

Boiling heat transfer augmentation on surfaces covered with phosphor bronze meshes

Lidia Dąbek¹, Andrej Kapjor², and Lukasz J. Orman^{1,*}

¹Kielce University of Technology, al. 1000-lecia P.P.7, Kielce, Poland

²University of Žilina, Faculty of Mechanical Engineering, Univerzitna 1, 010 26 Žilina, Slovakia

Abstract. The paper discusses the issue of boiling heat transfer augmentation on phosphor bronze wire mesh coatings during nucleate boiling heat transfer for distilled water and ethyl alcohol under ambient pressure. A significant enhancement of heat flux has been recorded for such treated surfaces in comparison to the smooth reference surface. The obtained results have been discussed and compared with models and correlations available in literature.

1 Introduction

Boiling heat transfer is highly efficient in dissipating significant heat fluxes at small temperature differences. Considerable improvement in the value of heat fluxes can be achieved by the application of heat enhancing microstructures on heat exchangers such as metal wire meshes, capillary – porous structures, sintered powders and other specially treated surfaces.

Poniewski [1] provided an overview of microstructures used for boiling heat transfer augmentation. According to the author, heat flux enhancement is caused by such a change in the heater structure that increases a number of active nucleation sites and ensures their stabilised operation. Boiling heat transfer enhancing structures are, among others, industrial microstructures, sintered or thermally sprayed powder structures as well as metal fibrous, wire mesh and combines structures [1].

Highly efficient are wire metal structures, which are the focus of the presented paper. They are cheap to produce and easily available on the market due to their other application in engineering. For example, they can be used for the production of heat pipes [2].

Sasin et al. [3] wrote one of the first papers on boiling heat transfer on mesh coated heaters. Water, ethanol and ether boiling was investigated on heat pipes of 300 mm and 470 mm length. It was found that at a given number of mesh layers there is an optimal aperture for which the maximal value of the critical heat flux can be obtained. Smirnov et al. [4] considered boiling of water and ethanol under different saturation pressures within the range of 0.1 bar to 1 bar. Copper and brass meshes were used. Generally, heat flux was independent of the structure height (namely, the number of layers) and weakly dependent on the structural material. Rannenberg and Beer [5] presented results of boiling of refrigerants R-11 and R-113 at ambient pressure on a horizontal copper

* Corresponding author: orman@tu.kielce.pl

surface covered with 2 – 9 layers of stainless steel and bronze meshes. Basing on the test results no impact of the structure height (the number of mesh layers) was concluded.

Tolubinskij et al. [6] experimented on water boiling under pressures ranging from 0.02 – 0.5 MPa on a surface covered with a stainless steel mesh of different aperture (0,04 – 3 mm). The coating was mechanically attached to the heater. According to the authors, heat transfer on single mesh layers is influenced by the value of the mesh aperture in relation to the bubble departure diameter. The paper by Tsay et al. [7] gave the test results of water boiling on a horizontal smooth and rough surface covered with a single stainless steel mesh layer. Basing on the visualisation studies it was concluded that the number of bubbles grown on the surface with the coating was higher than on the smooth surface.

Brausch and Kew [8] described the heat transfer phenomena in microstructures basing on the test results of water boiling on a heater surface covered with 1, 3 and 5 layers of mesh. It was reported that a single layer enhanced boiling heat transfer in comparison to the smooth surface at superheats up to 15 K, which the authors explained by the creation of additional nucleation sites. The visualisation studies proved an increased rate of bubble production at superheats up to 10 K on surfaces with a single layer. At higher superheats the mesh made the removal of bubbles from the structure more difficult.

Orzechowski [9] presented results of boiling heat transfer of water on a heater covered with 1, 2 and 3 copper mesh layers of wire diameter 0.18 mm and aperture 0.55 mm. Basing on the test results it could be concluded that the application of the coating enhances heat transfer in comparison with the smooth surface. Li et al. [10] listed four reasons of heat transfer enhancement in the porous layers, among others: the reduction of heat flux on the heater through additional surface extension and the presence of contact points which join the microstructure with the heater; this effectively reduces the process of vapour film forming on the surface. Liou et al. [11] investigated multi-layer copper meshes sintered to the heat pipe surface. Different combinations of structures of the mesh were used to form coatings of the height 0.26 mm – 0.8 mm. The authors concluded that with rising heat load, water film receded to form corrugated menisci in the analysed layer and evaporation resistance decreased till partial dry out occurred.

Since boiling on enhanced surfaces offers considerable advantages for industrial applications (for example in refrigeration or air conditioning systems, high performance cooling devices, etc.), more information is needed in terms of both experimental database and physical phenomena occurring during boiling of different working agents on various microstructure coated heaters.

2 Material and method

The considered material for the meshes was phosphor bronze. The analysed meshes had different aperture (distance between the neighbouring wires) of 0.32 mm and 0.40 mm but the same wire diameter of 0.20 mm. The experiments were carried out for distilled water and ethyl alcohol under the nucleate boiling regime and ambient pressure. The samples were prepared in such a way that the meshes were sintered to the copper discs in the reduction atmosphere of hydrogen and nitrogen to prevent oxidation.

The experiments were performed on the stand, whose main element – the heater – has been presented in Figure 1. The produced samples (copper discs with sintered meshes) were soldered to the copper heating block. The electric heater provided the heat flux which was conducted to the samples (the block was insulated from the surrounding with high temperature insulation). The power of the heater was increased during the measurements using the autotransformer with given steps to provide data points which enabled to draw the boiling curves.

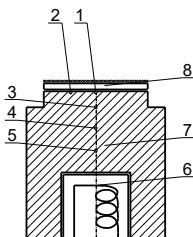


Fig. 1. Main unit of the experimental set-up: 1, 2 – thermocouples under the sample, 3, 4, 5 thermocouples in the axis of the heating block, 6 – electric cartridge heater, 7 – copper block, 8 – sample with the mesh [12].

The boiling curve is a dependence of heat flux and superheat (defined as the difference between the wall temperature and the saturation temperature of the liquid). The heat flux transferred to the samples was calculated using temperature readings recorded in the axis of the copper block. The temperatures under the sample were also recorded. As a result, the boiling curves could have been drawn. Boiling occurred in the thermally – resistant glass vessel located above the sample on the teflon plate. The generated vapour underwent condensation in a condenser located above it and was returned to the vessel gravitationally so that the liquid level above the sample was kept constant. The liquid temperature in the vessel was measured with a thermocouple. In the tests all thermocouples were of K type.

3 Test results and discussion

Two liquids have been considered, namely distilled water and ethyl alcohol of very high purity (over 99 %). The results obtained for the smooth surface (without any additional covering) have also been presented for reference purposes.

The influence of the aperture of the mesh layer on boiling heat transfer of distilled water and ethyl alcohol has been presented in Figure. 2 and 3, respectively. The wire diameter of the phosphor bronze meshes was 0.20 mm (which relates to the height of the microstructure of 0.40 mm). Two values of the aperture were considered in the experimental testing, namely 0.32 mm and 0.40 mm. The surface porosity amounted to 38 % and 44 %, respectively. The data on the smooth surface and the mesh of aperture 0.40 mm has been presented by the author in [12].

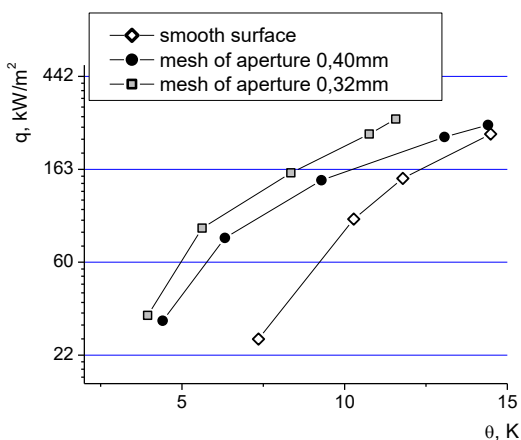


Fig. 2. Distilled water boiling curves for phosphor bronze meshes of different apertures.

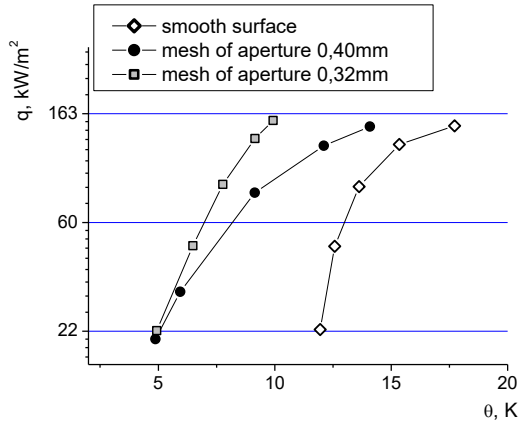


Fig. 3. Ethyl alcohol boiling curves for phosphor bronze meshes of different apertures.

For the analysed samples the best enhancement of heat transfer was provided by the mesh of the smaller aperture (as seen in figures below). It is especially evident in the case of water. For ethyl alcohol the results produced with the mesh of 0.32 mm aperture are also better, but the impact is much more significant for high superheats. For low temperature differences of ca. 5 K the results are very similar.

It seems that for smaller apertures the conditions of boiling heat transfer are improved. It can be related to the fact that the areas between the wires act as nucleation sites, where vapour bubbles are created and grown. As the aperture becomes smaller the density of active nucleation sites on the surface increases. Thus, heat transfer is enhanced. However, data from literature indicates that for very small apertures the heat transfer conditions are actually hampered. Consequently, this phenomenon needs to be considered taking into account the diameter of the bubbles (smaller bubbles are produced with ethanol boiling than with distilled water boiling).

The obtained test results also indicate that the highest influence of the meshes occurs for small superheats. For larger values data points might approach the values recorded for the smooth surface. It may be related to the fact that due to increased vapour generation within the coating there is a difficulty to sustain the process of efficient vapour removal from the microstructure and liquid transport to it. From this point a rapid transition to film boiling can occur. The details of the enhancement caused by the application of the mesh of aperture 0.32 mm have been presented in Figure 4.

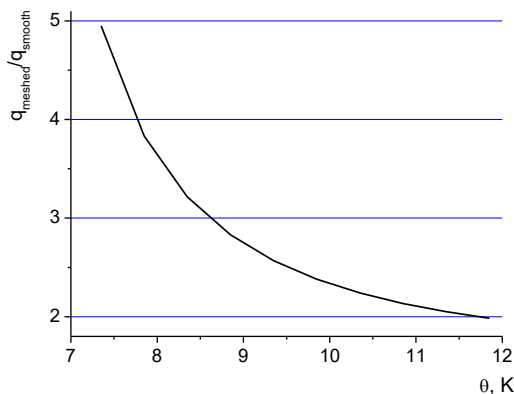


Fig. 4. Enhancement ratio for the mesh of 0.32 mm aperture for water boiling.

The enhancement ratio given in the figure above considers the heat flux dissipated from the meshed surface to the heat flux removed from the smooth reference surface for the same superheat value. The necessary data have been derived from Figure 2 for distilled water boiling. The calculations involved generating the polynomial fits of the second order of both the test results (the meshed and smooth surface) to produce a curve presented below.

The use of the mesh proved to be most efficient for lowest superheats where the heat flux for the meshed surface was almost five time higher than for the smooth surface. For larger superheats the effect diminished.

A different problem in the analysis of boiling heat transfer is modelling of this phenomenon. It is necessary for a proper design of heat exchangers. Data presented for the mesh of aperture 0.32 mm has been compared with selected correlations from literature, namely those developed by Smirnov et al. [4, 13, 14], Nishikava et al. [15] as well as Xin and Chao [16].

In order to make calculations according to the model presented by Xin and Chao, it was necessary to introduce certain modifications as for the geometrical parameters used in the formulae. The width of a single cell had to be considered as the total of wire diameter and aperture and the width of the tunnel as aperture. The results of the calculations have been presented in Figure 5 for ethyl alcohol as the boiling liquid.

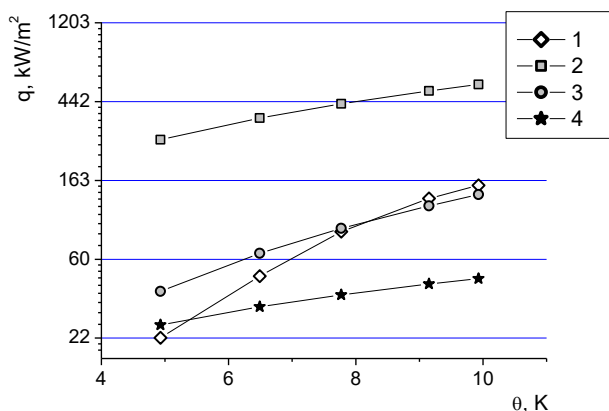


Fig. 5. Comparison of experimental data with the models for the mesh 0.32 mm x 0.20 mm (ethyl alcohol); 1 – experimental results as in Figure 3, 2 – calculation results according to Nishikava et al. correlation, 3 – calculation results according to Xin and Chao correlation, 4 – calculation results according to Smirnov et al. correlation.

The analysis of the produced results indicate that the best congruence of experimental data for the considered meshed surface was observed for Xin and Chao model, although the congruence is less evident for small superheat values (below about 7 K). The least efficient for the analysed case was the model by Nishikava et al., which gave much higher results than those obtained from the experimental analysis.

4 Conclusion

The application of the meshes can lead to significant enhancement of boiling heat transfer. Dissipated heat fluxes can be several times higher in comparison to the smooth surface without any additional coating. This might be linked to increased density of active nucleation sites on the heater. It might also be the reason why meshes of smaller aperture (0.32 mm) performed better than those of larger aperture value (0.40 mm) – both for distilled water and ethyl alcohol.

The comparison of the experimental data for boiling heat transfer on the phosphor bronze meshed surface of the mesh aperture of 0.32 mm with models from literature proved that the most precise was the model proposed by Xin and Chao with certain modifications, while the least accurate was the one presented by Nishikawa et al. It should also be noted that microstructural coatings can also be applied for flow boiling [17, 18] and not only for pool boiling as discussed in the present paper. They can be efficiently used for heat pipes, which are highly efficient heat exchangers [19].

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