Materials Research Proceedings **17** (2020) 185-190 https://doi.org/10.21741/9781644901038-28

Verification of Correlations for Pool Boiling Heat Transfer on Horizontal Meshed Heaters

RADEK Norbert [1,a], ORMAN Łukasz J. [1,b *], PIETRASZEK Jacek [2,c] and BRONČEK Jozef [3,d]

[1]Kielce University of Technology, al. Tysiaclecia P.P. 7, 25-314 Kielce, Poland

[2]Cracow University of Technology, Al. Jana Pawła II 37, 31-864 Cracow, Poland

[3]University of Zilina, Univerzitna 1, 01026 Zilina, Slovakia

[a]norrad@tu.kielce.pl, [b]orman@tu.kielce.pl, [c]pmpietra@mech.pk.edu.pl, [d]jozef.broncek@fstroj.utc.sk

Keywords: Boiling, Correlations, Heat Exchangers

Abstract. The paper considers the problem of the accuracy of enhanced boiling heat transfer correlations. The experimental results of boiling of distilled water and ethyl alcohol have been compared with models available in literature regarding heat flux values in the nucleate boiling mode. Based on the obtained data it can be stated that the correlations are generally inaccurate in the whole range of superheats. Only a modified correlation by Xin and Chao provided comparable results to the experimental data.

Introduction

Metal meshes are one of the passive methods of the enhancement of boiling heat transfer. They may be applied onto heating surfaces and provide the advantage of increasing heat transfer coefficients or heat flux at the same superheat (temperature difference). Due to their positive impact, meshes have been tested in various studies. Smirnov et al. [1] performed tests of boiling of water and ethanol on heaters with copper and brass mesh layers. These meshes were bonded mechanically to the base surfaces. The general finding was that heat flux was independent of the layer height and not particularly dependent on the kind of material from which it was made. Franco et al. [2] studied the performance of heaters covered with stainless steel, aluminum, copper and brass meshes under boiling of refrigerant R141b. The meshes were joined with the surface using a specially designed mounting that enabled the control of channels in the screen. It was observed that if meshes of different aperture were used together, the highest enhancement was obtained for layers consisting of finer meshes at the base on the surface and coarser meshes higher. Li et al. [3] experimentally analyzed water boiling on meshed surfaces. The authors used sintering as a technique to produce samples. The sintering temperature was 1030ºC and took place in the mixture of nitrogen and hydrogen. The specimens had maximally nine meshes. It was reported that the proper contact conditions between the heat exchanger elements led to an increased heat transfer - all meshed heaters enhanced boiling in comparison with the smooth surface (without such covering). It needs to be noted that other types of microstructures are also tested in view of boiling heat transfer augmentation. For examples in [4], data on R113 pool boiling of heaters with sintered powders made of bronze were presented. The porous coating tested by the authors had the height of 2 mm and the research was conducted under ambient pressure.

Materials Research Proceedings **17** (2020) 185-190 https://doi.org/10.21741/9781644901038-28

The use of meshes usually enhances boiling heat transfer. The level of enhancement depends on the number of factors. However, up to now the literature does not provide a model of heat transfer that would be successful in determining heat flux from meshed surfaces.

One of the easiest models of boiling heat transfer was proposed by Nishikawa et al. [4]. The authors used the assumption that the porous layer is filled with liquid, however due to a small Rayleigh number, natural convection may be disregarded and heat is transferred through conduction. Smirnov and co-workers [1] conduced experimental and theoretical study focused on boiling heat transfer on meshed surfaces. The model that the authors proposed is based on the assumption that vaporization occurs in each elementary cell of a microstructure, while the system of meshes located on the heater can be regarded as an array of microfins. Consequently, adequate formulae can be used for calculations. Xin and Chao [5] produced a model originally addressed to analyze the thermal performance of Gewa – T tunnel structures. It was later extended to consider also Thermoexcel porous coatings. In this model it was assumed that the internal tunnel within the structure is filled with vapor. Vaporization occurs within the internal surface of the covering from a thin liquid film. The thickness of this film was considered to decrease to zero with the approach to the heater surface.

The results obtained in this study seem to be very interesting for many branches of industry, both designing such heaters and using them utilitarily in their activities e.g. hydraulics of heavy-duty machines [6, 7], corrosion protection of agricultural machines [8], coupled problems of fatigue and thermomechanical loads [9, 10], especially at very high temperatures of techno-logical processes [11, 12]. The results will also influence the management and investment decision-making processes of the companies concerned [13-15], as well as the orientation of quantitative material assessments provided by image analyzes[16-18].

Material and method

The investigations were focused on the copper mesh layers sintered onto copper disks of 3 cm in diameter (Fig. 1). Such a system works as a heater located horizontally and supplied with heat from the lower part of the experimental set-up. A glass vessel is placed above the sample and sealed to the base. Here, the boiling process occurs, while condensation recovers the generated vapor so that the liquid level is kept constant. The details of the experimental stand have been discussed by the co-author in [5]. Two boiling liquids were used for the analyses, namely distilled water and ethyl alcohol of high purity (99.8%). The experiments were performed under ambient pressure. Cooling of the condensate was provided with the use of cold water in a glass condenser.

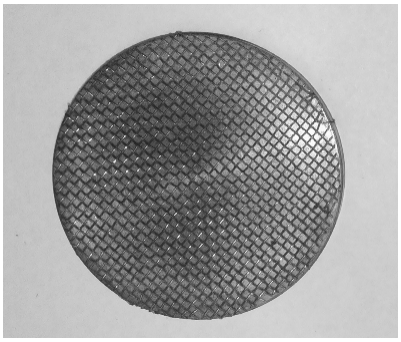

Fig. 1. Example sample of a single mesh layer sintered onto the copper base.

Materials Research Proceedings **17** (2020) 185-190 https://doi.org/10.21741/9781644901038-28

The thermal performance of the samples was obtained as boiling curves – representing the dependences of the heat flux values vs. wall superheat. The consecutive data points were determined with the rising heat flux values (obtained precisely with the autotransformer). The experiments were focused on the nucleate boiling mode of pool boiling heat transfer due to its highest practical applicability for the design of phase –change heat exchangers.

Results and discussion

The application of meshed surfaces generally provides additional advantage comparing to a smooth surface without such a coating (as indicated by many literature reports). Fig. 2 presents the enhancement ratio generated for a double mesh layer (raw data adapted from [19]). It is the ratio of the heat flux (q_{meshed}) exchanged from the meshed surface to the heat flux from the smooth surface (q_{smooth}) assuming the same superheat (θ). It is clearly visible that the performance of the microstructural coating is highest at small superheats (the enhancement ratio reaches the value of almost 6.5). As the heat flux is increased and the superheat rises, the thermal performance of the mesh coated samples becomes weaker but is still a few times higher than for the smooth reference surface (exactly three times at ca. 10 K superheat). It might be explained by the activation of more and more nucleation sites (locations where vapor bubbles grow and from where they depart) on the smooth surface, while they are already there on the mesh coated heaters due to the presence of metal wires on the surface. As a consequence, the smooth surface becomes more and more efficient as the temperature rises, while the microstructural coatings offer no significant additional advantage in this range of superheat.

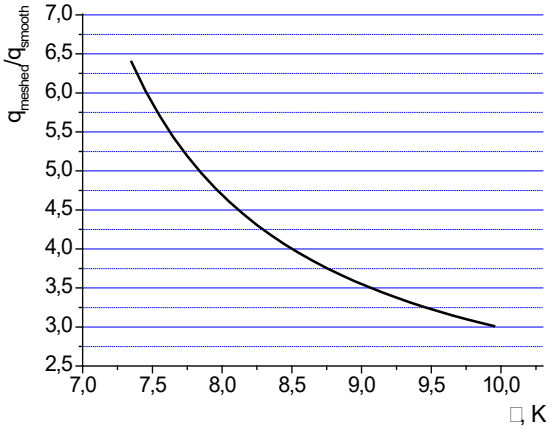

Fig. 2. The enhancement ratio of the double mesh layer.

Apart from experimental results obtained in the laboratory, another vital issue is a correct design of such phase – change heat exchangers. In order to do it properly, a reliable model of the phenomenon is necessary. However, despite many papers written on this subject and many research projects conducted, up to now models and correlations from literature that provide formulae for heat flux are often inaccurate. Some might provide good congruence with the experimental results, however, it is only for a certain kind of microstructural coatings or a very limited range of heat flux.

In order to verify if the selected models and correlations available in literature are precise in determination of heat flux based on the physical and chemical properties of the samples and boiling agents, an analysis was performed. Fig. 3 and 4 present the comparison of the experimental data adopted from [19] for meshed surfaces (respectively, for a single mesh of wire

Materials Research Proceedings **17** (2020) 185-190 https://doi.org/10.21741/9781644901038-28

diameter 0.50 mm and aperture 0.75 and a double mesh of wire diameter 0.32 and aperture 1.50) with correlations from literature. The following models were used: the one developed by Smirnov et al. [1], Nishikava et al. [4] and Xin & Chao [5]. The proper performance of calculations according to the model presented by Xin and Chao was only possible after certain modifications done onto the original morel. They included the width of a single cell to be considered as the total of wire diameter and aperture and the width of the tunnel as aperture. The results of the calculations are presented for both the working liquids (a –distilled water, b – ethyl alcohol).

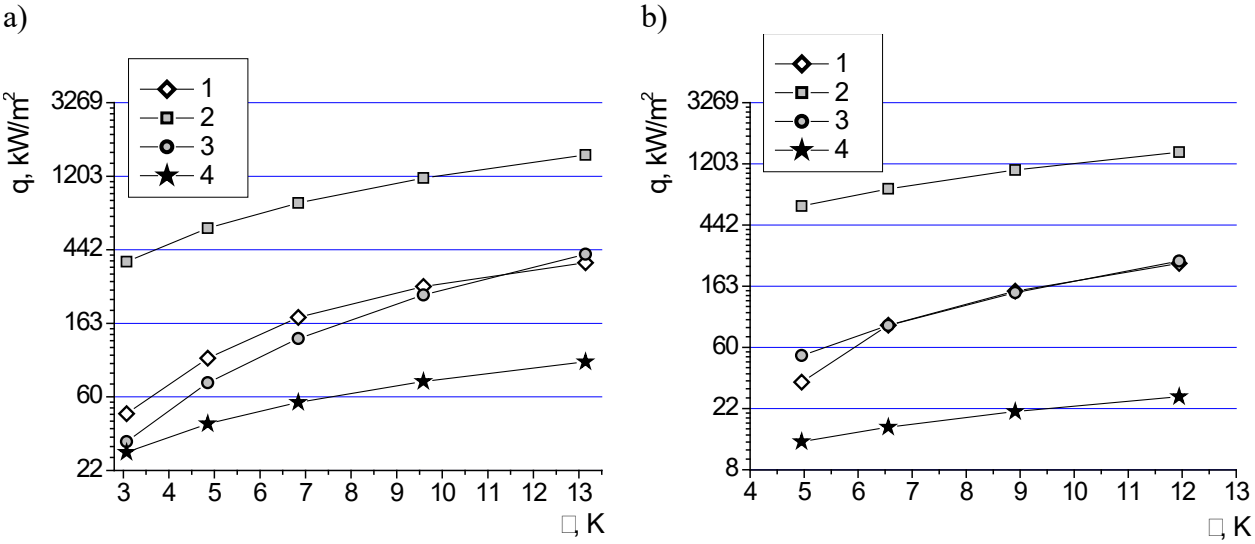

Fig. 3. Comparison of the experimental data for the single mesh 0.75x0.50 with the correlations; 1 - experimental results, 2 - calculation results with Nishikava et al. correlation, 3 - calculation results with Xin and Chao correlation, 4 - calculation results with Smirnov et al. correlation; a – distilled water, b – ethyl alcohol

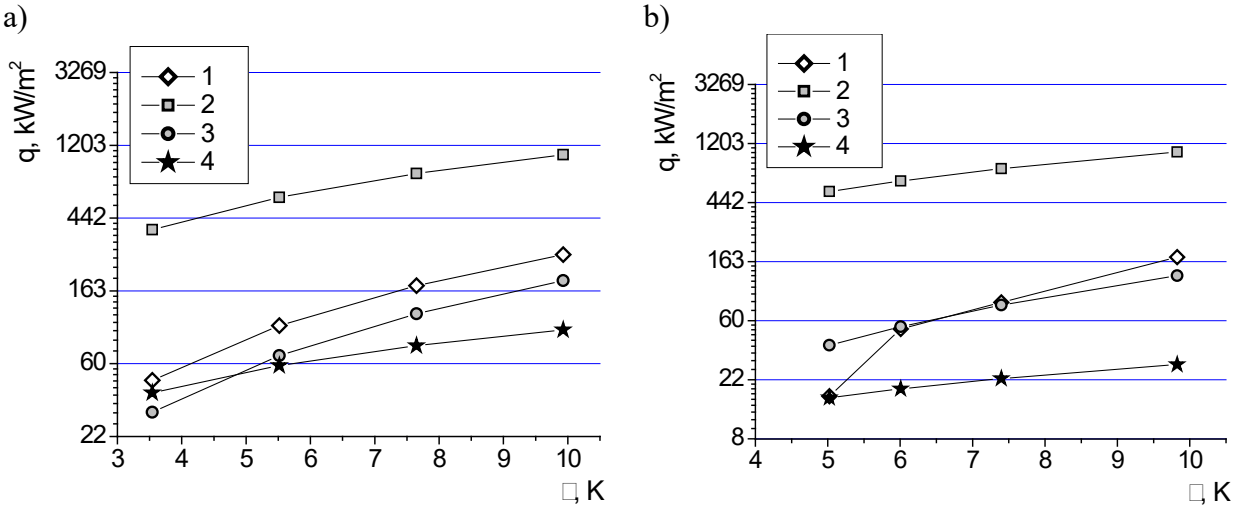

Fig. 4. Comparison of the experimental data for the double mesh 1.50x0.32 with the correlations; 1 - experimental results, 2 - calculation results with Nishikava et al. correlation, 3 - calculation results with Xin and Chao correlation, 4 - calculation results with Smirnov et al. correlation; a – distilled water, b – ethyl alcohol

The analysis of Fig. 2 and 3 reveals that the model by Xin and Chao with modifications proved to be the most accurate for the analyzed samples. The simplest model proposed by Nishikava et al. produced too high values probably due to the assumed model of heat transfer within the structural coating (and, thus, it was the least effective). The correlation by Smirnov et al. usually provided too low values, although in some cases the congruence, especially in the range of low superheats was high. The general findings of the paper are in agreement with literature of boiling on enhanced surfaces.

Conclusions

Sintered metal meshes are believed to be very effective in dissipating large heat fluxes with low superheat during pool boiling, although the treated surfaces also appear to be very efficient at flow boiling, as shown e.g. in experimental research [20], and in numerous computational studies, both in approaches directly based on Trefftz functions [21, 22] and inverse problems [23, 24]. However, models and correlations available in literature are often inaccurate. Their limitations often comprise a certain kind of the microstructural coating that was considered by the authors or a limited range of superheat values. Consequently, a new model is necessary to be developed and applied for the porous layers.

References

[1] G.F. Smirnov, A.L. Coba, B.A. Afanasiev, The heat transfer by boiling in splits, capilaries, wick structures, AIAA Paper (1978) 78-461. https://doi.org/10.2514/6.1978-461

[2] A. Franco, E.M. Latrofa, V.V. Yagov, Heat transfer enhancement in pool boiling of a refrigerant fluid with wire nets structures, Exp. Therm. Fluid Sci. 30 (2006) 263-275. https://doi.org/10.1016/j.expthermflusci.2005.07.002

[3] C. Li, G.P. Peterson, Y. Wang, Evaporation/boiling in thin capillary wicks (I) – wick thickness effects, J. Heat Transfer 128 (2006) 1312-1319. https://doi.org/10.1115/1.2349507

[4] K. Nishikawa, T. Ito, K. Tanaka, Enhanced heat transfer by nucleate boiling on a sintered metal layer, Heat transfer – Japanese Research 8 (1979) 65-81.

[5] M.-D. Xin, Y.-D. Chao, Analysis and experiment of boiling heat transfer on T-shaped finned surfaces, Chem. Eng, Comm. 50 (1987) 185-199. https://doi.org/10.1080/00986448708911825

[6] M. Domagala, H. Momeni, J. Domagala-Fabis, G. Filo, D. Kwiatkowski, Simulation of cavitation erosion in a hydraulic valve. Materials Research Proceedings 5 (2018) 1-6. https://doi.org/10.21741/9781945291814-1

[7] J. Krawczyk, A. Sobczyk, J. Stryczek, P. Walczak, Tests of new methods of manufacturing elements for water hydraulics. Materials Research Proceedings 5 (2018) 200-205.

[8] T. Lipinski, D. Karpisz, Corrosion rate of 1.4152 stainless steel in a hot nitrate acid. METAL 2019: 28th Int. Conf. on Metallurgy and Materials, Ostrava, TANGER, 2019, 1086-1091. https://doi.org/10.37904/metal.2019.911

[9] M.S. Kozien, J. Wiciak, Passive structural acoustic control of the smart plate - FEM simulation. Acta Phys. Pol. A 118 (2010) 1186-1188. https://doi.org/10.12693/APhysPolA.118.1186

[10] R. Ulewicz, P. Szataniak, F. Novy, Fatigue properties of wear resistant martensitic steel. METAL 2014: 23rd Int. Conf. on Metallurgy and Materials. Ostrava, TANGER (2014) 784-789.

[11] M. Hebda, S. Gadek, J. Kazior, Influence of the mechanical alloying process on the sintering behaviour of Astaloy CrM powder mixture with silicon carbide addition. Arch. Metall. Mater. 57 (2012) 733-743. https://doi.org/10.2478/v10172-012-0080-x

[12] D. Przestacki, M. Kuklinski, A. Bartkowska, Influence of laser heat treatment on microstructure and properties of surface layer of Waspaloy aimed for laser-assisted machining. Int. J. Adv. Manuf. Technol. 93 (2017) 3111-3123. https://doi.org/10.1007/s00170-017-0775-2

[13] J. Nowakowska-Grunt, M. Mazur, Safety management in logistic processes of the metallurgical industry. METAL 2015: 24th Int. Conf. on Metallurgy and Materials, Ostrava, TANGER, 2015, 2020-2025.

[14] J. Nowakowska-Grunt, M. Mazur, Effectiveness of logistics processes of SMES in the metal industry. METAL 2016: 25th Int. Conf. on Metallurgy and Materials, Ostrava, TANGER, 2016, 1956-1961.

[15] A. Pacana, K. Czerwinska, R. Dwornicka, Analysis of non-compliance for the cast of the industrial robot basis, METAL 2019 28th Int. Conf. on Metallurgy and Materials (2019), Ostrava, Tanger 644-650. https://doi.org/10.37904/metal.2019.869

[16] A. Gadek-Moszczak, S. Kuciel, L. Wojnar, W. Dziadur, Application of computer-aided analysis of an image for assessment of reinforced polymers structures. Polimery 51 (2006) 206-211. https://doi.org/10.14314/polimery.2006.206

[17] A. Szczotok, M. Sozanska, a comparison of grain quantitative evaluation performed with standard method of imaging with light microscopy and EBSD analysis. Prakt. Metallogr.-Pract. Metallogr. 46 (2009) 454-468. https://doi.org/10.3139/147.110043

[18] A. Gadek-Moszczak, History of stereology. Image Anal. Stereol. 36 (2017) 151-152. https://doi.org/10.5566/ias.1867

[19] L. Dąbek, A. Kapjor, Ł.J. Orman, Distilled water and ethyl alcohol boiling heat transfer on selected meshed surfaces, Mech. Ind. 20 (2019) 701. https://doi.org/10.1051/meca/2019068

[20] K. Strąk, M. Piasecka, B. Maciejewska, Spatial orientation as a factor in flow boiling heat transfer of cooling liquids in enhanced surface minichannels, Int. J. Heat Mass Transf. 117 (2018) 375-387. https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.019

[21] M. Grabowski, S. Hożejowska, A. Pawińska, M.E. Poniewski, J. Wernik, Heat transfer coefficient identification in minichannel flow boiling with hybrid Picard-Trefftz method, Energies 11 (2018) 1-13. https://doi.org/10.3390/en11082057

[22] B. Maciejewska, M. Piasecka, An application of the non-continuous Trefftz method to the determination of heat transfer coefficient for flow boiling in a minichannel, Heat Mass Transf. 53 (2017) 1211-1224. https://doi.org/10.1007/s00231-016-1895-1

[23] L. Hożejowski, S. Hożejowska, Trefftz method in an inverse problem of two-phase flow boiling in a minichannel, Eng. Anal. Bound. Elem. 98 (2019) 27-34. https://doi.org/10.1016/j.enganabound.2018.10.001

[24] B. Maciejewska, M. Piasecka, Trefftz function-based thermal solution of inverse problem in unsteady-state flow boiling heat transfer in a minichannel, Int. J. Heat Mass Transf. 107 (2017) 925-933. https://doi.org/10.1016/j.ijheatmasstransfer.2016.11.003