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Application of laser treatment technology for boiling heat transfer augmentation

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Abstract

Boiling heat transfer can be enhanced when the heater's surface morphology is altered. The paper discusses the use of the laser beam to produce efficient heat exchangers. Two types of samples were investigated with distilled water and ethyl alcohol as boiling agents. The specimens differed with the height of the microfins: 0.19 mm and 0.89 mm. It was observed that both of them enhanced boiling heat transfer in comparison to the smooth reference surface. However, the sample with higher microfins performed better, especially in the region of low temperature differences, where the heat flux was about three times higher than in the case of the smaller microfins. The comparison of the experimental data with selected models of boiling heat transfer revealed significant differences with regard to the heat flux. The laser-made samples dissipated larger heat fluxes than it could be anticipated according to the models. It might be linked with high surface roughness of the area between the microfins, generated as a result of the laser beam interaction with the surface.

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1. Introduction

Boiling heat transfer performance can be enhanced by adequate treatment of the heat exchangers' surfaces to produce additional roughness, extension of the surface area, development of cavities and etc. As a result a modified heater can dissipate higher heat flux values than in the case of the untreated (smooth) surfaces. One of the relatively new methods of surface treatment is the application of the laser beam. This technology can provide augmentation of the heat transfer conditions during nucleate boiling and lead to better performance of the heaters.

2. Literature review

In (Zupančič et al., 2015) the results of distilled water boiling tests conducted on stainless steel thin foils covered with polydimethylsiloxane-silica coatings were given. The heater surfaces were treated with the laser beam to produce square patterns of 0.25 - 2 mm^2 spot size. The sample with the value of 0.25 mm^2 turned out to be most efficient. Moreover, the critical heat flux of that sample was almost 200% bigger in relation to the smooth surface (without laser modification). The authors (Sitar et al., 2020) experimentally studied surfaces textured with the laser beam and found that they generally performed better during distilled water boiling than the smooth reference surface (although not all the samples). The surface roughness of the laser treated heaters was up to ca. 3 μm. The same boiling liquid was tested in (Može et al., 2019). The researchers reported enhancement of both the critical heat flux and heat transfer coefficient values of the modified surfaces. Besides, their operation was more stable. Similarly, the laser-vibration textured steel surfaces analysed in (Grabas, 2015) provided higher values of the heat transfer coefficient and the critical heat flux – by over 4 and almost 2 times, respectively – in comparison to the untreated ones. The surface roughness of the most efficient sample was almost 20 μm. The study (Dharmendra et al., 2020) contains data on distilled water boiling on the surfaces with square grooved shapes of the depths

30 – 100 μm generated with a picosecond laser device. The deepest grooves performed best, but all of the specimens proved to be better than the smooth surface, especially at low temperature differences. The authors (Nirgude and Sahu, 2018) conducted tests of water and acetone boiling on surfaces with longitudinal grooves, which were made with the laser beam. All of the produced surfaces provided augmentation of heat flux (the value of the heat transfer coefficient was maximally almost two times higher than for the reference surface). Research on FC-72 boiling on the fins covered with microfins generated with laser was presented in (Orzechowski, 2009). At low temperature differences augmentation of heat transfer in relation to the smooth surface was clearly noticeable, however at high heat fluxes the performance of the laser processed surfaces and the smooth surface proved to be quite similar. The study (Orman et al., 2020) was focused on copper surfaces treated with laser, on which longitudinal grooves of the fin width 0.50 mm and 1.10 mm and height 0.25 mm and 0.55 mm were produced. All the specimens augmented heat transfer in relation to the smooth surface. Water and ethanol were the boiling agents.

Nanofluids are currently widely investigated due to their significant heat transfer augmentation potential (Wciślik and Mukherjee, 2022; Mukherjee et al., 2024). The authors (Karthikeyan et al., 2018) focused their paper on examining the combined effect of the laser modification of the surface and the application of ethanol-based nanofluids as the boiling agent. Almost sixty percent heat transfer enhancement in comparison to the smooth surface and pure base liquid was stated by the authors.

The laser beam technology can also be applied to generate other types of surfaces of modified morphology (Radek et al., 2014) and performance properties (Radek et al., 2018; Radek et al., 2021). Modeling emerging physicochemical phenomena requires complex analysis, involving well-known in thermodynamics adjustment calculation methods (Styrylska and Pietraszek, 1992), DOE methodology (Pietraszek, 2003), and machine learning (Pietraszek and Gądek-Moszczak, 2013; Pietraszek et al., 2014), but the effects are very beneficial, among others in cutting tools production (Szataniak et al., 2014). This type of treatment may generate harmful solid and gaseous waste, especially metal-related waste, but their proper utilization and neutralization has already been refined, both chemically (Kozłowski et al., 2002; Ulewicz et al., 2003) and organizationally (Ulewicz and Ulewicz, 2020). The paper (Wang and Leong, 2018) considers boiling of the commercial fluid FC-72 on the surface covered with microstructures made from AlSi10Mg powder, which was shaped with laser to form cells. The enhancement of heat transfer was almost three times. On the other hand, 3D grid structures were produced with the same technique and studied in (Zhang et al., 2019) with water as the boiling agent. Despite the fact that not all of the specimens augmented heat transfer, those which did increased the critical heat flux even three times. Another work (Zhang et al., 2020) focuses on boiling tests on a surface with laser – made shells and the internal open channel. It was reported that all of the surfaces enhanced heat transfer. A confirmation of the heat flux augmentation during boiling on laser – treated silicon surfaces can be found in (Serdyukov et al., 2021). The authors (Eid et al., 2022) analysed the heater surfaces with micro-cavities produced with a fiber laser, whose depth was 0.5 mm. It was stated that the maximal improvement in heat flux reached over 120% for water boiling. The same liquid was tested in (Zupančič et al., 2022). Thin metal foils modified with laser were produced and a set of triangular lattice forms was made on each sample. The heater containing the largest density of the cavities proved to be the most efficient.

Naturally, the morphology of the surface obtained with the laser treatment depends on the parameters of the process. The research (Vilhena et al., 2009) presents the study of the influence of pulse energy and its duration on the micropores made with a pulsed laser. The authors reported that the value of the pore diameter typically rose as the pulse energy increased. At the same time the pores' depth decreased. On the other hand, the article (Zuhlke et al., 2013) focuses on the development of nickel micro- and nanostructured surfaces with the femtosecond laser device. It was stated that ablation of surface valleys and flow of melt material were some of the mechanisms responsible for the creation of a modified surface.

The process parameters during laser beam interaction with the surface influence the propertied of the generated surfaces. The effect of theses parameters was given in (Nirgude and Sahu, 2020a), where the samples were generated with nanosecond laser of the power 0.8W – 4.6W and wavelengths 355 nm – 1064 nm. The authors observed the largest augmentation of boiling heat transfer in the case of the surface produced with the biggest laser power (and also the largest wavelength). A comparison of the boiling performance of surfaces made with two types of lasers (the pulsed and continuous wave ones) was given in (Nirgude and Sahu, 2020b). The devices differed with the laser power (up to 4.6W in the case of the pulsed laser and up to 50W in the case of the continuous wave laser). The largest augmentation of heat flux, which amounted to over two times, occurred for the surface modified with the continuous wave laser.

The development of efficient heat exchangers made with the laser beam can provide significant advantages such as dissipation of higher heat fluxes and more stable operation in the pool boiling mode. Thus, they could be effectively used as part of many engineering devices including small scale domestic systems (Wojtkowiak et al., 2020; Dudkiewicz and Szałański, 2019) or large power plants (Mukherjee et al., 2022).

The present paper experimentally analyses the performance of the heating surfaces produced with the laser beam during boiling of distilled water and ethyl alcohol of high purity. The data in this area available in literature is quite scarce (with some reports even being contradictory to each other) and the current experimental effort aims to provide additional knowledge in this area, which could also have significant and widespread practical application potential.

3. Experimental

The preparation of the samples was based on the use of a pulsed fiber laser of the power 20W and pulse duration of 60 and 250 ns. The device was programmed to generate longitudinal grooves on the whole surface of the 3cm circular copper samples (thickness of 3mm). Figure 1 presents a schematic of the produced microstructure, while Figure 2 a photo of the sample.

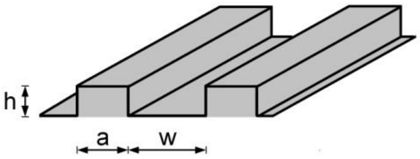

Fig. 1. Schematic of the laser – treated sample

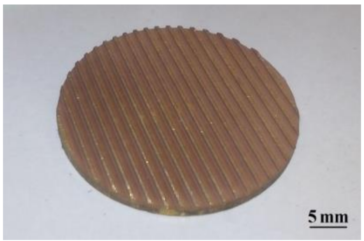

Fig. 2. Photo of the laser – treated sample

The use of adequate treatment parameters enables to obtain surfaces of pre-designed microstructural parameters (regarding the geometry). The height (h) of the produced microfins as well as their width (a) and distance between them (w) can be adjusted according to the heat transfer requirements of the considered system. Figure 3 presents microfins and grooves made with different geometrical parameters on the same common copper substrate. In the middle the untreated copper base is easily seen. Generally, the application of large pulse duration values leads to the development of higher microfins (or deeper grooves).

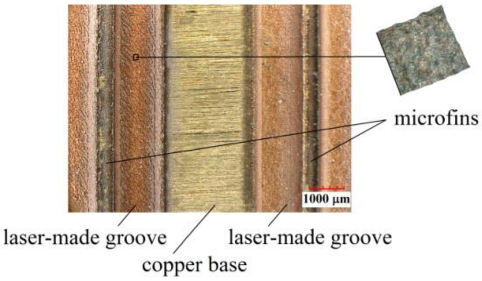

Fig. 3. Image of the grooves and microfins on the copper base (optical microscope, magnification 140x) with the 3D image of the bottom surface

The above figure also shows the morphology of the bottom of the groove (as the close-up on the upper right-hand side). The evaporation of the metal results in a highly irregular morphology of the surface. There are hills and cavities present on the surface. Figure 4 presents the detailed image of the bottom surface of the groove produced with laser. The surface roughness is high and, in the case of the image, amounts to ca. 7.7 µm. However, the differences between the lowest and highest points of this surface are significant. Such a surface is very efficient for boiling applications.

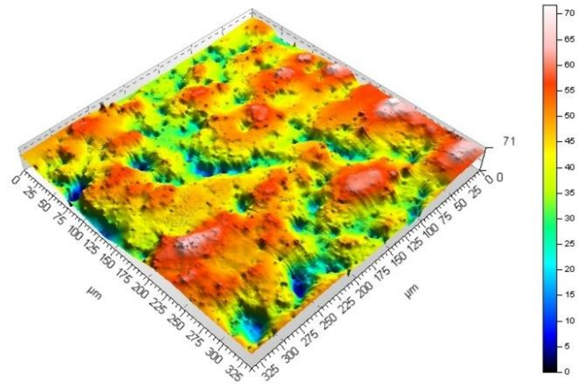

Fig. 4. Surface morphology of the laser – treated surface

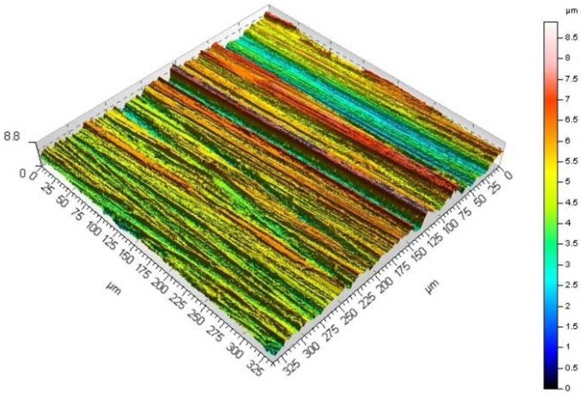

Fig. 5. Surface morphology after treatment with emery paper no 280.

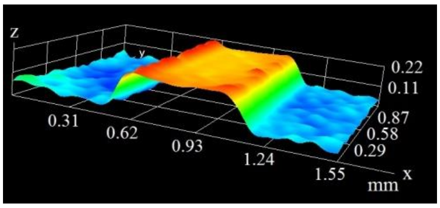

Fig. 6. Optical microscope image of the laser - made microfins of the height 0.19 mm

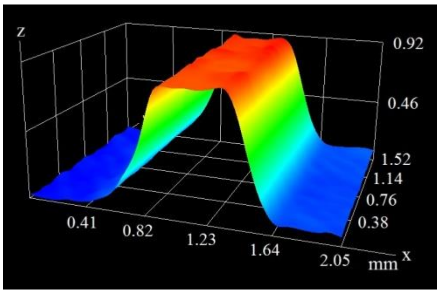

Fig. 7. Optical microscope image of the laser - made microfins of the height 0.89 mm

Naturally, rough surfaces can also be produced with other methods, such as with emery paper. In this case, the surface characteristics is different and contains longitudinal microgrooves (Figure 5), whose depth depend on the emery paper roughness.

The present paper analyses the boiling heat transfer augmentation potential of two kinds of laser – treated copper surfaces. The first one has been made with the laser beam of the pulse duration 60 ns, which has led to the development of the structure of microfin height 0.19 mm (Figure 6).

The second surface contains microfins of the height 0.89 mm (generated using the pulse duration 250 ns), as shown in Figure 7. The distance between the microfins (e.g. the width of the groove) is the same and amounts to 1.5 mm.

As can be seen in the above figures, the cross-section of the microfins is not a rectangular. It is wider at the bottom and becomes thinner at the top. This shape results from the laser processing and evaporation of the material from top to bottom. In the case of both the microfins their width is ca. 0.65 mm (measured in the middle of their height).

The boiling heat transfer experiments have been performed on the stand, whose main element is the electric heater on which the samples with modified geometry are located (attached to the heater with soldiering). Above the sample boiling liquid (distilled water and ethyl alcohol) in a glass vessel is located and undergoes pool boiling. The details of the experimental stand were given in (Orman et al., 2020).

4. Results and discussion

The process of boiling is linked with the development of vapour bubbles on the heater surface. In the case of the laser – treated surfaces, the bubbles appear first on the rough surface between the microfins. However, as the heat flux increases the process intensifies, the number of bubbles rises and they are created on the whole surface . They frequently merge with each other to form larger bubbles of even vapour columns. Figure 8 presents the images of the boiling phenomenon occurring at various heat fluxes. The time interval between each picture amounts to 0.012 s.

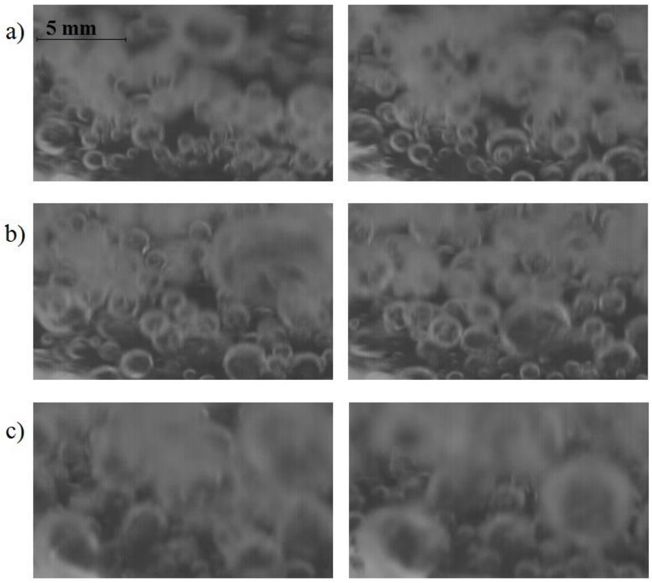

Fig. 8. Images of the boiling phenomenon at the heat flux of ca.: 21 kW/m^2 (a), 45 kW/m^2 (b), 88 kW/m^2 (c)

The performance of a sample during boiling is graphically represented by a boiling curve, which shows a dependence of the heat flux (q) vs. wall superheat (θ) (which is a difference between the heater surface temperature and the liquid saturation temperature). The boiling curves of the analysed samples and both boiling agents have been presented below in Figure 9 and 10. For reference, the smooth (not treated with laser) sample test results have also been provided for distilled water and ethyl alcohol boiling.

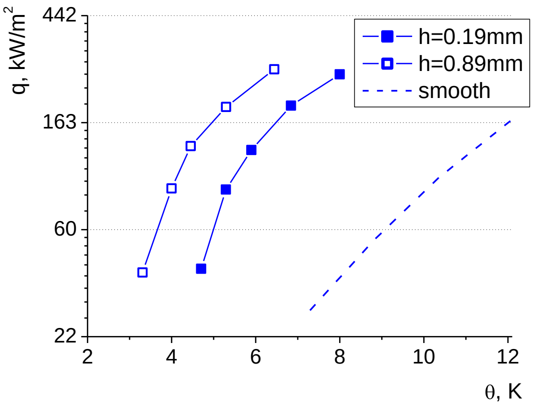

Fig. 9. Boiling curves for distilled water: laser – made surfaces of the microfin height 0.19mm and 0.89mm and the smooth surface

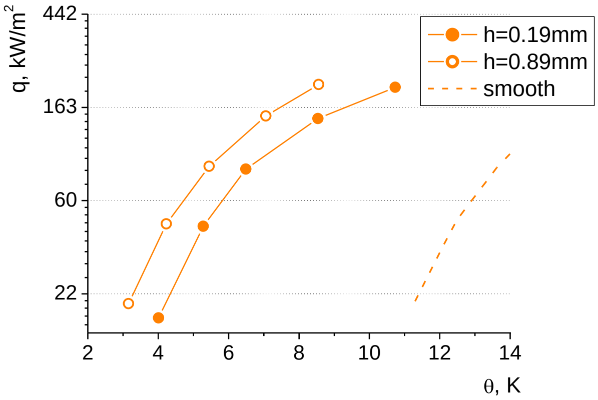

Fig. 10. Boiling curves for ethanol: laser – made surfaces of the microfin height 0.19mm and 0.89mm and the smooth surface

As can be seen the application of the laser treatment resulted in significant augmentation of heat transfer in comparison to the results obtained during boiling on the smooth (reference) sample without any laser-made modifications. This augmentation manifests itself with shifting the boiling curves of the treated specimens into the area of small temperature differences. As a consequence, the same heat flux might be dissipated to the boiling liquid at smaller temperature of the heaters. This increases the efficiency of the process. However, there is also another aspect. The heat flux transferred off the laser – treated surface proved to be larger than for the reference surface at the same temperature difference (which is visible for the sample of 0.19mm microfin height and water as the boiling agents). The calculations could be done only for that sample due to the fact that boiling on the smooth sample did not even occur for the other sample in the case of water and for both samples with ethanol as the boiling agent. The heat flux of the 0.19mm microfin height sample was 7.7 times higher in relation to the smooth surface test results at the temperature difference of 7.3K and 6.4 times higher at the temperature difference of 8K. It could be observed that the augmentation potential decreases with rising temperature of the heater. This observation is backed by other researchers, albeit for slightly different microstructural coatings (Kaniowski and Pastuszko, 2018; Pastuszko et al., 2021).

It can be easily noticed that the performance of the sample with the higher microfin (h=0.89mm) was better than the other sample (h=0.19mm) for both the boiling agents and at the whole range of temperature differences (as evidenced by the left-hand shift of the boiling curves). For more detailed view of this phenomenon Figure 11 presented the ratio of the heat flux dissipated from the surface covered with the grooves of the height 0.89mm to the heat flux recorded for the height of 0.19mm (this ratio has been denoted as enhancement ratio - “Eh” in the picture). The range of temperature differences has been reduced to about 4.5 – 8.5 K, in which both of these boiling curves are present.

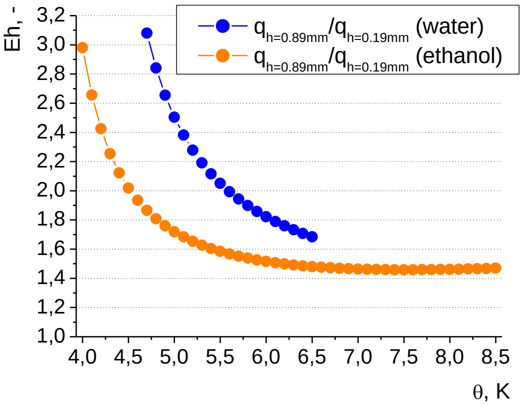

Fig. 11. Enhancement ratio of the laser – made samples of the microfin height 0.89mm and 0.19 mm for water and ethanol

At low temperature differences the heat flux exchanged with the boiling fluids can be about three times higher in the case of the sample with the higher microfin height of 0.89mm (comparing to the sample of the height 0.19mm). It might be linked with a significantly larger heat transfer area. The augmentation potential decreases as the temperature of the heater surface rises and reaches the value of ca. Eh = 1.7 for distilled water and ca. Eh = 1.45 for ethanol. A stabilization of the enhancement ratio can indicate that at larger heat fluxes the boiling performance might be less dependent on the morphological properties of the heater surface. However, the physical fundamentals of the phenomenon of boiling heat transfer augmentation seem to be very similar.

As can be noticed the difference in the boiling performance of the surfaces is also related to the boiling liquid. Typically, bigger values of the enhancement ratio characterize water as the boiling agent. It could be explained by higher value of heat of evaporation for this fluid. In the case of water vapour bubbles are also bigger and this fact could also favourably impact heat transfer performance from the sample of relatively large distance between the microfins (1.5 mm). During boiling of ethanol, the bubbles are very small and might be beneficial for the overall heat exchange potential, if this distance between the microfins was lower.

A correct design of heat exchanging systems requires detailed knowledge about the physical processes which take place within those systems. Consequently, a reliable model of the boiling phenomenon is needed. In order to verify if the experimental results presented above can be successfully modeled with a correlation adopted from literature, two equations for the heat flux value have been considered. The first model proposed in (Smirnov, 1977) was developed with the assumption that a sample of the modified microgeometry can be considered to be a set of independent microfins. Naturally, the temperature along the fins diminishes as the distance from the base of the fins rises. The formula for the heat flux takes into account many properties of the sample-fluid system, among other: the volumetric porosity of the structure, thermal conductivity of the liquid and the sample material, heat of vaporisation, surface tension and density. It also contains the constants, which were calculated using the experimental data for the wire mesh microstructures (which is a clear limitation of the application of this model, but wire meshes are regular geometry structures, so the discrepancies might not be too large). The second model selected for the analysis was presented in (Xin and Chao, 1987). Here, the microstructure in the form of longitudinal microfins of the ‘T’ shape is considered to be fully filled with vapour with the exception a thin liquid film covering the internal surface. In this model the periodic cycle of bubble growth and departure was disregarded. Here, the limitation is a slightly different shape of the fins in comparison to the laser – made groove like patterns of the considered samples. The equation for the heat flux contains elements such as geometrical parameters of the microstructure (but without porosity), heat of vaporization, surface tension and density of both the liquid and vapour phases as well as viscosity. Naturally, in both of the above-mentioned models the heat flux is proportional to the temperature difference between the heater surface and the saturation temperature in the liquid pool, albeit to a different order.

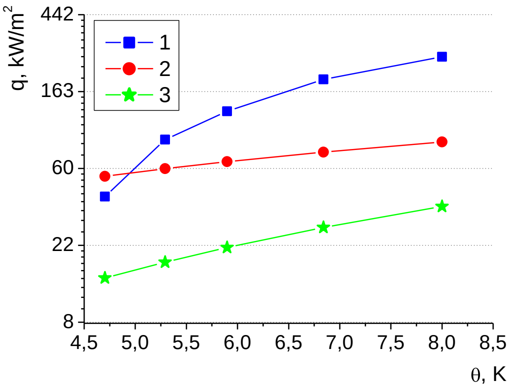

Fig. 12. Comparison of the experimental data for the sample of h=0.19mm (1) with selected models: 2 – calculation results according to (Smirnov, 1977), 3 – calculation results according to (Xin and Chao, 1987); boiling agent: distilled water

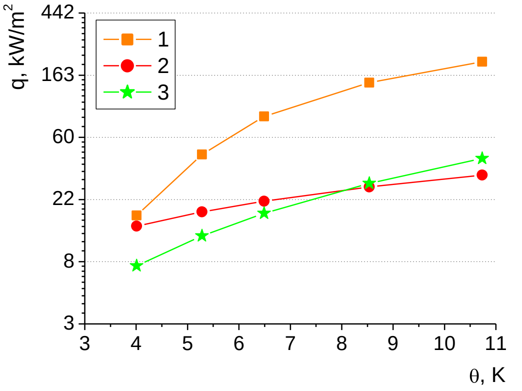

Fig. 13. Comparison of the experimental data for the sample of h=0.19mm (1) with selected models: 2 – calculation results according to (Smirnov, 1977), 3 – calculation results according to (Xin and Chao, 1987); boiling agent: ethyl alcohol

The comparison of the above-mentioned models with the experimental data of the sample with microfins of 0.19mm has been presented in Figures 12 and 13 for distilled water and ethyl alcohol, respectively.

As can be seen none of the models has been able to properly describe the performance of the laser – made heater of the microfin height of 0.19mm (with the exception of the lowest temperature difference and the Smirnov's model). The heat flux dissipated from the surface during the experiments proved to be higher than the calculation results according to the models. It might indicate that there is an additional element of the laser – treated specimens that improves heat exchange during pool boiling. This element might be the rough surface between the microfins, which is characterized by high roughness of ca.7.7um. The rough area provides favourable conditions for vapour growth due to the presence of cavities, which can trap vapour after bubble departure. Neither of the considered models takes this phenomenon into account. As a result, considerable discrepancies can be observed between the experimental data and model-based calculation results.

Future research could be focused on the development of a completely new model of boiling on the laser – treated surfaces together with the application of nanofluids as boiling agents. Their use could considerably improve the performance of the heaters. Moreover, the tests of such surfaces could be carried out in the flow boiling mode, which would offer additional practical applications (Piasecka et al., 2024).

5. Summary and conclusion

The application of the laser beam can be considered an effective method of pool boiling heat transfer augmentation. The development of microfins on the surface due to the laser – induced evaporation of the base material leads to the extension of the heat transfer area, while significant roughness developed between the microfins provides advantageous conditions for vapour bubble growth (which further intensifies the process of the phase – change heat transfer). Consequently, augmentation of heat flux has been observed in relation to the smooth surface – for both boiling agents – which manifested itself by the shift of the boiling curves leftwards (thus, the same heat flux can be exchanged at smaller temperature differences) as well as higher values of heat flux dissipated from the laser – made sample of 0.19mm in the case of distilled water at the same temperature differences.

It has also been observed that the sample with higher microfins (h=0.89mm) performed better than the one with microfins of the height 0.19mm. The enhancement potential was highest for the lowest temperature differences and amounted to about 3. It decreased as the heat flux increased, but seemed to stabilize at a certain level (at 1.45 in the case of ethanol), although insufficient experimental data makes it hard to form solid statements in this case.

The significant potential of heat transfer augmentation with the use of the laser technology might offer even more opportunities, for example regarding the increase in the critical heat flux value, however this phenomenon has not been investigated in the present study and can be the focus of future work.

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