{k} \cdot \Delta\mathbf{T}_{bb}^{ss} \cdot \mathbf{\Theta}^{\mathbf{m}} \cdot \boldsymbol{\lambda}_{ks}^{0,25} \cdot \mathbf{D}_{ef}^{p}, \quad (2)$$

where $\Delta\mathbf{T}_{bb}^{ss}$ – temperature pressure of the beginning of boiling water on the technical smooth surfaces (defined by formulas known from the literature); coefficient p = 0.25; m = 0,25; p = 0,15. The coefficient k depends on the thermal conductivity of metal fiber fractions. For copper MPM it is calculated by the empirical formula (3) as follows:

$$\mathbf{k} = 2{,}15 - 0{,}003 \cdot \lambda_{\mathbf{met}} \quad (3)$$

The effect of heat conductivity of fibers obtained from other metals on the beginning of boiling in the latter conditions should be investigated further. The values of calculated parameters and characteristics of MPM in obtained formulas (in SI units) are used in dimensionless form.

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Стаття прийнята в редакцію 25.03.2015.