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Pool Boiling Heat Transfer from Rough and Microstructure Coated Surfaces

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1. Introduction

Boiling heat transfer is affected by a number of factors related to the conditions of the process as well as material and geometrical parameters of the heater surface. These factors occur simultaneously and interact with each other. The value of the heat transfer coefficient depends significantly on, among others, saturation pressure, thermophysical properties of the working fluid as well as surface characteristics (material properties, dimensions, surface finish, thickness) (Pioro et al. 2004).

Surface microgeometry is an important parameter affecting thermal performance of the phase – change heat exchangers. Such surfaces are easy to produce, because in the most simple case emery paper could be used. In (Nishikawa et al. 1982) the test results of the impact of pressure and surface roughness on boiling of refrigerants R-11, R-21, R-113 and R-114 were presented. The experiments were performed on vertical smooth copper surfaces of diameter 20 mm and 40 mm. Roughness amounted to 0.022-4.310 μm. It was reported that the highest impact of roughness on the heat transfer coefficient could be observed under small pressures, while for higher ones this effect diminishes and disappears when pressure is critical. The paper (Kang 2000) contains research results of water boiling on tubes with different orientations – 0°, 45°, 90° (vertical) and mean roughness 60.9 nm and 15.1 nm. Tube diameters were 9.7 mm, 19.05 mm and 25.4 mm. Increased roughness enhanced heat transfer, which must be related to a higher density of active nucleation sites (locations were bubbles are generated). This effect was more evident for more inclined tubes. At high values of superheat (defined as the difference between surface and saturation temperatures) vapour agglomeration decreased heat flux. The work (Ribatski & Saiz Jabardo 2003) analyses the effects of roughness and found that an increase in heat flux with surface roughness is related to a larger number of vapour producing nucleation sites. As a result, heat flux is enhanced on surfaces of higher roughness. In (Hosseini et al. 2011) experimental tests of boiling of R-113 on horizontal copper surfaces of different roughness: 0.901 μm, 0.735 μm, 0.65 μm and 0.09 μm were presented. It was found that the heat transfer coefficient improved with increasing roughness. The sample with roughness of 0.901 μm provided 38.5% higher value of the heat transfer coefficient than the smoothest surface of 0.09 μm.

Another method of surface modification is the application of additional coatings. Many such technologies are available, for example capillary – porous structures made from metal fibers, sintered powders, mesh structures and others. Typically, observations prove that they enhance boiling heat transfer. However, scientific reports found in literature are not entirely unanimous or even ambiguous and there is still discussion what impact such coatings have on the boiling phenomenon.

Most works considering pool boiling heat transfer on heaters with capillary – porous coatings state that the influence of their application is very favourable. In (Zaripov et al. 1989) boiling of water, nitrogen and acetone was tested. The microstructural layer was composed of copper, nickel and steel fibers. Its maximal porosity reached 93% and maximal height 10 mm. The authors found the optimal height of the layer, for which the thermal performance was highest. The work (Poniewski 2001) provides test results for boiling of water, ethanol and R-113 on horizontal isothermal surfaces with copper fibrous structures of fiber diameter 50 μm. The author confirmed the advantageous effect of this porous layer. For example the value of the heat transfer coefficient during boiling of water on a specimen of 85% porosity at the pressure of 0.1 MPa was 5.5 times higher than for the smooth surface at the same heat flux. In (Wójcik 2005) investigation of water boiling heat transfer on tubes covered with porous copper – fibrous layers of the heights in the range of 0.5 to 2.0 mm was presented. As in the earlier work of this author (Wójcik 2004) a large improvement of thermal performance was observed for the microstructural coverings. The paper (Kalawa et al. 2016) provides the test results of water boiling on heaters with porous structures from steel fibers. The authors observed enhancement of heat transfer in relation to the smooth surface (for example heat flux dissipated from the surface covered with the coating of fibers ϕ25 μm was about 3.5 larger than for the surface without any coating).

In all the presented references, the test of boiling heat transfer have been obtained on the isothermal surfaces – similarly to the author's own research for example (Orman 2016). Non – isothermal surfaces of fins are hardly ever tested due to significant measurement complexities. Thus, in order to expend the knowledge in this area, the current paper is focused on the impact of the application of the porous microstructure and surface roughness on the thermal performance of the non – isothermal heaters.

2. Material and method

The test have been performed on the rough copper surface and the surface covered with a porous layer made of copper fibers of 50 μm diameter. The microstructure was attached to the base using the sintering process in the reduction atmosphere in order to prevent oxidation of the specimen. Figure 1 presents the image of the produced porous layer on the copper base in form of the fin. The volumetric porosity of the layer was 68%, while its height 1 mm.

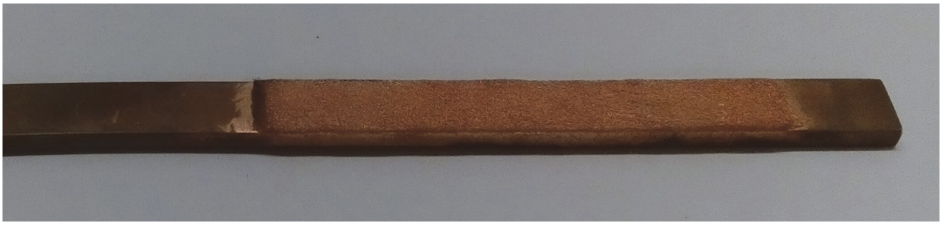

Fig. 1. The fin with the microstructural covering

Another tested surface has been treated with emery paper in order to produce certain roughness. The emery paper number was 280. Details of the roughness profile has been presented in Figure 2a, while the generated surface morphology in Figure 2b.

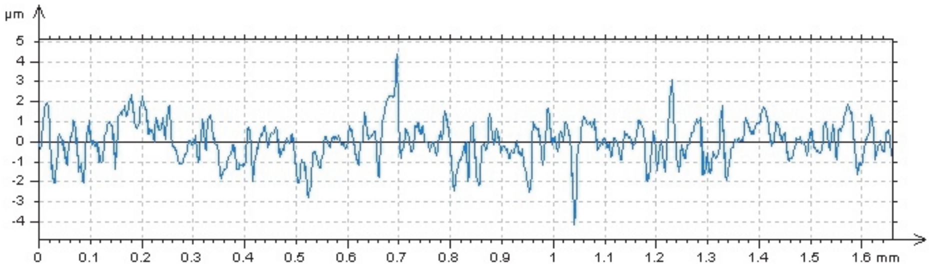

Fig. 2a. Surface roughness profile

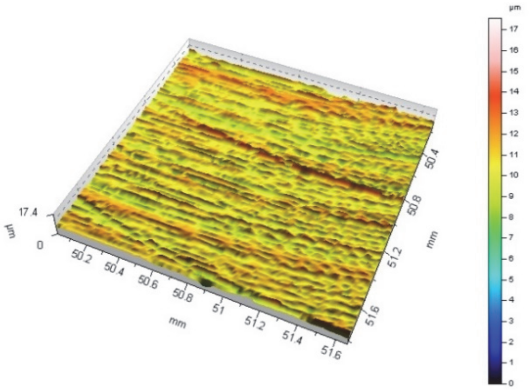

Fig. 2b. Rough surface morphology

Boiling heat transfer has been analysed at atmospheric pressure. The main component of the experimental set-up was a fin (as presented in Fig. 1). Its height was 12 mm, width 4 mm and length 90 mm. It is part of one side of the vessel, in which liquid was boiled (Fig. 3). The fin was in contact with the liquid on one side and on the other with the surroundings – this side was observed with a thermovision camera. Heat was supplied to the base of the fin by an electric cartridge heater. As a result, a temperature gradient was generated along this element. Measurements of temperature have been carried out with the infrared camera. The generated vapour was returned to the vessel so that the liquid level could have been kept constant during the experiments.

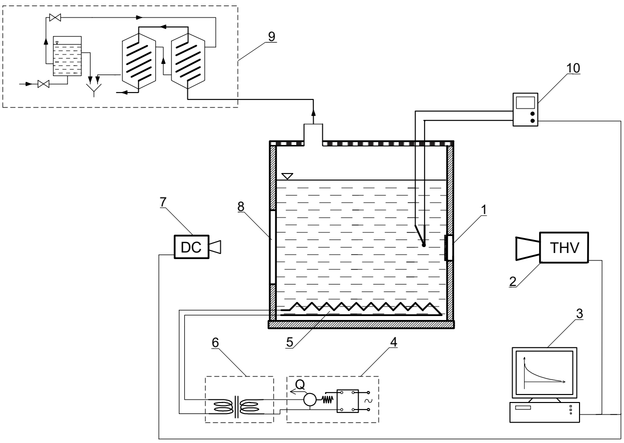

Fig. 3. Schematic of the experimental stand: 1 – fin, 2 – infrared camera, 3 – data acquisition unit, 4 – autotransformer, 5 – auxiliary heater, 6 – electrical current separation unit, 7 – digital camera, 8 – window, 9 – cooling and condensate retrieval unit, 10 – temperature measurement device (Orzechowski & Orman 2006)

The use of the thermovision camera enables the determination of surface temperature at many points of the observed element. This number is determined by the resolution of the device. Local values of the heat transfer coefficient can be found using a method presented in (Orzechowski 2003) and described below. In this technique boiling heat transfer coefficient α is assumed to depend exponentially on superheat θ (the difference between the surface and saturation temperature):

$$\alpha = a\,\theta^{n} \tag{1}$$

where a, n are constants, whose experimental determination leads to a formula for the boiling curve. Having considered equation (1) together with other assumptions, the formula for temperature distribution in the fin equals:

$$\frac{d^2\theta}{dx^2} = m^2\theta^{n+1} \tag{2}$$

which was analysed in (Ünal 1985). Differentiation of (2) results in an equation for superheat gradient along the fin, which in logarithmic coordinates equals:

$$\ln\left(\frac{d\theta}{dx}\right)^2 = \ln\left(\frac{2m^2}{n+2}\right) + (n+2)\ln\theta \tag{3}$$

where $n \neq 2$, while m^2 is defined as:

$$m^2 = \frac{a\,P}{\lambda F} \tag{4}$$

P and F describe the circumference and surface area of the fin, respectively. λ is the thermal conductivity of the material. For long fins no heat transfer at the tip can be assumed. In this case C equals 0, as has been considered in (3).

Results from linear fitting lead to the determination of constants (a, n) and, consequently, boiling curves can be drawn as a function of local values of the heat transfer coefficient and wall superheat according to (1). In order to more precisely determine the heat transfer coefficients the measurement results can be analysed assuming the non-linear dependence for the heat transfer coefficient as proposed in (Orzechowski 2007).

3. Results and discussion

In the present study surface roughness produced with emery paper and the application of the copper porous microstructural coating have been considered as factors affecting nucleate pool boiling heat transfer under ambient pressure. Figures 4 and 5 present the boiling performance of the microstructure coated surface (whose porosity was 68% and the height 1 mm) for distilled water and ethyl alcohol (purity 99.8%) as the dependence of the superheat gradient vs. wall superheat.

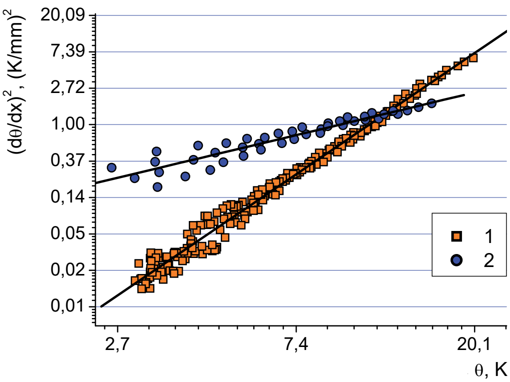

Fig. 4. Superheat gradient vs. wall superheat for distilled water: 1 – smooth surface, 2 – porous layer of porosity 68% and 1 mm height made of fine copper fibers

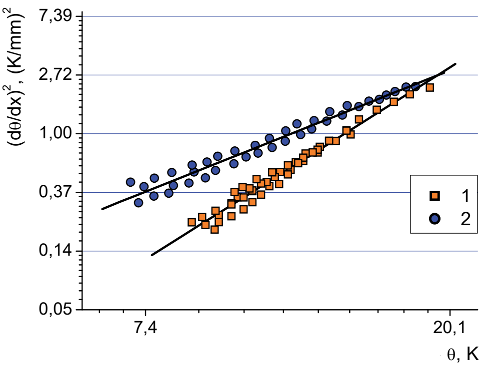

Fig. 5. Superheat gradient vs. wall superheat for ethyl alcohol: 1 – smooth surface, 2 – porous layer of porosity 68% and 1 mm height made of fine copper fibers

The application of the porous microstructure resulted in the enhancement of pool boiling heat transfer for both the working fluids in the area of low range of superheats. For higher temperature differences the performance of the capillary – fibrous heater is similar (or even worse in the case of water) to the one observed in the case of the smooth surface. It might be related to the fact that vapour production is low at small superheats and vapour removal from the microstructure is easy for all the surfaces (including the porous layers). However, at high superheats more vapour is produced and permanent vapour blanket might be created inside the layer regardless of its porosity. Consequently, its performance diminishes. However, the porous layer provides more nucleation sites that are already active at low heat fluxes. This fact explains better thermal performance for low superheats – for both the boiling liquids.

In order to better visualize the obtained results and confront them with the rough surface tests, they have been presented in form of boiling curves as a dependence of heat flux vs. wall superheat. Figures 6 and 7 show the results for both the working fluids.

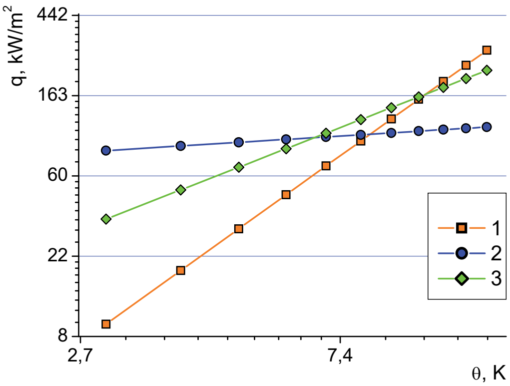

Fig. 6. Boiling curves for distilled water: 1 – smooth surface, 2 – copper fibrous microstructure, 3 – rough surface

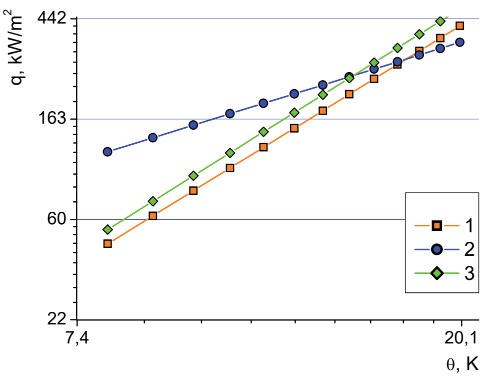

Fig. 7. Boiling curves for ethyl alcohol: 1 – smooth surface, 2 – copper fibrous microstructure, 3 – rough surface

Boiling heat transfer has been enhanced by roughening the surface in the wide range of superheats for ethyl alcohol and for lower superheats in the case of water. Roughness of the surface provides additional nucleation sites which are active at small superheats. This explains why the performance in the low superheats region is better. At higher heat fluxes more nucleation sites become active on the smooth surface, so the improvement of thermal performance becomes smaller and even diminishes. However, in the case of ethyl alcohol the diameter of bubbles is much smaller and even at high heat fluxes, when bubble coalescence occurs, the rough surface is very efficient. It is worth noting that the general trend is that the rough surface is able to provide heat transfer enhancement, however, the application of the porous covering is much more efficient in the range of small temperature differences. It is related to the fact that the microstructure traps the vapour bubbles at higher heat fluxes and an insulating vapour blanker is created within the porous layer.

The details of the enhancement possibilities have been presented in Figure 8 as the enhancement factor – the ratio of the heat flux for the microstructural heaters q_m (fibers or roughness) and for the smooth surface q_s.

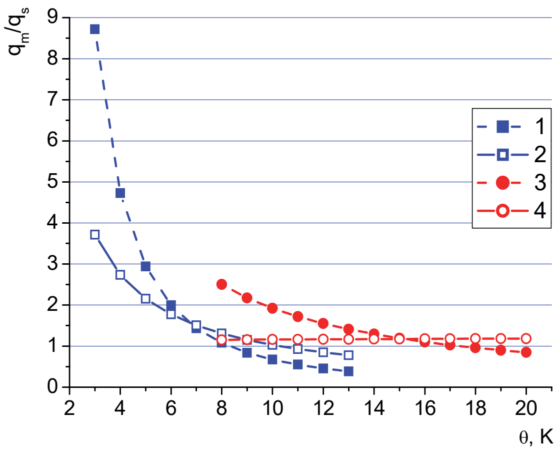

Fig. 8. Enhancement factor: 1 – distilled water, porous layer, 2 – distilled water, rough surface, 3 – ethyl alcohol, porous layer, 4 – ethyl alcohol, rough surface

As can be seen in the above figure, the largest enhancement is possible with the use of the porous layer and water as the boiling liquid. Here, the heat flux dissipated from the microstructural coating can be almost nine times higher than for the smooth surface. The rough surface provides lower improvement possibilities in the low range of superheat, however for higher ones it proves to be better. The same phenomenon can be observed in the case of ethyl alcohol, but the enhancement ratios are much lower.

A different and quite complex problem is providing a reliable model of boiling on surfaces of modified morphology. Currently, there is no efficient correlation available in literature, which could successfully determine the boiling performance of heaters based on physical and chemical properties and parameters. In the current experiment, the obtained experimental test results of water boiling have been compared with correlations for pool boiling heat transfer available in literature and presented below in Figure 10. In the case of the metal fibrous layer, the model proposed in (Nishikawa et al. 1979) has been used. It was developed for the sintered porous coatings. While the calculations for the rough surface have been performed with the Cooper model (Cooper 1984).

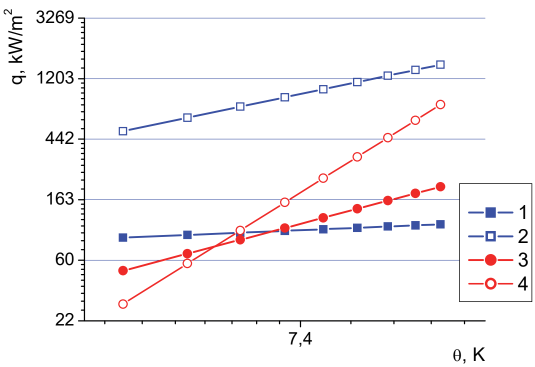

Fig. 9. Comparison of the test results and calculations according to selected correlations; microstructural surface: 1 – test results, 2 – calculation results according to Nishikawa et al. model; rough surface: 3 – test results, 4 – calculation results according to Cooper correlation

The simple model based on the assumption of the leading role of conduction (Nishikawa et al. 1979) provided much higher results than the experimental values. Although the Cooper model has been more accurate for the rough surface, still significant difference occur – especially as the superheat increased. The discrepancies in the results and calculations indicate that a new model or correlation of boiling heat transfer is necessary for surfaces of modified morphology. It needs to be noted that the results have been obtained on the non-isothermal surface of the analysed fin, while the considered correlations were developed based on the isothermal surface data.

4. Conclusions

Pool boiling heat transfer is enhanced by the application of porous and rough surfaces layers in comparison to the smooth surface. The heat flux values at the same superheat might be several times higher if additional microstructure is applied. Generally, roughening the heat exchanger surface improves the heat transfer performance in a larger range of superheats, however, the maximal enhancement is much lower than for the porous layers. The mechanism of heat transfer enhancement seems to be a combination of two factors. One is an increased number of nucleation sites (both for rough and porous surfaces) and the surface extension (only in the case of metal fibrous layer). The complexity of the phenomenon might be responsible for the fact that a successful model or a correlation for boiling heat transfer on microstructural coatings is still unavailable.

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Abstract

The paper presents the test results of pool boiling heat transfer on the rough surface and the surface covered with capillary – porous microstructure. The porous layer is made of copper fibers sintered in the reduction atmosphere. The volumetric porosity amounted to 68%, while its height 1 mm. Distilled water and ethyl alcohol were used as the working fluids. The experiments have been carried out under the atmospheric pressure. Enhancement of heat transfer in relation to the smooth reference surface has been recorded especially for the low range of superheats, which might be related to the density of active nucleation sites. Experimental results have been compared with selected models of boiling available in literature.

Keywords:
boiling heat transfer, porous coatings, rough surface

Wymiana ciepła przy wrzeniu na powierzchniach chropowatych i z pokryciem mikrostrukturalnym

Streszczenie

Artykuł przedstawia wyniki badań wymiany ciepła przy wrzeniu na powierzchniach chropowatych i z porowatym pokryciem metalowo-włóknistym. Mikrostruktura porowata została wykonana z włókien miedzianych spiekanych w atmosferze redukcyjnej. Porowatość objętościowa wynosi 68%, a wysokość warstwy 1 mm. Badania prowadzono dla wody destylowanej i alkoholu etylowego jako cieczy wrzących pod ciśnieniem atmosferycznym. Zaobserwowano intensyfikację wymiany ciepła w porównaniu do powierzchni gładkiej, szczególnie w zakresie małych przegrzań, co może być związane z gęstością aktywnych centrów nukleacji. Wyniki badań eksperymentalnych porównano z wybranymi modelami wrzenia dla danych powierzchni.

Słowa kluczowe:
wymiana ciepła przy wrzeniu, pokrycie porowate, chropowatość