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DISCUSSION OF THE HEAT FLUX CALCULATION METHOD DURING POOL BOILING ON MESHED HEATERS

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Abstract: The paper discusses nucleate boiling heat transfer on meshed surfaces during pool boiling of distilled water and ethyl alcohol of very high purity. It presents a correlation for heat flux developed for heaters covered with microstructural coatings made of meshes. The experimental results have been compared with the calculation results performed using the correlation and have been followed by discussion. Conclusions regarding the heat flux determination method have been drawn with the particular focus on the usefulness of the considered model for heat flux calculations on samples with sintered mesh layers.
Keywords: boiling, coatings, heat flux, meshes

1. INTRODUCTION

The need for more efficient heat exchanges is the driving force for developing new methods of heat transfer intensification. One of such techniques is the application of metal mesh layers onto heaters and transfer heat using the phase – change process of boiling/vaporisation. Their application usually leads to increased heat flux.

In (Rannenberg and Beer, 1980) experimental test results of boiling of refrigerants R-11 and R-113 have been presented. The samples were made of up to nine mesh layers. Stainless steel and bronze were the materials of the coatings. The aperture (distance between the wires) was 0.078 – 0.51 mm; while the diameter of the wire: 0.05 – 0.155 mm. A considerable intensification of heat transfer was observed for the low heat flux range in relation to the smooth surface. Moreover, the authors reported no influence of the height of the microstructural covering (the number of meshes) on heat transfer. The authors provided a description of four mechanisms of heat transfer in such coating, namely: conduction without phase change, convection and conduction without phase change, conduction with phase change and convection with phase change. In (Orzechowski, 2003) a review of literature on boiling on mesh layers was given and experimental results. The author provided test results of boiling heat

transfer of water on the fin's surface with up to three copper mesh layers. The wire diameter was 0.18 mm and the aperture 0.55 mm. These results indicate an intensification of heat transfer for the meshed surfaces comparing to the smooth surface. It was most visible for one mesh layer, while the increase in mesh layers from two to three does not cause such a great rise in dissipated heat flux. Recently, the paper (Dąbek et al., 2019) that deals with heat transfer on copper and bronze meshes confirms a significant possibility of heat transfer intensification with the use of metal meshes for pool boiling. Moreover, such microstructural coatings are also efficient for flow boiling applications (Maciejewska and Piasecka, 2017; Maciejewska and Piasecka, 2017; Strąk et al., 2018; Grabowski et al. 2018, Hożejowski and Hożejowska, 2019). The practical applications of the meshed surfaces are significant and cover, among others, their use in heat pipes (Nemec et al., 2017).
The ability to perform heat transfer calculations in such complex conditions may also be important for analogous heat transfer issues, e.g. fuel cells (Włodarczyk et al., 2011), plant biotechnology equipment (Skrzypczak-Pietraszek, 2018a; Skrzypczak-Pietraszek et al., 2018b; Skrzypczak-Pietraszek et al., 2019), laser machining of coatings (Radek et al., 2017) and shapes (Radek et al., 2019), and self-sliding kinematic pairs (Korzekwa et al., 2016). Heat transfer calculations are also of the great importance in heavy-duty machines design (Domagala, 2013), production (Filo, 2013; Filo, 2015) and maintenance (Domagala et al., 2018a; Domagala et al., 2018b), and especially in their failure scenarios investigation (Fabis-Domagala, 2013; Fabis-Domagala and Domagala, 2017).

2. METHODOLOGY

Literature provides extensive data on pool boiling intensification with the use of metal meshes. However, equally important in correct design of heat exchangers is modelling of the boiling phenomenon. Currently, no correlation can properly determine heat flux based on the material and geometrical parameters of the microstructural covering.
An attempt to describe the phenomenon of boiling on structural heaters has been done in (Rannenberg and Beer, 1980). The authors observed that due to vapour growth, bubble detachment and movement of the liquid phase the forces convection mode of heat transfer should be used here. Having considered the single phase convection as well as conservation of mass, momentum and energy principles under the steady state condition the following equation was produced:

$$\mathrm{Nu} = 3.8\,(\mathrm{Re}\,\mathrm{Pr})^{0.59}\,\mathrm{b}^{0.16}\left(\frac{\lambda_{\mathrm{eff}}}{\lambda_{\mathrm{l}}}\right)^{0.28}\frac{\mathrm{w}}{\delta} \tag{1}$$

where: Nu - Nusselt number, Re - Reynolds number, Pr - Prandtl number, w - width, λ - thermal conductivity, δ - coating height, l – liquid. The values of b and λ_{eff} are calculated using material and geometrical parameters of the coating. The equation correlated the authors' experimental data within 15% accuracy range.
This formula can be used to determine the heat flux values dissipated from the samples. It is done based on the experimental research results of pool boiling of distilled water and ethyl alcohol on the horizontal samples. The specimens have been prepared by sintering meshes on copper disks. The sintering was done in the reduction atmosphere – during this process no oxidation occurs.

3. RESULTS AND DISCUSSION

The calculations according to the correlation developed in (Rannenberg and Beer, 1980) have been performed basing on data adopted from the work by the co-author (Dąbek et al., 2019) in order to verify the usefulness of the considered equation (1). The selection of samples is broad and covers single mesh layers made of copper (aperture 0.75 mm and wire diameter 0.50 mm) and bronze (aperture 0.20 mm and wire diameter 0.12 mm) as well as a double mesh coating consisting of two copper meshes of aperture 1.50 mm and wire diameter 0.32 mm. The results of the comparison between the actual experimental results for the single mesh layer (Dąbek et al., 2019) and calculations have been presented below in Fig. 1a and 1b.

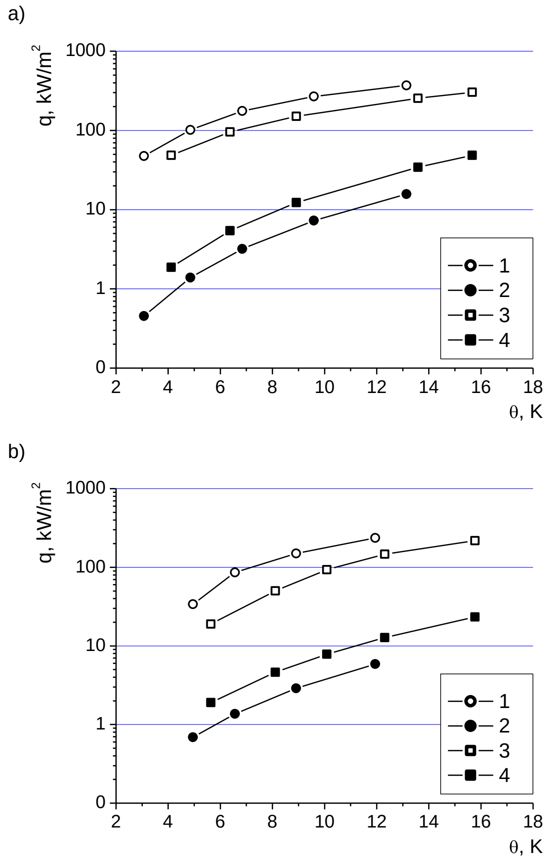

Fig. 1. Comparison between correlation results and experimental data for the single meshes: 1 - experimental results for the mesh 0.75x0.50, 2 - calculation results with Rannenberg&Beer correlation for the mesh 0.75x0.50, 3 - experimental results for the mesh 0.20x0.12, 4 - calculation results with Rannenberg&Beer correlation for the mesh 0.20x0.12;
a – distilled water, b – ethyl alcohol

As can be seen in the above figures, the calculation results performed according to the correlation proposed in (Rannenberg and Beer, 1980) produces much lower results than those observed during the actual experiments for the samples, which were made of single mesh layers. The application of the multilayer meshes might lead to higher heat fluxes, however wires of the meshes move into the free space within the apertures. Thus, volumetric porosity is reduced in relation to the single meshes. Fig. 2 presents the calculation and experimental results for a double mesh coating (Dąbek et al., 2019) to verify if the observations from Figs. 1a and b relating to single meshes might be better applicable for multilayer structural coverings.

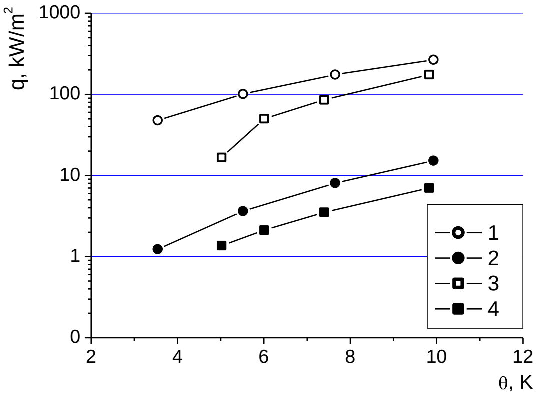

Fig. 2. Comparison between the correlation results and experimental data for the double mesh 1.50x0.32; 1 - experimental results (distilled water), 2 - calculation results with Rannenberg&Beer correlation (distilled water), 3 - experimental results (ethyl alcohol), 4 - calculation results with Rannenberg & Beer correlation (ethyl alcohol)

Analyses of Figs. 1 and 2 reveal that the considered correlation adopted form literature provides much lower values of heat flux than those of the experiments – for both single and double mesh layers. We can explain it with the selection of experimental constants. These values were determined in the course of data fitting for refrigerants – fluids of different properties than those of distilled water and ethyl alcohol that were used here.

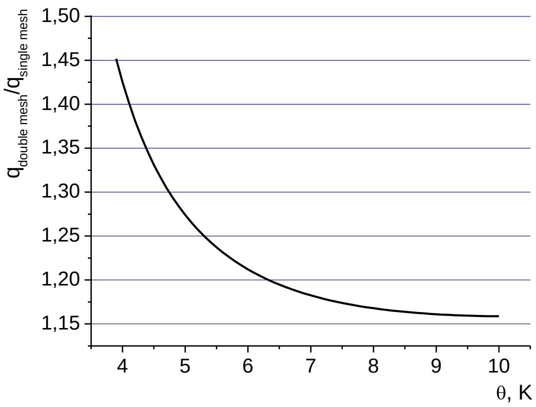

Fig. 3. Ratio of heat flux for the double and single mesh of 1.50x0.32 (distilled water)

Another phenomenon worth noting for multilayer meshes is the fact that the application of the additional coating usually provides larger heat flux. Fig. 3 presents the ratio of the heat flux dissipated from the double mesh sample to the heat flux from the single mesh. The aperture of the mesh was 1.50 mm, while its wire diameter: 0.32 mm. Data for drawing the figure below has been adopted from (Dąbek et al., 2019), with such a modification that raw data on the boiling curve were approximated with a polynomial curve to provide a smooth curve of the ratio.

It can be seen that the advantageous affect of the additional mesh is most visible in the low range of heat fluxes. Here, it exceeds 1.45, which means that the double layer of the mesh is about 45% better then the single mesh considering the heat flux dissipated from the heaters. For higher values of heat flux the beneficial influence of the second layer is reduced with rising superheat and at about 9 K and higher is kept constant at the level of ca. 1.15 despite further increases in temperatures. This might mean the limit of enhancement for this type of coatings.

3. CONCLUSION

The paper considered boiling heat transfer as an efficient mode of dissipating heat from heaters covered with additional coating made of metal meshes. The samples consisting of copper disks with meshes (one or two layers) were considered. Based on the conducted analyses a few important conclusions can be given regarding the analyzed issue.

First of all, needs to be noted that the correlation (Rannenberg and Beer, 1980), which was developed for the meshed surfaces, cannot properly determine the heat flux values dissipated from the heaters. The differences in the experimental results of copper and bronze meshes under boiling of distilled water and ethyl alcohol are too large to be acceptable. The results of the calculations generate much lower values – even of two orders of magnitude. Undoubtedly, these differences are the result of the constants that were originally obtained for refrigerants. Probably, if the constants were determined for fluids of properties similar to water or ethanol, the results could be different and the correlation could be much more efficient and practical.

The use of a double mesh produces better results than the single mesh layer. The improvement in heat flux is most significant in the low range of heat fluxes (bigger almost by half). As the temperature rises, this improvement becomes smaller and, eventually, reaches about 1.15.

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