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CORRELATION FOR BOILING HEAT TRANSFER ON POROUS SURFACES TUBES

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This paper deals with the enhancement of heat transfer by means of passive techniques applied to heat transfer surfaces, namely depositing metallic porous layers, by using welding methods. The tube surfaces so obtained 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. The authors proposed specific heat transfer correlation, effects obtained with it compared with other researchers' correlations.

Key words: Heat transfer, Modified surfaces, Porous layer, Vaporization, Correlation, Thermal performance.

1. INTRODUCTION

The existing state-of-the-art in the field of heat transfer is focused on increasing heat transfer coefficients. The existing techniques to enhance heat transfer are relatively inefficient.

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 [6]. 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 the global heat transfer coefficient leads to reduce general operating expenses by lower thermal agent flow rate.

In general, enhancement of heat transfer trough a separating surface (for example tube) is made, in convection case, by ribs execution on 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 convection heat 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 evaporators, due to specific of boiling process, it is not enough to increase heat exchange surface area or to create artificial turbulence. In last years, several researches of boiling heat transfer have been accomplished [5, 13, 18, 19, 20, 21]. Were investigated different surfaces behavior and also different vaporizing fluids behavior. For certain operating conditions and for certain surface types, there are different behaviors from one operating mode to another, from a fluid to another, from a surface type to another [13, 19].

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 [16, 19]. Nucleation centers or vapor nuclei are places on the vaporization area where boiling occurs. Vapor nuclei are born here as it receives heat.. 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.

The objectives of the work is to present specific enhance heat transfer technique and a proper heat transfer correlation.

2. EXPERIMENTAL RESEARCHES ON POROUS METALLIC 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 vapor from pores. But if they are interconnected, vapor formed in a pore can activate one or more adjacent pores so boiling is initiated and maintained with little dependence on amount of vapor contained in each pore. At least part of the matrix of interconnected pores is assumed that fill with fluid other pore. As the bubbles rise, they become detached from capillaries interconnected due to the continuous generation of vapor in capillary and rise in liquid layer that cover it.

Growth of heat transfer coefficient results from the fact that more intense vaporization occurs 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 than for rough surfaces [5, 19].

A proper porous surface could be obtained by sintering particles of 1…50 μm mean diameter [6]. These particles should better be of a metal with high thermal conductivity, e.g. 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.

In order to achieve the purpose, tree types of surfaces were obtained by welding technology depositing porous metallic layers of different materials. The tubes so prepared were tested by authors within an experimental work in order to establish the boiling heat exchange coefficient increase for each created tube compared with the witness tube with the plane surface.

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

In [20] are presented main parameters of technological processes of metallization applied. For each metallic layer applied by metallization process, the geometric characteristics have been established by quantitative metallographic analysis. Are also presented in the same paper the two methods of quantitative metallographic analysis for porous metallic surfaces deposited on tubes.

Figure 1 shows appearance of metallic layers deposited on each tube seen with electronic microscope, increased 100 times. These appearances are on transversal section of metallized tubes on which are made photos.

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 (de mineralized water degassed) while maintaining in permanent regime the saturation parameters.

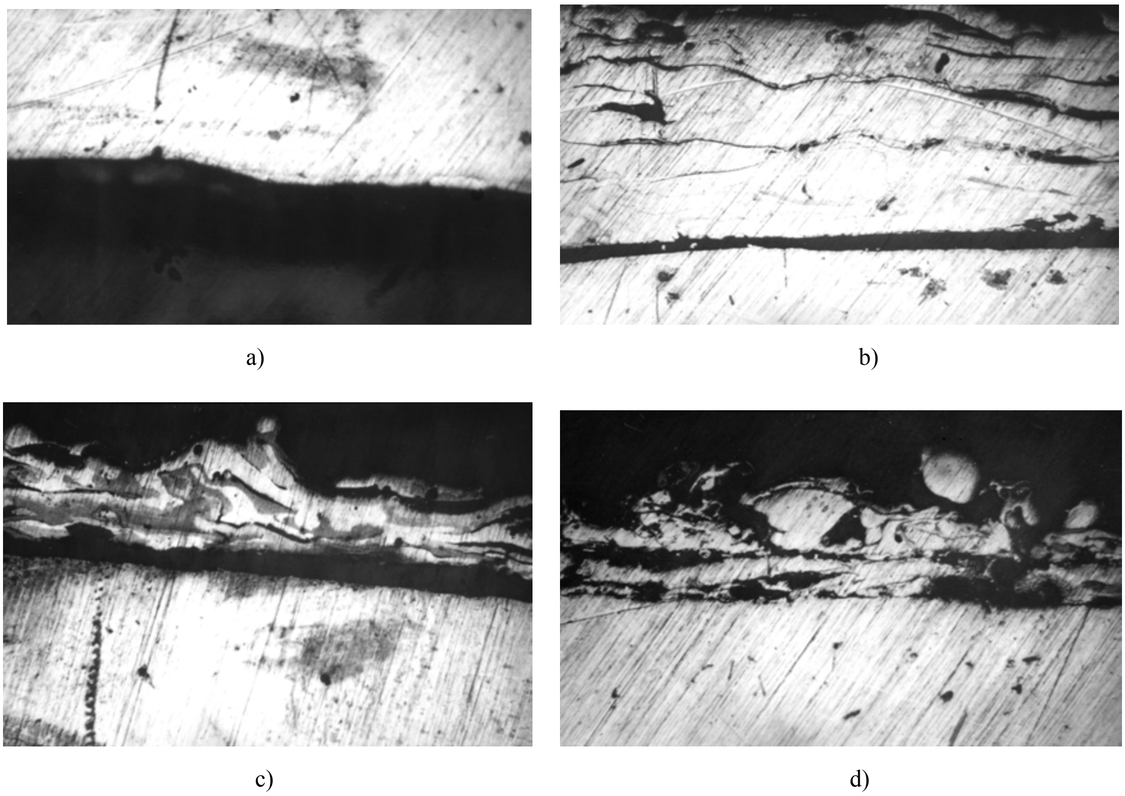

Fig. 1 – Metallic layers deposited on cooper tubes:
a) stainless steel; b) bronze; c) cooper1; d) cooper2.

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 [19].

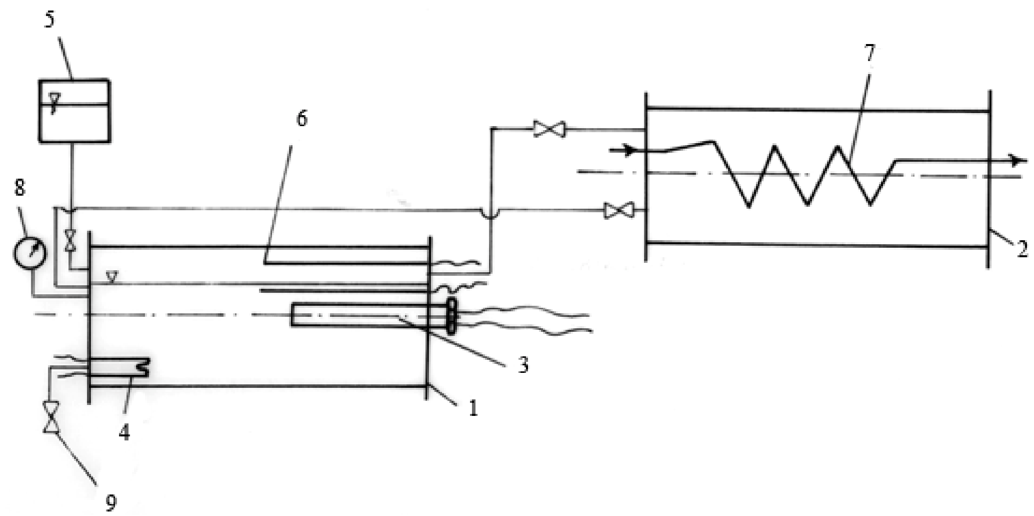

Fig. 2 – Experimental facility used: 1– evaporator; 2–condenser; 3–sample; 4–additional electrical resistance heater; 5–vessel for filling vaporizer/evaporator; 6–thermo sensitive elements; 7–cooling coil; 8–manometer; 9–drain connection.

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 are determined heat flux coefficients for each sample (tube). Ratios between these coefficients and heat transfer coefficient of smooth tube are named "increase coefficient" symbolized *inj*. These coefficient were calculated and plotted for each sample depending on heat flux density q[W/m^2].

Increase coefficient *inj* variation with heat flux density q for metallized tubes samples are presented in Table 1 and Fig. 3. For each sample, *lnj* is the regression right line corresponding to the *inj* variation, according to experimental data.

Sample numbers are: 15–stainless steel; 16–bronze; 17–copper1; 18–copper2.

Table 1

Increase coefficient results

Sample	Increase coefficient	Mean increase 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

For each sample the increase coefficient variation with heat transfer density q show differences due to material of porous metallic layer and metallization process. The best results were obtained with sample 16, highlighted also by best mean increase coefficient.

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

Figure 3 present not a monotonous variation (red curves) due to measurement incertitude. However, blue curves show the trend of these coefficients.

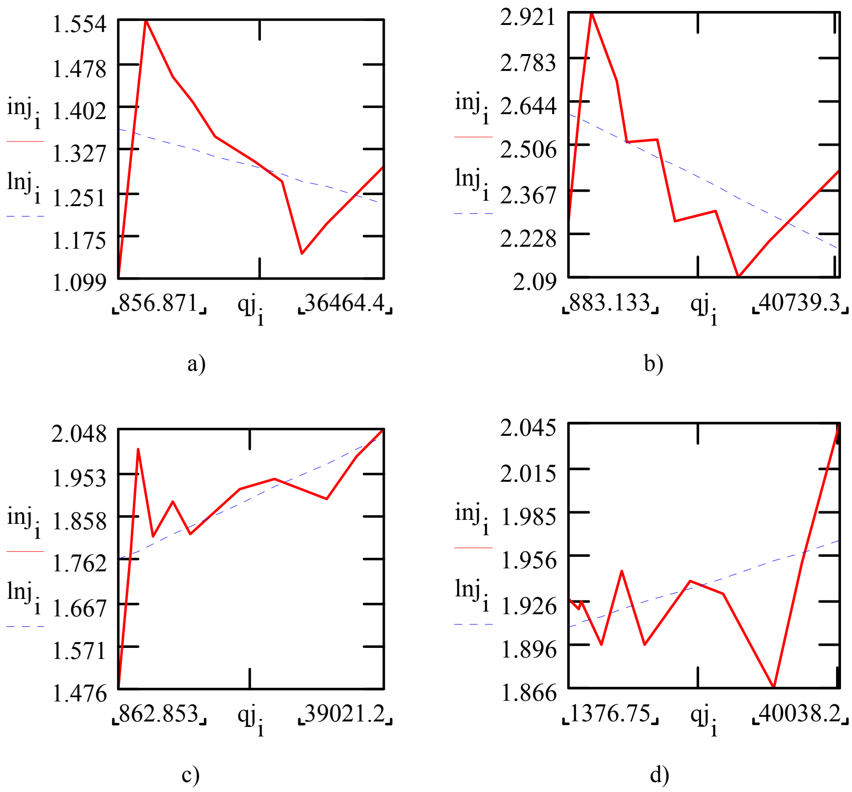

Fig. 3 – Increase coefficient variation depending on heat flux density q [W/m^2] for metallization with:
a) stainless steel; b) bronze; c) copper1; d) copper2.

3. CORRELATIONS FOR BUBBLE BOILING AND POROUS SURFACES

One of specific correlations for boiling process is Stefan and Abbelsalam formula, proposed in [17]:

$$h = 207\frac{k_l}{d_e}\left(\frac{q \cdot d_e}{k_l \cdot T_{sat}}\right)^{0.745} \cdot \left(\frac{\rho_v}{\rho_l}\right)^{0.581} \cdot \left(\frac{\nu_l}{a_l}\right)^{0.533}, \tag{1}$$

where:

$$d_e = 0.146\beta b, \tag{2}$$

$$b = \left[\frac{2\sigma}{g(\rho_l - \rho_v)}\right]^{0.5} = La, \tag{3}$$

$$a_l = \frac{k_l}{\rho_l \times c_{pl}}, \tag{4}$$

in which: h is heat exchange coefficient on evaporation in W/m^{2}K; k_l – thermal conductivity of liquid in W/mK; d_e – bubble detachment diameter of vapor in mm; T_{sat} – saturation absolute temperature in K; ρ_l – liquid density in kg/m^3; ρ_v – vapor density in kg/m^3; β – contact angle; ν_l – kinematic viscosity of liquid in m^2/s; a_l – liquid diffusivity in m^2/s; g – acceleration of gravity in m/s^2; La – Laplace's number; c_{pl} – liquid specific heat. This formula is suitable for bubble boiling process of water on smooth surfaces.

In [18] is cited the correlation derived in 1982 by Nishikawa and Ito for porous layers. This has following form:

$$\frac{h \cdot t_p}{k_m} = 0.001\left(\frac{\sigma^2 \cdot h_{lv}}{q^2 \cdot t_p^2}\right)^{0.0284} \cdot \left(\frac{t_p}{d_p}\right)^{0.56} \cdot \left(\frac{q \cdot d_p}{\varepsilon \cdot h_{lv} \cdot \mu_v}\right)^{0.593} \cdot \left(\frac{k_l}{k_m}\right)^{-0.708} \cdot \left(\frac{\rho_l}{\rho_v}\right)^{1.67}, \tag{5}$$

where:

$$k_m = k_1 + (1 - \varepsilon) \times k_p, \tag{6}$$

in which: h_{lv} is the latent heat of vaporization in J/kg; ε – porosity in %; μ_v – vapor's dynamic viscosity in Ns/m^2; k_m, k_l – conductivity of porous metallic layer and of liquid respectively in W/mK; t_p – thickness of porous layer deposited in mm; d_p – characteristic size of metal particle, in μm.

In [14], pore size is defined as the diameter of the circle inscribed in that pore.

For theoretic study of pool boiling the following are defined:

$$\mathrm{Pr}_l = \mu_l \cdot \frac{c_{pl}}{k_l}, \tag{7}$$

$$\mathrm{Pe} = q\frac{\mathrm{La}}{a_l \cdot \rho_v \cdot h_{lv}}, \tag{8}$$

$$a_l = \frac{k_l}{\rho_l \cdot c_{pl}}, \tag{9}$$

$$\mathrm{Nu} = h \cdot \frac{\mathrm{La}}{k_l}, \tag{10}$$

in which: Pr_l – Prandtl's number for liquid; μ_l – liquid's dynamic viscosity; 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 depending 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 geometrical parameters of the surface on which the vaporization take place.

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

$$\mathrm{Nu}_m = 30\frac{t_p}{k_s}\cdot\left(\frac{d_m}{t_p}\right)^{0.3}\cdot \mathrm{Pr}_l^{1,2}\cdot\left(\frac{k_m\cdot d_p}{k_l\cdot d_m}\right)^{0.16}\cdot\left(\mathrm{Pe}_m\cdot a_l\cdot\rho_v\cdot\frac{h_{lv}}{t_p}\right)^{0.384}\cdot\frac{\varepsilon}{V_b}, \qquad (11)$$

where:

$$k_s = \varepsilon\times k_1 + (1-\varepsilon)\times k_m, \qquad (12)$$

$$\mathrm{Nu}_m = h\frac{t_p}{k_s}, \qquad (13)$$

$$\mathrm{Pe}_m = \frac{\varepsilon\, t_p}{a_l\,\rho_v\, h_{lv}}, \qquad (14)$$

$$V_b = 1-\varepsilon \qquad (15)$$

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

The conditions for which the proposed correlation (11) 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 %.

4. COMPARISON BETWEEN VALUES COMPUTED WITH PROPOSED CORRELATION AND OTHER FORMULAS

In Fig. 4 is made a comparison between heat transfer coefficients-in the ordinates axis (in W/m^{2}K) based on authors' experimental data, heat transfer coefficient calculated with Stefan and Abbelsalam formula [17] symbolized h_S and Cornwell and Houston formula [2] symbolized h_{ch} respectively. In this figure heat transfer coefficient calculated based on experimental data is symbolized h_{16}, while heat transfer coefficient calculated based on equation (11) is symbolized h_{va}. In abscissa: heat flux density q [kW/m^2]. Is noticed a good agreement especially with formula from [2]. The huge difference between the results by the authors and those by Stefan and Abdelsalam could be explained by the types of boiling for which formula were established: authors' formula is specific for water bubble boiling on porous surfaces, while Stefan and Abdelsalam formula is for natural convection boiling on smooth surfaces.

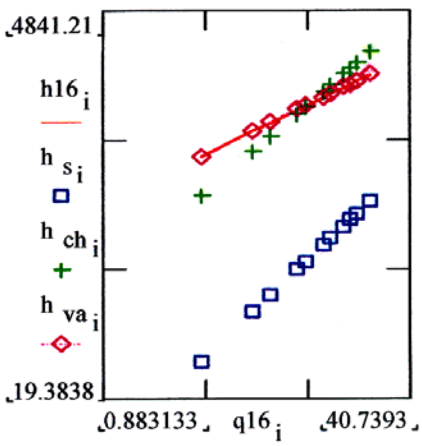

Fig. 4 – Comparison of heat transfer coefficient variation with other researchers' results.

The equation (11) has a good application for other layers deposited by metallization too, having same parameters.

6. 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 by the authors. 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 depositing porous metallic layers by metallization. The results for some of these surfaces were that heat transfer coefficient on boiling side of surfaces almost doubled. Thus, starting from the qualitative aspects targeting vaporizers surface geometry, the result is growth of the coefficient of heat exchange with 30 ... 140%.

Paper presents the materials and methods used in order to obtain porous metallic surfaces, for which the authors propose specific heat transfer correlation. This correlation contains elements essential and defining for the type of surface and can be used for heat transfer coefficient calculation.

Information contained in present paper enriches the overall database in the field.

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