Correlations for enhanced boiling heat transfer on modified surfaces tubes

Ioan Sarbu and Emilian Stefan Valea

Abstract**—** The paper treats the method of decreasing the size of surfaces of heat exchangers in general by increasing the heat transfer coefficients, the importance of heat transfer enhancement in general and for vaporization in special, also the used methods. This increase is achieved in our case by passive methods applied to heat transfer surfaces, namely mechanical processing, covering with sle-eves made by metallic tissues or covering with metallic porous layers, made using welding methods. These tube surfaces are used for increasing heat transfer coefficients from inner heating source to outer vaporizing liquids. Are mentioned also the most important particularities for vaporizing enhanced heat transfer from metallic porous layers. Results for tests made with improved heated surfaces, comparison between different surfaces are presented after personal research. Are proposed specific heat transfer correlations and results obtained with it compared with other researchers' results. Are described the way of establish and the correlations that could be used in the work of design for heat exchangers which are to be made from tubes having the described and used types of surfaces.

Keywords**—** Heat transfer, Modified surfaces, Porous layer, Vaporization, Correlation, Thermal performance; Metallografic analyses.

I. Introduction

THE paper treats heat transfer enhancement, its importance for change of phase, respective vaporization, in special. After studying results obtained by other researchers concerning the same subject, was chosen specially constructed surfaces to enhance heat transmission. It is known that nucleation site density is fundamental to the development of mechanistically based nucleate boiling heat transfer [17]. Knowing that nucleation site density can be increased by different methods that modify geometrical parameters of surfaces, authors have created such type of surfaces. Appling passive methods the enhanced surfaces have the main common characteristic that all are designed to have much more nucleation sites than plane surfaces.

The enhanced boiling heat transfer follows heat transfer coefficient increasing in concrete operating conditions, contributing by this to global heat transfer coefficient increase and, for imposed thermal power, to reducing heat exchanger surfaces. Reducing heat exchanger surfaces, lead to reduce investment expenses. Increasing global heat transfer coefficient leads to reduce general operating expenses by lower thermal agent flow.

In general, enhancement of heat transfer trough a separating surface (for example tube) is made, in convection case, by finning the surface. This leads to heat transfer surface increase i.e. increase contact surface with heat changing medium. On the other hand, by braking or reducing thermal layer thickness, the convective transfer coefficient increases. Fins and supplemental roughness, besides increasing the contact surface, are promoters of turbulence and the turbulent heat exchange is intensified.

In case of vaporization heat exchangers, due to specific of boiling process, it is not enough finning, increasing heat exchange surface or creating artificial turbulence. In last years, several researches of boiling heat transfer have been accomplished [6, 19, 26, 27; 28, 30]. It has been followed different surfaces behavior and also different vaporizing fluids behavior. For certain operating conditions and for certain surface, there are different behaviors from one operating mode to another, from a fluid to another, from a surface type to another [19, 27].

It can although highlight the most important factors that characterize generally vaporization and bubble vaporization in particular. Bubble vaporization could be considered preferential due to high heat transfer coefficients. These factors are also important for increase heat transfer coefficients and in this way to reduce heat exchange surfaces (compacting) the vaporization heat exchangers.

It is well known that only those imperfections of heat transfer surfaces which are not completely wetted could become active nucleation centers [23, 27]. Nucleation centers or vapour nuclei are places on the vaporization area where occure boiling. Here are born vapour nuclei, in which develop vapour bubble as the acquisition of heat through the heat transmitting surface. Bubbles detach finally from surface. After detachment, bubbles are transported by ascension forces (Archimedes) through the liquid layer until free surface of liquid. Here bubbles break and vapor spread in the available space.

II. Importance and Consequences of Heat Transfer Enhancement

The enhanced boiling heat transfer follows heat transfer coefficient increasing in concrete operating conditions, con-

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III. Experimental Researches

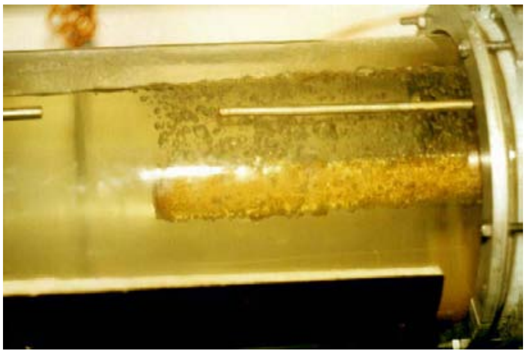
In order to achieve the purpose, tree types of surfaces on the outside of some copper tubes are made: for the first groupe of tubes, the outside wall was mechanical processed, for the second the tubes were covered with tissues made of different metallic materials and for the third the outside of the tubes were covered by welding with porous metallic layers of different materials. The tubes so prepared were tested within an experimental work in order to establish the boiling heat exchange coefficient increase for each created tube compared with the witness tube which is that tube with the plane surface as it was obtained in the factory, when it was processed.

Specially built facility allows vaporization study on copper tubes outside, having 22 mm diameter and 2 mm wall thickness. The outside surfaces prepared as presented above was drowned in the working fluid (demineralized water degassed) while maintaining in permanent regime the saturation parameters at momentary atmospheric pressure. So, the tests were made for pool boiling in stationary process, at atmospheric pressure, on the outside of the surfaces already mentioned and tubes heated with inner electric cartridge. The used methods for making the described surfaces, the experimental apparatus and the way of work are detailed described in [27].

In the experiments were measured for each sample (tube with outside surface enhanced), under saturated boiling conditions, differences between outer temperature of metallic wall t_p [°C] and saturation temperature of boiling water t_s [°C], for each of heat flux density q [W/m^2] consumed. Heat flux density varies with supply voltage variation of electric resistance cartridge heater in range 800…41,000 W/m^2. Based on experimental data is determined heat flux coefficient for each sample (tube). Reports of these coefficients and coefficients of heat transmission tube with a smooth outer surface are named "increase coefficient" symbolized *inj*. These reports were calculated and plotted for each sample depending on heat flux density q.

To assess the thermal performance of surface modified pipes, is necessary to establish for each of them and for smooth tube also, heat transfer coefficients for each operating domain and for each heat flux density.

Photos taken during experiments with smooth surface tube are presented in Figure 1.



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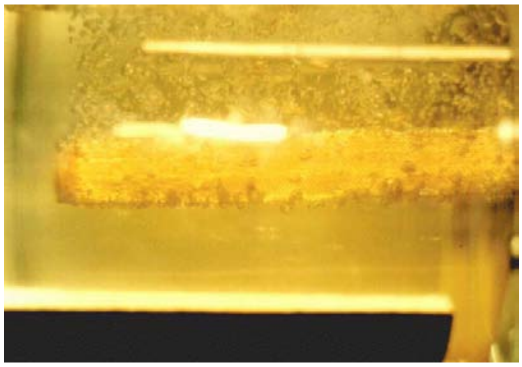

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Fig. 1 Aspects of boiling on smooth tube
a) q = 39 w/m^2; b) q = 28 W/m^2

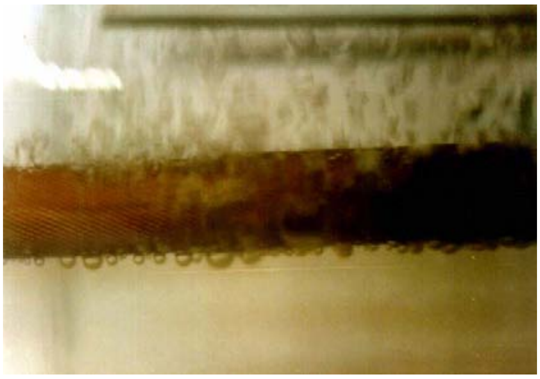
For each type of surface are compared thermal performances with those of smooth tube.

A. Mechanical Processed Tubes

This groupe of tubes have outer surface mechanical processed as follows: longitudinally channeled; screw channeled; simple thumb screw; double thumb screw; screw–cut and thumb screw; sanded with sand; sanded with corundum; plane winded with copper wire. In Figure 2 are shown boiling aspects on simple thumb screw surface for two heat flux density.

B. Tubes Covered with Tissues Made of Different Metallic Wires

The tubes were covered with sleeve made of metallic wire tissues. The tissues used were made of different materials: brass; bronze; copper; galvanized steel small step; galvanized steel large step. In Figure 3 are shown all the tubes covered.



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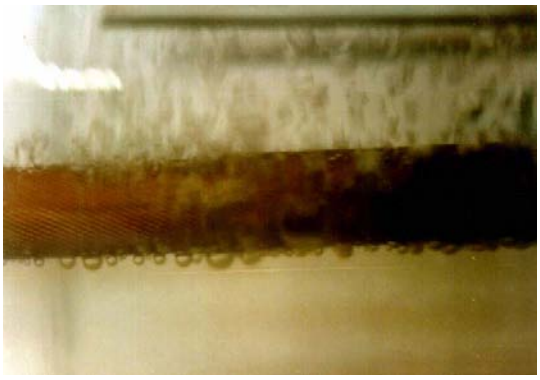


b)

Fig. 2 Boiling aspects on simple thumb screw surface:
a) q = 40 kW/m^2; b) q = 7.2 kW/m^2

Fig. 3 Sleeves made by metallic tissues mounted on tubes

C. *Tubes Covered with Metallic Porous Surfaces*

A porous surface has a lot of interconnected capillaries, partially filled with liquid, which act as nuclei for the development of many bubbles in the boiling liquid. If pores were not interconnected, their performance as nuclei would be dependent on the amount of air or vapour from pores. But if interconnection, vapour formed in a pore can activate one or more adjacent pores so boiling is initiated and maintained wich little dependence on amount of vapour contained in each pore. At least part of the matrix of interconnected pores is assumed that fill with fluid others nearby. As the bubbles rise, they become detached from capillaries interconnected due to the continuous generation of vapour in capillary and rise in liquid layer that cover it. Growth of heat transfer coefficient results from the fact that vaporization takes place priority on porous surface, reducing the thermal boundary layer that should be crossed by the heat leaving the base material surface. It is estimated in literature that the growth factor of heat transfer coefficient is higher that rough surfaces.

A proper porous surface could be obtained by sintering particles of 1…50 μm mean diameter [14]. These particles should better be of a metal with high thermal conductivity, eg copper. The particles are so applied on base surface to form a thickness layer of 0.1…1.0 mm. Spaces between particles must be free of foreign metal particles and interconnected in depth. Interconnected pores will be between 1…150 μm in size and in great numbers on the surface unit, i.e. with high density.

Particle shape can affect more than its size, since such fine spherical particles can lodge more compact than those with irregular granular and thus created gaps will be reduced. It is therefore advisable to determine by testing on samples of porous surfaces, equivalent pore radius, which actually represents characteristic size (radius) of bubbles of vapor that can leave the cavity with the same size as the equivalent radius. Must be determined all the geometrical characteristics of deposited metal layer: thickness, average pore size (diameter), average particle size of the metal layer, layer porosity (percentage volume occupied by pores in whole deposited layer). Equivalent pore radius r can be determined by vertically soaking of surface covered with porous layer in a liquid and measuring the height that the fluid ascends by capillarity in porous surface. Then:

$$r = \frac{2\times\sigma}{\rho\times h} \tag{1}$$

in which: σ is the superficial tension; ρ – specific mass; h – height of ascent.

One of the methods of preparing such a surface is that using a temporary binder which makes and maintain uniform cover of basic material. Binder decomposes and evaporates during heating and sintering. The binder is diluted in a suitable solvent such as kerosene or carbon tetrachloride add enough metal powder to form a viscous mixture evenly with a metal weight ratio of about 92 to 1 plastic.

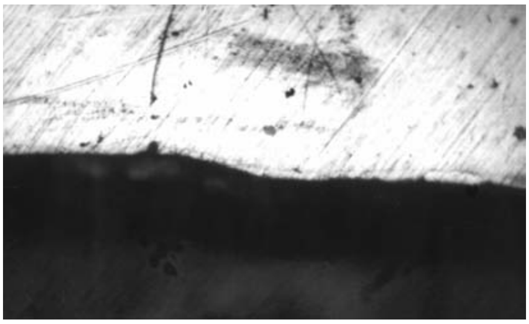
Milton [14] propose a method in which the mixture formed by 32 g copper powder in 2 % solution water–methyl–cellulose polymer is applied on basic material and then sintered at a proper temperature. If the porous layer must be obtained on inside surfaces of tubes, the mixture is introduced in tube and then centrifuged at 200 rpm speed, dried during rotation and then sintered. Grant [7] proposed another procedure of forming a porous metal layer with an equivalent pore radius of 0.05…7.5 μm on an impermeable layer of alloy 99% copper and 1% iron. As mechanical strength, area has been tested by brushing with a wire brush and was found to be satisfactory, equivalent to that obtained by sintering.

Grote [8] created surfaces named “capillary pumped”, formed by gear surface with a recess of 3…6 times greater than the channel width. Deposit of an aluminum powder porous mixture is applied under vacuum on gear cutting surface with bottlenecks channels to their peak. Robertson [20] proposes to produce a porous surface by metal powder spraying (flame spraying) on the outside of ribs already created.

For authors' experimental researchers on porous metallic surfaces, the additional depositing material which could be provided in powder form has been used metallization process with flame and powder and installation having commercial named Thermospray 5P. For additional depositing material available (copper) only wire form with 3.2 mm diameter, has been used metallization process with flame and wire and installation "METCO 10E".

In [28] are presented main parameters of technological processes of metallization applied. In order to establish geometric characteristics of metallic layer made by metallization, for each of tested tubes named probes, have been made quantitative metallographic analyses, on "metalized surface" and on "polished surface". Also, are presented in the same paper the two methods of quantitative metallographic analysis for porous metallic surfaces deposited on tubes.

Figure 4 shows appearance of metallic layers deposited on each tube seen with electronic microscope, magnified for 100 times. These appearances are on transversal section of metallized tubes on which are made photos.



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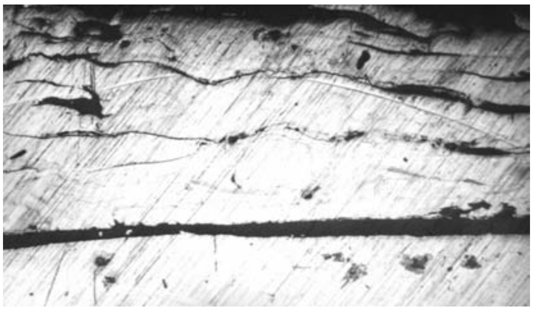


b)

c)

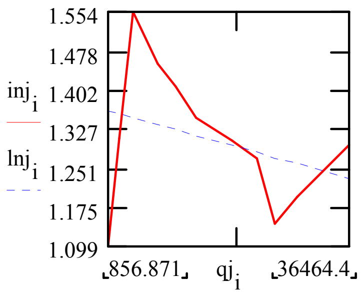
d)

Fig. 4 Metallic layers deposited on copper tubes
a) stainless steel; b) bronze; c) copper1 d) copper2

Increase coefficient *inj* evolution for metalized tubes samples are presented in Table I and Figure 5. For each sample, *lnj* is the regression right line corresponding to the *inj* evolution, according to experimental data. Sample numbers are: 15–stainless steel; 16–bronze; 17–copper1; 18–copper2.

Table I. Increase coefficient results

Sample	Increase coefficient	Mean coefficient
15	1.35…1.25	1.30
16	2.6…2.2	2.40
17	1.76…2.02	1.89
18	1.91…1.96	1.93



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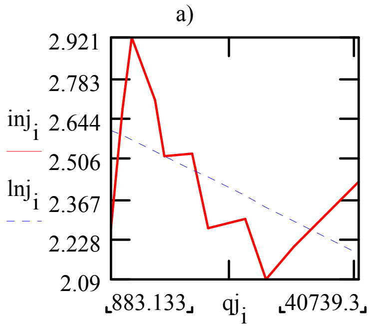

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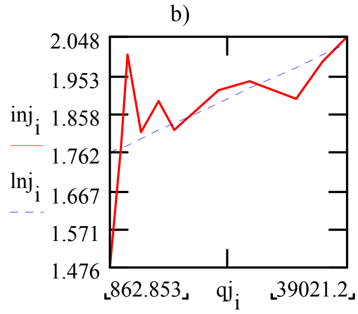

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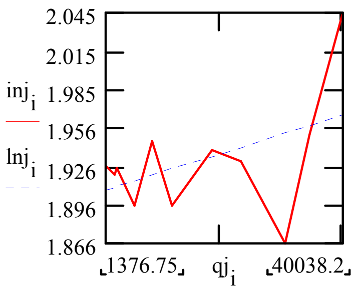


d)

Fig. 5 Increase coefficient evolution depending of heat flux density q [W/m^2] for metallization with:
a) stainless steel; b) bronze; c) copper1; d) copper2

All the specially constructed surfaces were characterised by some of main parameters, used in proposed heat transfer correlations. The metallized surfaces were metallographic analyzed, starting with technological processes of metalization and tested in order to highlights the operational behavior and thermal performances.

IV. Correlations for Bubble Boiling

Stefan şi Abdelsalam (1980) formula, proposed in [24]:

$$h = 207\frac{k_l}{d_e}\left(\frac{q \cdot d_e}{k_l \cdot T_{sat}}\right)^{0.745} \cdot \left(\frac{\rho_v}{\rho_l}\right)^{0.581} \cdot \left(\frac{\nu_l}{a_l}\right)^{0.533} \quad (2)$$

where:

$$d_e = 0.146\beta b \quad (3)$$

$$b = \left[\frac{2\sigma}{g(\rho_l - \rho_v)}\right]^{0.5} = La \quad (4)$$

$$a_l = \frac{k_l}{\rho_l \times c_{pl}} \quad (5)$$

in which: h is the heat exchange coefficient on evaporation; k_l – thermal conductivity of liquid; d_e – breaking the equilibrium diameter; T_{sat} – saturation absolute temperature; ρ_l – liquid density; ρ_v – vapor density; β – contact angle; ν_l – kinematic viscosity of liquid; a_l – liquid difusivity; g – acceleration of gravity; La – Laplace's number; c_{pl} – liquid specific heat.

In [26] is cites the correlation derived in 1982 by Nishikawa and Ito for porous layers. This has following form:

$$\frac{h \cdot t_p}{k_m} = 0.001\left(\frac{\sigma^2 \cdot h_{lv}}{q^2 \cdot t_p^2}\right)^{0.0284} \cdot \left(\frac{t_p}{d_p}\right)^{0.56} \cdot \left(\frac{q \cdot d_p}{\varepsilon \cdot h_{lv} \cdot \mu_v}\right)^{0.593} \times$$
$$\times \left(\frac{k_l}{k_m}\right)^{-0.708} \cdot \left(\frac{\rho_l}{\rho_v}\right)^{1.67} \quad (6)$$

where:

$$k_m = k_1 + (1-\varepsilon) \times k_p \quad (7)$$

in which: h_{lv} is the latent heat of vaporization; ε – porosity; μ_v – vapor's dynamic viscosity; k_m, k_l – conductivity of porous metallic layer and of liquid respectively; t_p – thickness of porous layer deposited; d_p – characteristic size of metal particle, in μm.

In [26] pore size is defined as the diameter of the circle inscribed in that por.

Rohsenow's equation [21] is:

$$q = \mu_l \cdot h_{lv}\left[\frac{g(\rho_l - \rho_v)}{C \cdot \sigma}\right]^{0.5} \cdot \left(\frac{c_{pl} \cdot \Delta T_p}{c_v \cdot h_{lv} \cdot Pr_l^{1.7}}\right)^3 \quad (8)$$

in which: μ_l is the liquid's dynamic viscosity; c_v – vapour specific heat; ΔT_p – temperature difference between fluid and wall; Pr_l – Prandtl's number for liquid; C – proportionality constant equal to 1 kg·m/N·s^2.

Cornwell and Houston equation [4] is applicable to water, cold liquid and vaporized organic liquid bath and tube having diameter 8…50 mm. It's general form:

$$Nu = A \cdot F(p) \cdot Re_b^{0.67} \cdot Pr_l^{0.4} \quad (9)$$

where:

$$Re_b = \frac{qD}{\mu_l h_{lv}} \quad (10)$$

$$F(p) = 1.8 p_r^{0.17} + 4 p_r^{1.2} + 10 p_r^{10} \quad (11)$$

$$p_r = \frac{p}{p_c} \quad (12)$$

in which: A is the surface's aria; D – tube diameter; p_r – ratio between opperating pressure p and critical pressure p_c.

For theoretic study of pool boiling the following are defined:

$$Pr_l = \mu_l \cdot \frac{c_{pl}}{k_l} \quad (13)$$

$$Pe = q\frac{La}{a_l \cdot \rho_v \cdot h_{lv}} \quad (14)$$

$$a_l = \frac{k_l}{\rho_l \cdot c_{pl}} \quad (15)$$

$$Nu = h \cdot \frac{La}{k_l} \quad (16)$$

in which: Pe – Peclet's number; a_l – diffusivity of liquid; Nu – Nusselt's number.

The values of these expressions are to be compute using the parameters that they depend on at the saturation state because the experiments were made at this state. Beside the influence of these upon the studied phenomena, it was checked out the influence of gemetrical parameters of the surface on which the vaporization take place.

A. Correlation for Mechanical Processed Surfacest

Missing one apparatus for measuring roughness, this was appreciated as mean difference on cross section between the upper and the lower part of the material from surface. Starting from the established relation between heat transfer coefficient and the flow heat transfer density, using a liniar regression method, the correlation proposed for the mechanical processed surfaces on the uouside of tubes is (17):

$$Nu = 23.5 \times \frac{La}{k_l} \times \lg\left(\frac{1}{\Delta}\right) \times Pr_l^{1.29} \times$$

$$\times \left(Pe \times a_l \times q_v \times \frac{h_{lv}}{La} \right)^{0.405} \qquad (17)$$

The correlation (17) is valid under presented experimental conditions, $\Delta = 0 \ldots 0.6$ mm and $D = 10 \ldots 50$ mm.

In Figure 6 are shown heat transfer coefficients evolution calculated with correlation (17) ($h2$, $h7$) and those calculated using equation (2) symbolised with h_s and respectively with equation (14) symbolised h_{ch}.

It is noticed a good agreement between correlation proposed and those of Cornel and Houston especially.

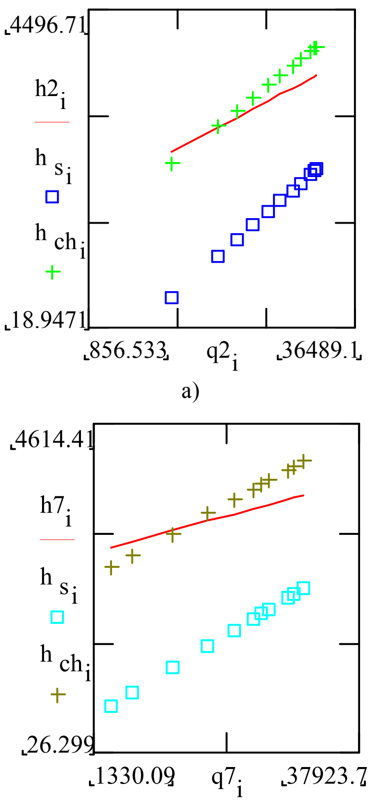


Fig. 6 Heat transfer coefficients obtained with formula (17), respectively equations (2) and (14)

B. Correlation for Surfaces Covered with Metallic Tissues

For a metallic tissue a chracteristic parameter is the usefull surface for passing through S_u, computed after following formula:

$$S_u = \frac{l^2}{t^2} \times 100 \qquad (18)$$

in which l is the dimension of inner size that forms square tissue; t – distance between two consecutive wire, step.

Taking into account the behavior of the surfaces during the tests, of the geometric characteristic measure of these, it has been decided that the adequate correlation is:

$$Nu = 41.3 \frac{La}{k_l} \cdot \log(\frac{1}{Su}) \cdot Pr_l^{1.29} (Pe \cdot a_l \cdot \rho_v \cdot \frac{h_{lv}}{La})^{0.425} \qquad (19)$$

The passing through sift S_u for which the correlation (19) is valid: $S_u = 0.3 \ldots 0.7$ %.

C. Correlation for Porous Surfaces

The proposed correlation, taking into account the specific of heat transfer in porous media and charactersistics of porous layer and liquid in change of phase is:

$$Nu_m = 30 \frac{t_p}{k_s} \cdot \left(\frac{d_m}{t_p}\right)^{0.3} \cdot Pr_l^{1,2} \cdot \left(\frac{k_m \cdot d_p}{k_l \cdot d_m}\right)^{0.16} \times$$

$$\times \left(Pe_m \cdot a_l \cdot \rho_v \cdot \frac{h_{lv}}{t_p} \right)^{0.384} \cdot \frac{\varepsilon}{V_b} \qquad (20)$$

where:

$$k_s = \varepsilon \times k_1 + (1 - \varepsilon) \times k_m \qquad (21)$$

$$Nu_m = h \frac{t_p}{k_s} \qquad (22)$$

$$Pe_m = \frac{\varepsilon\, t_p}{a_l\, \rho_v\, h_{lv}} \qquad (23)$$

$$V_b = 1 - \varepsilon \qquad (24)$$

in which: d_m is the mean diameter of metallic particle; V_b – volume occupied by metallic grains.

The conditions for which the proposed correlation (20) is valid are:

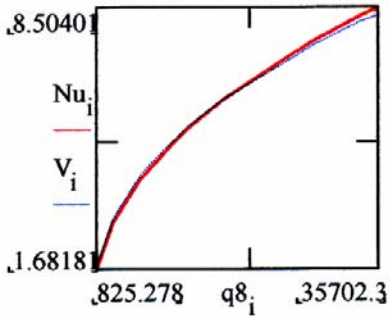
– porosity: 40 % < ε < 65 %;
– mean diameter of pore: 5 μm < d_p < 30 μm;
– thickness of metallic porous layer set: 0.1 mm < t_p < 0.4 mm;
– mean diameter for metallic particles: 5 μm < d_m < 50 μm;
– relative frequency of pores with d_p < 30 μm: over 85 %.

- *Comparison between values computed with proposed correlation and the measured ones.* Evolution of experimental data is best represented by power function.

For mechanic processed surfaces, in Figure 7 are shown: a) invariant Nusselt evolution computed based on experimental data following the associated power function Nu_i compared with invariant Nusselt computed with correlation (17) named V_i and b) invariant Nusselt evolution computed directly based on experimental data Nu_i compared with the same invariant Nusselt computed with correlation (17).

For surfaces covered with metallic tissues, in Figure 8 are shown the values of Nusselt invariant computed with experimental data Nu_i compared with those computed using correlation (15) named Va_i. In Ox axe: is heat flow density q [W/m^2].

It is interesting to observe that sample 16 (tube metallized with bronze) has thermal performance similar for tube with roughness $\Delta = 0.2$ mm.



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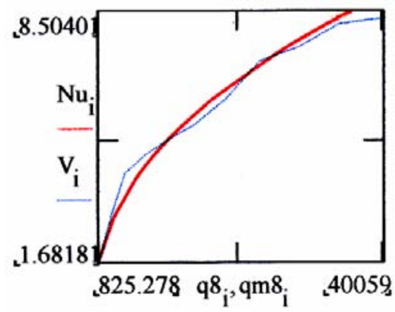

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Fig. 7 Correspondence between experimental data and those calculated with correlation (17)

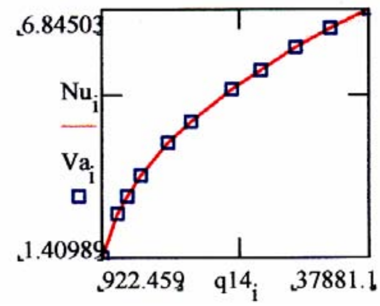
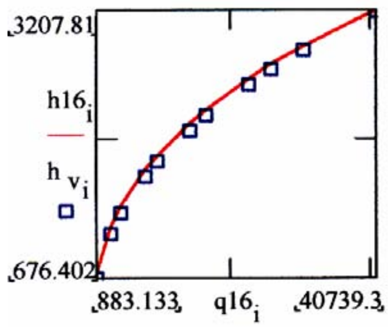


Fig. 8 Parallel between values computed based on correlation (18) and experimental data

Figure 9–a presents the evolution of heat transfer coefficient h_V [W/m^{2}K], calculated with formula (17), and heat transfer coefficient *h16* (bronze) calculated bazed on experimental data. Figure 9–b shows in addition h_{va} obtained using formula (20).



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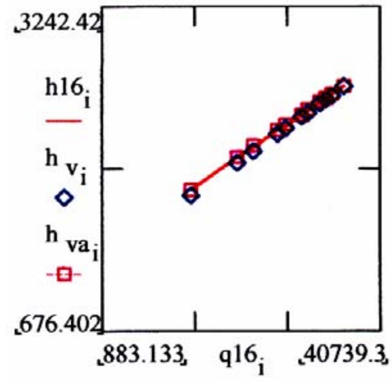

b)

Fig. 9 Comparison between experimental data and calculation results

- *Comparison between values computed with proposed correlation and other formulas*. In Figure 10 is made a comparison between previous heat transfer coefficients and those calculated with formula Stefan and Abdesalam [24] symbolised h_S and Cornwell and Houston [4] symbolised h_{ch}. In this figure heat transfer coefficient calculated based on formula (20) is symbolised h_{va}. In abscissa: heat flux density q [W/m^2]. Is noticed a good agreement especially with formula from [4].

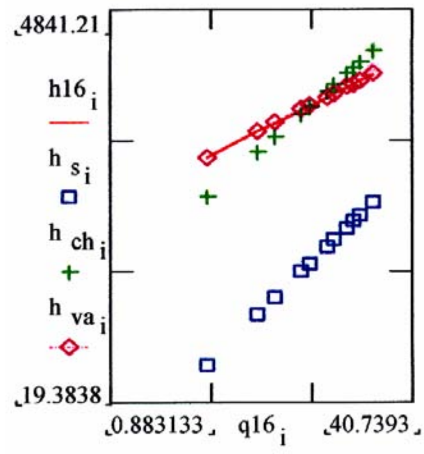

Fig. 10 Comparison with other results

The equation (20) has a good application for other layers deposited by metallization too, having same parameters.

V. Conclusions

Based on reliable principle that nucleation site density increase has the effect of increasing vaporization heat transfer coefficient, pool boiling experiments were carried out in a closed recipient at atmospheric pressure. These experiments had been made in order to investigate the potential of using special surfaces to enhance nucleate boiling heat transfer. These surfaces were obtained by mechanical processing in order to create artificial roughness or by coating tube surfaces with metallic wire tissues or with porous metallic layers deposited by metallization. The results for some of these surfaces were that heat transfer coefficient on boiling side of surfaces almost doubled.

Paper present metods of mechanical processing of outside surface of metallic tubes, methods of cover with sleeves made of metallic wire tissue and some methods to obtain porous metallic surfaces. For each group of types of surfaces, authors propose specific heat transfer correlations. These correlations contain elements essential and difining for the type of surface and can be used for heat transfer coefficient calculation.

Informations contained in present paper enrich the overall database in the field.

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