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Performance of Laser Treated Heaters in Pool Boiling

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Abstract. The article is focused on the heat transfer phenomenon during the boiling of specimens produced with the laser beam. The study discusses the enhancement of heat flux values, which is possible thanks to the use of surface extension with the laser treatment process. The visualization of the boiling process with the high-speed camera enables us to better understand the phenomenon of boiling. The paper also discusses the application of a selected model to determine heat flux values of the laser-treated sample during the process of distilled water and ethyl alcohol boiling under atmospheric pressure.

Introduction

Treatment of various materials with the laser beam alters the morphology of the surfaces, on which it is applied. The introduction of this technology into the heat transfer area has led to the discovery of significant possibilities that this technique has for improving heat transfer during phase change processes.

In fact, any change in the surface morphology might have a larger or smaller influence on the heat transfer phenomenon during pool boiling as well as flow boiling (where significant enhancement is possible as pointed out by Piasecka et al. [1, 2], who used laser texturing as a tool for surface modifications). In the case of pool boiling Kaniowski and Pastuszko [3] investigated the boiling of water on samples made in the form of microchannels, whose depth was from 0.2 to 0.5 mm. The maximal value of the heat flux was even two and a half times larger than in the case of the sample without such grooves. The authors also measured the average diameters of the departing vapor bubbles. These values increased and the departing frequency decreased as the heat flux rose. In their next paper [4] the authors tested FC – 72 as the boiling fluid. In this case, they also observed that there was an improvement caused by the modification of the surface. The values of the heat transfer coefficient increased by over five times and were considered to be similar to those generated with the nanotubes. The final remarks in the paper state that the boiling phenomenon is influenced by specimens' roughness, contact angle as well as wettability. In the paper [5] laser treatment was applied to produce samples of longitudinal fins on copper circular samples. The depth of the grooves was 0.25 mm and 0.55 mm, while their width was 0.60 mm and 1.15 mm. Such specimens were tested in water and ethanol and proved to be very efficient in dissipating heat. In the paper, a modification of the model was developed for these kinds of microstructures. It needs to be mentioned that the improvement of heat flux values can also be additionally obtained if nanofluids are used [6, 7]. In the case of using both nanofluids and laser treatment of samples, a significant enhancement might be obtained. Although in this case tests should also cover the long-term impact of the nanoparticles on the microstructure on the bottom of the grooves, which offers additional nucleation sites for further boiling enhancement.

Generally, many types of microstructures are produced and used for heat exchanger design, both on the laboratory scale as well as commercially. Some are part of heat pipes, which are very efficient and widely used devices for heat transfer in various applications as pointed out by Hrabovsky et al. [8] and Nemec [9]. They might also be applied in HVAC systems. A paper by Zender-Świercz [10] is focused on the issues of air and its quality considering the outdoor air properties.

The laser treatment is characterized by the production of grooves of regular and repeatable microgeometry. At their bottom, the morphology is altered, which might lead to increased heat fluxes, especially in the range of low-temperature differences. The current paper analyses the phenomenon of pool boiling on such microstructures during water and ethanol nucleate boiling conditions under ambient pressure.

Material and Method

Laser treatment of copper samples of 3 cm diameter enables the generation of various geometrical shapes and sizes of the microstructure. The precise design of samples enables a generation of specimens of optimal dimensions. Fig. 1 presents example samples produced with the SPI G3.1 SP20P pulsed fiber laser with an impulse frequency of 60 Hz and scanning velocity of 200 mm/s. The laser pulse during the fabrication of the specimens lasted 60 ns and the focal spot size was 35 μm.

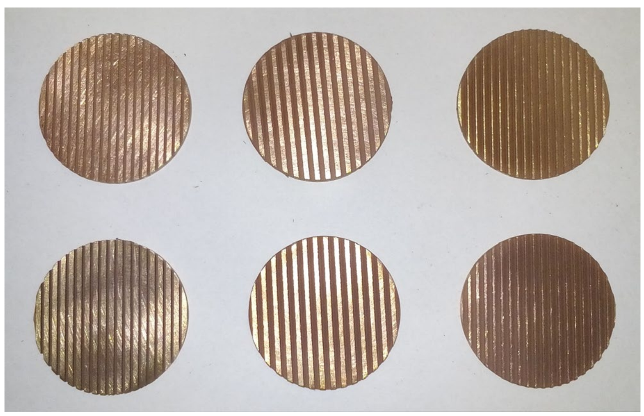

Fig. 1. *Examples of laser-treated samples of various groove depths and widths.*

The experimental determination of boiling of the laser-treated samples was done on the stand equipped with an electric heater, whose aim was to provide heat so that boiling could be sustained. The heat flux was changed using an autotransformer to generate high temperatures for nucleate boiling tests. Distilled water and ethyl alcohol were boiled and their vapor was recovered with the cooling coils. Before the actual tests both the liquid had to be degassed so that dissolved gases would not influence the experiment.

Results and Discussion

The performance of microstructure-covered samples can be done by determining how much heat is dissipated. However, it is also important to know how the physical process occurs. In order to do this, a high-speed camera can be applied. This device enables one to take a sequence of photos at extremely short time intervals. Fig. 2 presents example photos of the boiling phenomenon of distilled water at high heat flux values.

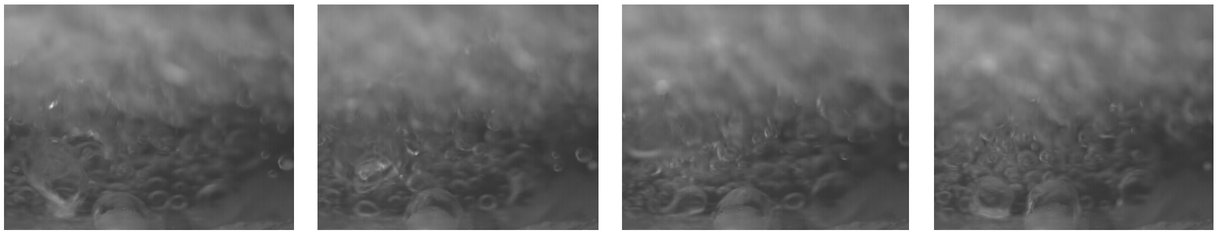

Fig. 2. *Pictures of boiling of water with the high speed camera – time between each frame: 0.02 s.*

As can be seen, the whole sample participates in the process of bubble generation and release. The convective forces seem to be quite strong at this stage of the developed nucleate boiling mode.

The study of the performance of the laser-treated samples indicates that some are more efficient than others. Fig. 3. presents the ratio of the heat flux dissipated by sample 1 (of 0.55 mm groove depth and its width of 1.15 mm) to the heat flux values dissipated by sample 2 (of 0.25 mm groove depth and its width of 0.60 mm) – based on data presented by the authors in [5].

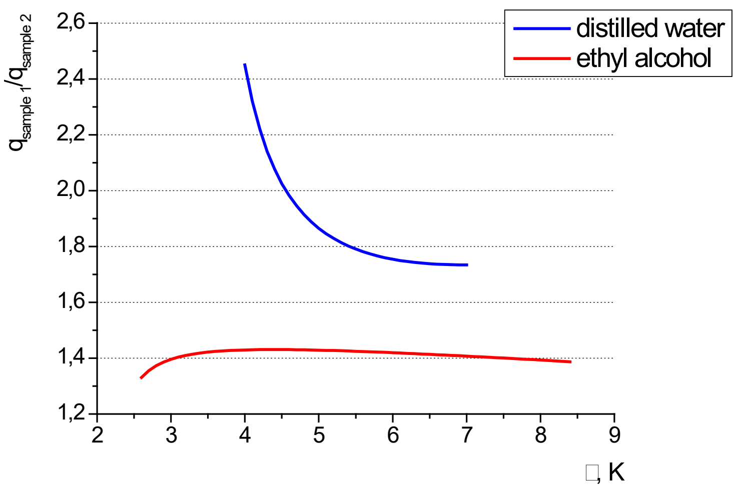

Fig. 3. *Enhancement ratio for two samples at water and ethanol boiling.*

Here we can see that sample 1, whose grooves are bigger and their width larger than sample 2, performs better during the boiling of both liquids. In the case of ethyl alcohol this enhancement is stable over various temperature differences and amounts to about 1.4. A different situation occurs for water. Here, sample number 1 outperformed number 2 to a larger degree, especially in the area of low-temperature differences. The different character of those changes for both the analyzed liquids might result from their different wetting characteristics. Surface tension for ethanol is smaller, while for water it is much larger.

The design of heat exchangers requires that their performance should be quite precisely determined with models or correlations. Different techniques can be applied in terms of mathematical modeling as the discussed example in [11 - 13], but their aim is to properly determine a certain quality. In the present paper, Nishikava et al. [14] model will be used. The experimental data taken from the paper by the authors [5] regarding samples 1 and 2 (mentioned earlier) have been compared with the calculation results according to the above-mentioned model and presented in Fig. 4 for distilled water and Fig. 5 for ethyl alcohol.

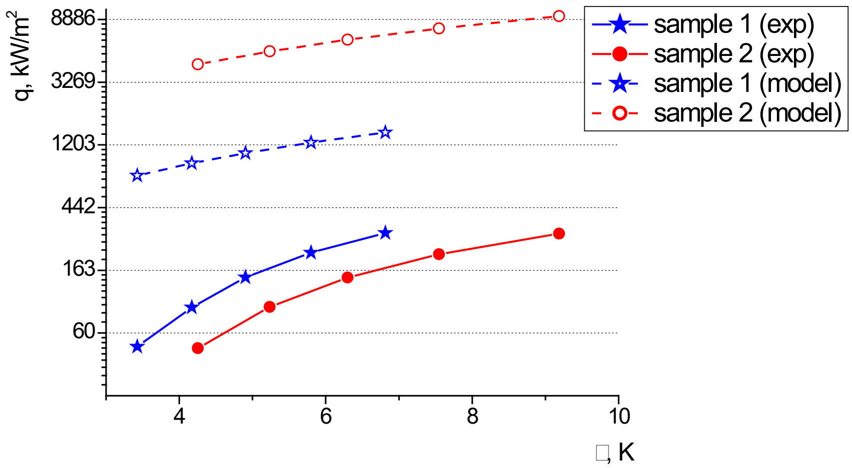

Fig. 4. *Comparison of the experimental and model calculated data for distilled water.*

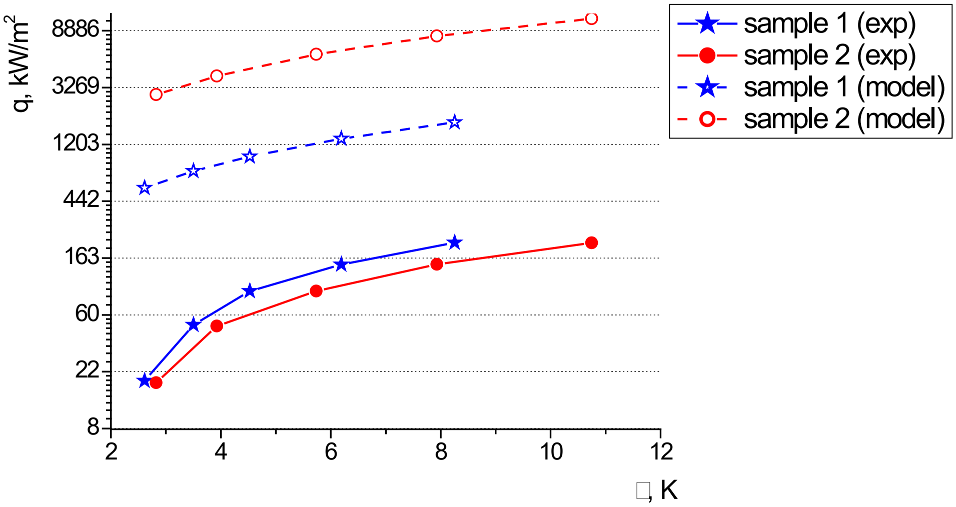

Fig. 5. *Comparison of the experimental and model calculated data for ethyl alcohol.*

The Nishikava et al. [14] model is quite simple among all the boiling models. It is the main assumption is that heat transfer within the microstructural element (in the analyses case longitudinal fins) occurs due to the conduction mode in the two-phase system composed of the boiling liquid and the solid material (in this case copper fins). The proposed correlation requires the calculation of the effective (substitute) thermal conductivity value as the product of the conductivity values of the liquid and solid phases as well as the volumetric porosity of the whole system. On the other hand, the heat flux values are calculated based on the already determined conductivity as well as the temperature difference between the heater and the saturation temperature. The height of the structure is also considered in the model.

The experimental and model data points differ significantly as can be seen in Fig. 4 and 5 for both the boiling liquids considered in the study. Undoubtedly, the simplicity of the model that was selected for calculations might be responsible for such results. The Nishikava et al. [14] model does not take the movement of vapor bubbles and the convection forces into account. It also needs to be noted that the structure generated by the laser beam is non-uniform and significant surface roughness is produced at the bottom of the grooves. Thus, additional nucleation sites are produced, which might lead to elevated heat flux and heat transfer coefficient values. The model adopted from literature does not take it into account either. Moreover, the laser-generated fins do not have the same width along with the height. It is reduced at the top and is larger at the bottom, which results from the laser treatment technique itself. While the calculations according to the considered model did not take this fact into account, the impact of this simplification might not be large enough to be visible in the graphs above.

Summary and Conclusions

Laser treatment is a modern and efficient method used to alter the morphology of various surfaces and can be effectively applied for boiling heat transfer enhancement. The various shapes and sizes that can be designed enable the production of highly efficient heaters that can considerably improve boiling conditions and lead to more heat being exchanged in such phase–change heat exchangers at the same temperature differences.

The differences between various samples with regard to heat flux values might be significant and depend on the temperature differences (as in the case of water), or be independent of it (as for ethyl alcohol). However, the proper design of such a heater can lead to higher values of heat transfer coefficient for such surfaces.

The comparison of the experimental data with the model calculations according to the calculation adopted from the literature has shown major differences. They might be related to the fact that the model is quite simple and does not consider the specific features of the laser-treated metal surfaces as those presented in the paper. However, a proper modification of the presented model, with the alternations mentioned earlier in the paper, could provide more accuracy for laser-treated heat exchanging surfaces [15-17]. It is a very interesting issue worth an in-depth study with the use of various computational and analytical tools [18-20].

References

[1] M. Piasecka, K. Strąk. Influence of the surface enhancement on the heat transfer in a minichannel, Heat Transfer Engineering 40 (2019) 1162-1175. https://doi.org/10.1080/01457632.2018.1457264

[2] M. Piasecka, K. Strąk, B. Grabas. Vibration-assisted laser surface texturing and electromachining for the intensification of boiling heat transfer in a minichannel, Archives of Metallurgy and Materials 62 (2017) 1983-1990. https://doi.org/10.1515/amm-2017-0296

[3] R. Kaniowski, R. Pastuszko. Pool boiling of water on surfaces with open microchannels, Energies 14 (2021) art. 3062. https://doi.org/10.3390/en14113062

[4] R. Kaniowski, R. Pastuszko. Boiling of FC-72 on surfaces with open copper microchannel, Energies 14 (2021) art. 7283. https://doi.org/10.3390/en14217283

[5] Ł.J. Orman, N. Radek, J. Pietraszek, M. Szczepaniak. Analysis of enhanced pool boiling heat transfer on laser – textured surfaces, Energies 13 (2020), art. 2700. https://doi.org/10.3390/en13112700

[6] S. Wciślik. Efficient Stabilization of Mono and Hybrid Nanofluids, Energies 13 (2020) art.3793. https://doi.org/10.3390/en13153793

[7] S. Wciślik. A simple economic and heat transfer analysis of the nanoparticles use, Chemical Papers 71 (2017) 2395-2401. https://doi.org/10.1007/s11696-017-0234-4

[8] P. Hrabovsky, P. Nemec, M. Malcho. Compare cooling effect of different working fluid in thermosyphon, EFM14 Int. Conf. on Experimental Fluid Mechanics 2014, Český Krumlov,

Czech Republic, EPJ Web of Conferences (2015), art. 02024. https://doi.org/10.1051/epjconf/20159202024

[9] P. Nemec. Visualization of various working fluids flow regimes in gravity heat pipe, EFM16 Int. Conf. on Experimental Fluid Mechanics 2016, Marienbad, Czech Republic, EPJ Web of Conferences (2017), art. 02079. https://doi.org/10.1051/epjconf/201714302079

[10] E. Zender-Świercz. Analysis of the impact of the parameters of outside air on the condition of indoor air, Int. Journal of Environmental Science and Technology 14(8) (2017) 1583-1590. https://doi.org/10.1007/s13762-017-1275-5

[11] M. Krechowicz. Comprehensive risk management in horizontal directional drilling projects, Journal of Construction Engineering and Management 146 (2020) art. 04020034. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001809

[12] B. Szeląg, J. Drewnowski, G. Łagód, D. Majerek, E. Dacewicz, F. Fatone. Soft sensor application in identification of the activated sludge bulking considering the technological and economical aspects of smart systems functioning, Sensors 20 (2020) art. 1941. https://doi.org/10.3390/s20071941

[13] B. Szeląg, K. Barbusiński, J. Studziński. Activated sludge process modelling using selected machine learning techniques. Desalination and Water Treatment 17 (2018) 78–87. https://doi.org/10.5004/dwt.2018.22095

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

[15] N. Radek, J. Pietraszek, A. Gadek-Moszczak, Ł.J. Orman, A. Szczotok. The morphology and mechanical properties of ESD coatings before and after laser beam machining, Materials 13 (2020) art. 2331. https://doi.org/10.3390/ma13102331

[16] I. Nová, K. Fraňa, T. Lipiński. Monitoring of the Interaction of Aluminum Alloy and Sodium Chloride as the Basis for Ecological Production of Expanded Aluminum. Physics of Metals and Metallography 122 (2021) 1288-1300. https://doi.org/10.1134/S0031918X20140124

[17] N. Radek, J. Konstanty, J. Pietraszek, Ł.J. Orman, M. Szczepaniak, D. Przestacki. The effect of laser beam processing on the properties of WC-Co coatings deposited on steel. Materials 14 (2021) art. 538. https://doi.org/10.3390/ma14030538

[18] T. Styrylska, J. Pietraszek. Numerical modeling of non-steady-state temperature-fields with supplementary data. Zeitschrift fur Angewandte Mathematik und Mechanik 72 (1992) T537-T539.

[19] J. Pietraszek. Response surface methodology at irregular grids based on Voronoi scheme with neural network approximator. 6th Int. Conf. on Neural Networks and Soft Computing JUN 11-15, 2002, Springer, 250-255. https://doi.org/10.1007/978-3-7908-1902-1_35

[20] J. Pietraszek, E. Skrzypczak-Pietraszek. The uncertainty and robustness of the principal component analysis as a tool for the dimensionality reduction. Solid State Phenom. 235 (2015) 1-8. https://doi.org/10.4028/www.scientific.net/SSP.235.1