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Correlation for Nucleate Boiling Heat Transfer on Microstructural Coatings

Łukasz J. Orman
Kielce University of Technology
al.Tysiaclecia P.P.7, 25 – 314 Kielce, Poland
orman@tu.kielce.pl

Abstract **-** The paper presents the issue of nucleate boiling heat transfer enhancement with the use of microstructural coatings of regular and non – regular geometry. The considered coatings are metal wire meshes, pin – fins and capillary - porous structures made of fine metal fibres. In order to properly determine heat flux dissipated from the heaters covered with different coatings, a modified correlation has been developed for the nucleate boiling regime for these three different types of microstructures and two working fluids – distilled water and ethyl alcohol boiling under ambient pressure. It proved to be quite precise with the great majority of the experimental heat flux points falling within the assumed error band.

Keywords**:** Boiling Heat Transfer, Microstructural Coatings.

1. Introduction

Boiling on surfaces covered with microstructural coatings can be significantly enhanced in relation to boiling on smooth surfaces. There are many techniques to produce heat enhancing structures. Most common and often found in literature are metal meshes, pin – fins, capillary – porous layers made of fine metal fibers, sintered or thermally sprayed powders. However, many other are possible. For example Cieśliński [1] investigated water boiling heat transfer on horizontal copper surfaces with electrochemically deposited microstructures. These aluminium, copper and silver coatings were 0.3 – 1.1 mm high. It was observed that the heat transfer coefficient of the copper layer was highest – ca. 4 times higher that of the smooth surface. Significant heat transfer enhancement possibilities are also reported by El-Genk and Ali [2] with boiling of PF-5060 dielectric liquid on copper micro-porous surface layers deposited on 10x10 mm copper substrates using two-stage electrochemical process. Covering heaters with nanostructures could also enhance boiling. Kwark et al. [3] experimentally studied nanoparticle coatings for water boiling. Nanoparticles were deposited on the square 1 cm x 1 cm copper heater and were found to have the ability to increase the critical heat flux, as confirmed in another work by Kwark et al. [4].

Extensive author's own research (for example [5, 6]) indicates a possibility for a significant enhancement of heat flux with the use of special coatings (wire meshes, pin – fins, capillary porous structures or laser treatment). However, for the proper design of heat exchangers and for solving other engineering problems, it is often necessary to precisely determine heat flux dissipated by a system. It might be done using dependencies of heat flux on physical and chemical properties. According to Webb [7] correlations and models developed for microstructure coated surfaces can be divided into: exponential correlations (produced with data fitting procedures basing on dimensional and non-dimensional variables, which researchers consider important); asymptotic correlations (developed between minimal and maximal values), analytical models (that take into account heat transfer and fluid movement mechanisms); numerical solutions of complex equations of fundamental laws governing the process. It needs to be noted that there are many models and correlations available in literature for different coating types. Researchers mathematically described boiling heat transfer to suit their own ideas of the physical phenomena of boiling (often backed by observation of bubbles' creation on heaters and their departure with high speed digital cameras), while not enough attention is given to the idea of producing a universal model or correlation for different types of coatings.

Due to the complexity and nature of the process of phase – change during boiling on microstructual coatings, precise determination of heat flux for different types of microstructures is very difficult. The present paper discusses a possible modification of the correlation for nucleate boiling heat transfer and its usability for the selected types of coatings.

2. Experimental Data

Two kinds of microstructures have been tested by the author: wire meshes and pin – fins, while distilled water and ethyl alcohol were the working fluids. Table 1 presents the details of the mesh samples. Also, pin-fin samples were tested, whose height varied from 0.4 mm to 0.9 mm, while the distance between the pins was changed from 0.64 mm to 0.84 mm.

Table 1: Geometrical and material parameters of the meshes.

Material	Number of layers	Wire diameter *d, mm*	Aperture *a, mm*	Structure height δ, *mm*	Surface porosity, *%*	Volumetric porosity, *%*
copper	1	0.32	0.50	0.64	37	70
	1	0.32	1.50	0.64	68	82
	1	0.25	0.50	0.50	44	73
	2	0.32	0.50	1.02	37	62
	3	0.32	0.50	1.58	37	63
	4	0.32	0.50	2.15	37	64
phosphor bronze	1	0.20	0.32	0.40	38	71
	1	0.20	0.40	0.40	44	75
	1	0.25	0.40	0.50	38	71
	1	0.32	0.50	0.64	37	71
brass	1	0.32	0.50	0.64	37	72

The samples with microstructural coating were soldiered to the copper block of diameter 3 cm, inside which an electric cartridge heater was located. Boiling occurred in the glass vessel placed above the sample. Vapour generated during the process was condensed in the condensing unit supplied with cold water and flew back to the vessel. Determination of the boiling curve requires data on the superheat values at the surface of the sample as well as the heat flux transferred to the sample. Thus, temperature measurements were performed with five K-type thermocouples located within the heating block, based on which heat flux was calculated. One thermocouple measured the saturation temperature. Data points were registered for increased heat flux to produce a couple of experimental points for each sample. The recent paper [6] by the author provides extensive data on the experimental stand, data measuring technique and error analysis.

Figure 1a presents the boiling curves (dependences of heat flux vs. wall superheat) for two samples: the smooth reference surface and one pin – fin microstructure of the 0.9 mm height with distilled water as working fluid. The heat flux has been related to the actual (extended) surface of the sample. Figure 1b shows the performance of two meshed surfaces of different porosities (70% and 82%) also in relation to the smooth surface.

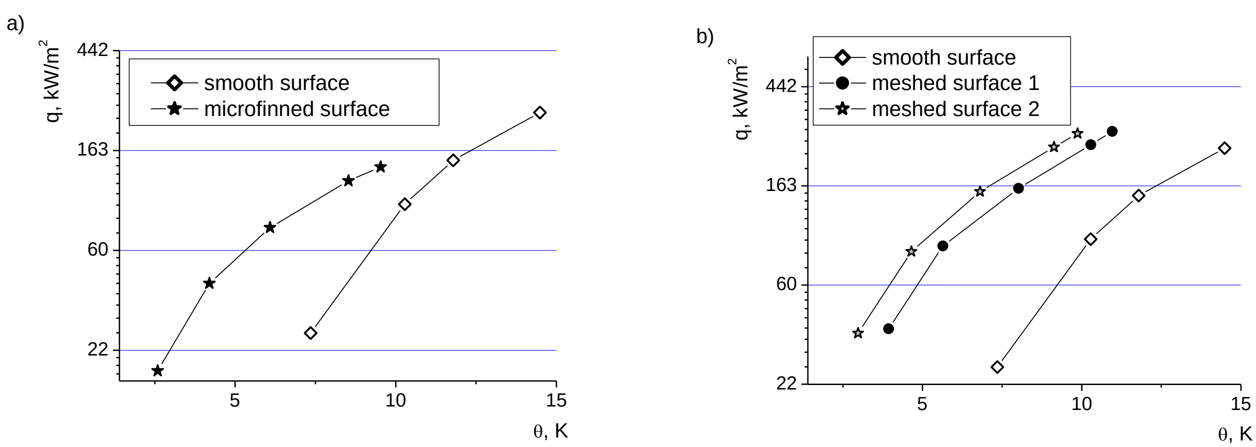

Fig. 1: Heat flux vs. wall superheat for: a) microfins of 0.9 mm height (heat flux of pin–fins calculated for actual (extended) surface area); b) copper meshed surfaces: no 1 (volumetric porosity 82%) and no 2 (volumetric porosity 70%).

The analysis of the figures indicates a significant enhancement possibility for the modified surface covered with microfins and meshes. Heat flux proved to be much higher than for the smooth surface and the boiling process begins at much lower superheats. The enhancement is most evident for the low superheat region and becomes less visible for higher heat fluxes. Further increase in the heat flux could lead to obtaining data which are similar to this for the smooth reference surface.

3. Results and Discussion of the Modified Correlation

The successful theory of boiling heat transfer on different microstructural coatings (of both regular and non – regular geometry) is still to be presented. In this work a modification of a correlation originally proposed by Yamaguci and James [8] will be used. This calculation method has actually been developed for wire mesh coatings. It is assumed that boiling heat transfer can be described with a dependency that is typical of convection heat transfer in the following form:

$$Nu = C\,Re^{pn} Pr_v^{sn} \tag{1}$$

The Nusselt and Reynolds numbers are defined as:

$$Nu = \frac{\alpha l^*}{\lambda_{eff}}, \tag{2}$$

$$Re = \frac{q l^* \rho_l}{r \rho_v \varepsilon \mu_l} \tag{3}$$

where:

$$l^* = \frac{c_{pl} \rho_l \sigma T_{sat}}{(r \rho_v)^2} \tag{4}$$

Effective thermal conductivity (λ_{eff}) has been determined as:

$$\lambda_{eff} = \frac{\lambda_l\left[(\lambda_l + \lambda_w) - (1-\varepsilon)(\lambda_l - \lambda_w)\right]}{\left[(\lambda_l + \lambda_w) + (1-\varepsilon)(\lambda_l - \lambda_w)\right]} \tag{5}$$

In the above equations the subscripts l, v and w refer to liquid, vapour and surface wall, respectively. Other elements denote the following: Pr - Prandtl number, q - heat flux, r - heat of vaporisation, c - specific heat, T - temperature, α - heat transfer coefficient, λ - thermal conductivity, ρ - density, ε - porosity, u - dynamic viscosity, σ - surface tension.

Porosity in the original correlation was calculated considering the height of the whole layer, number of meshes and the height of a single mesh layer. The constants in equation (1) for water and R-113 boiling were determined by Yamaguci and James as C = 35, pn = 0.41, sn = 0.1. This correlation was quite successful for the authors' own results of water boiling, while for R-113 the discrepancies were larger especially for the coarsest mesh (of the biggest aperture). It was explained by the fact that for a refrigerant of low surface tension the impact of a course mesh was insignificant.

In this work a modification of this correlation will be done to cover both regular geometry structures already mentioned (meshes and pin-fins) and the capillary – porous coatings (made of fine metal fibres and taken from literature) for distilled water and pure ethyl alcohol. Porosity has been taken as the actual value (determined by measurements and not calculated as in the original formula). The microstructures which were analysed by the author comprise meshes (copper, phosphor bronze, brass) and copper pin – fins. The aperture of meshes (distance between the wires) ranged from 0.32 mm to 1.50 mm as given in Tab. 1, while the distance between the pin – fins ranged from 0.64 to 0.85. For each sample a few data points were considered (heat flux vs. wall superheat). Selected data regarding the capillary – porous coverings was adopted from [9], where copper fibres of diameter 50 μm and length 3 mm were sintered to produce the structural coatings of 40%, 70% and 85% porosity. In that paper the height of the microstructures varied from 0.2 mm to 2.0 mm.

The regression method was used to obtain the constants in the above mentioned correlation (1). They have been determined as: C = 0.83, sn = 4.075 and pn = 0.062. A comparison of calculation results according to the proposed correlation and the experimental data for three considered types of microstructures has been presented in Figure 2.

As can be seen in the figure the modification of the correlation proposed by Yamaguci and James is quite useful. A great majority of data points is located within the 50% error band. Naturally, there is still room to produce a better model that will provide more accurate results especially for low heat fluxes, however, considering that the analysis covered three different types of microstructures – of both regular and non – regular geometry, it may be considered as quite successful.

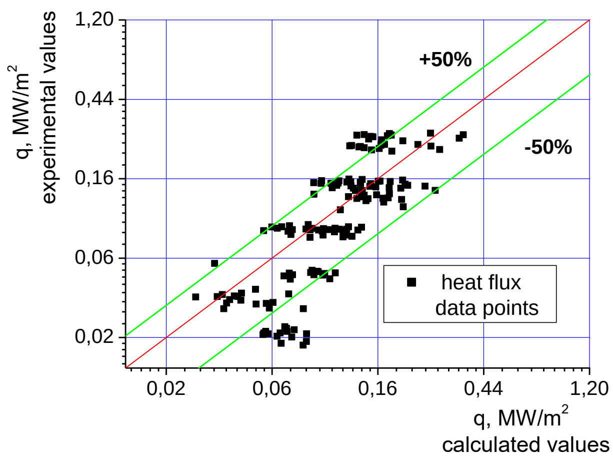

Fig. 2: Comparison of experimental data and calculation results according to the modified correlation.

4. Conclusion

The microstructural coatings offer significant possibilities for boiling heat transfer enhancement. The proper design of phase – change heat exchangers requires the development of a universal model or correlation, which would predict heat flux for both regular and non – regular microstructures. The modified correlation presented in the paper proved to be very useful. Much of the experimental data for various microstructures (meshes, pin – fins, porous layers made of fine metal fibres) fall within the 50% error band. Further work on this subject should focus on providing even more precise correlations for more types of microstructural coatings.

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