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LAYERED COMPOSITE HEAT EXCHANGERS – MODELLING OF THERMAL AND STRENGTH PROPERTIES

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There are many heat enhancing structures available on the market and already researched, but the application of layered composites for their development has not been completely investigated, especially regarding modelling of the physical phenomena of boiling heat transfer and mechanical properties. The present paper presents a modified model of boiling heat transfer and modelling of the strength properties of composite heat exchangers made of mesh layers. The experimental results (obtained by the authors) of the boiling heat transfer of distilled water and ethanol under atmospheric pressure on copper substrates covered with brass, bronze and copper layers were used for modified model development. It needs to be noted that the problem of modelling the heat transfer of such structures has not been properly addressed to date with many issues in need of clarification. The present paper's novelty is mainly focused on providing a more reliable equation for heat flux regarding boiling on metal composite mesh layers. It also proposes a calculation procedure for selected strength properties of such structures. The application of the modified boiling heat transfer correlation resulted in almost all the measurement points lying within or close to the ±100% error band, while in the case of the original model none of the experimental points was even close to this error band (the differences reached even about one order of magnitude).

Keywords: **boiling, composite heat exchangers, layered composites, model modification, strength properties**

INTRODUCTION

Heat exchangers are among the most important parts of present-day engineering applications [1–3], especially regarding their use in renewable energy systems [4–6], which are now becoming increasingly more common. The modern requirements of various technological devices (including machinery parts) to release significant heat fluxes from them for cooling have led to the development of technologies for heat transfer augmentation. Highly efficient and effective heat exchangers operating under boiling conditions may release large heat fluxes at small temperature differences between the heater surface and the boiling agent, which is of considerable importance. Proper design of the heater microstructure can lead to considerable improvement in heat transfer, for example, in [7] it was reported that in comparison with the smooth surface, the heat transfer coefficient of a surface with microchannels increased three-fold, while in [8] it was twice. Both of these papers focused on copper samples with parallel grooves. Such surface modification led to an increase in the maximum heat flux, which amounted to 1035 kW/m2 in [7] and 262 kW/m^2 in [8] (different boiling agents were used in these two studies). At the same time, the application of composite heat exchangers for boiling enhancement also seems to be very promising and it has been the focus of some research projects throughout the world. Liang and Yang [9] experimentally analysed the boiling of pentane on copper and aluminium structures with graphite fibers. The authors reported that the heat flux dissipated from the composite microstructure (with fibers) was even eight times higher in relation to the sample without the fibers. This phenomenon was explained, among other factors, by a larger density of nucleation sites (locations where vapour bubbles develop) if graphite was present. Moreover, it was stated that graphite fibers caused a reduction in hysteresis effects at low heat flux values, while at high values the heat transfer performance proved to be more enhanced if copper was used for the composite production rather than aluminium. The same type of structure was investigated by Yang et al. [10]. It was stated that such metal-graphite composite surfaces may generate three to six times enhancement in boiling heat transfer in comparison with the pure metal surface. Moreover, these surfaces reduce the pressure drop, which is an additional benefit. Owing to the fact that the composite surfaces consisted of graphite microfibers interspersed in a metal matrix (copper or aluminium), they had high thermal conductivity. Their application resulted in obtaining boiling heat transfer augmentation, which was comparable or even superior to commercially available boiling heat transfer enhancement surfaces. Białek et al. [11] tested water and ethanol boiling heat transfer on a composite heat exchanger made of a copper disk covered with a single brass mesh layer. Two types of meshes were used – one with a wire diameter of 0.10 mm and the other of 0.25 mm. The distance between the wires was 0.16 mm and 0.40 mm, respectively. Both samples exhibited improved performance with the heat flux being even several times higher than in the case of the reference surface without a mesh, although this effect became weaker as the temperature difference rose. What is more, the specimen with the larger wire diameter proved to be more efficient. The authors also compared their experimental results with heat transfer models and only in the case of water were the calculation and experimental results quite close, but only for one out of the two models considered. A confirmation of the positive effect of the application of composite heat exchanges can also be found in [12], where the research results of boiling on stainless steel and bronze meshes attached to a copper base were presented. The number of mesh layers ranged from two to nine. The authors claimed that the impact of the number of meshes on the heat flux was not clearly observed. Additionally, the authors reported that the relation between the heat flux and temperature difference was not linear – the angle of inclination for the meshed surfaces changed its value at smaller temperature differences than in the case of the smooth reference surface.

The papers by the present authors [13, 14] dealt, among others, with distilled water and ethyl alcohol boiling heat transfer research conducted using composite heat exchangers. The samples were fabricated with brass, bronze and copper meshes sintered to a copper base. All the samples exhibited improved thermal performance in relation to the smooth reference surface (without any mesh), especially at small heat flux values. The copper meshes proved to be the most efficient due to the highest thermal conductivity of this material and enhanced conduction heat transfer performance of the whole sample. The highest heat flux value in [13] was recorded for the copper-bronze composite heat exchanger and amounted to ca. 288 kW/m2 for water and 160 kW/m2 for ethanol. In [14] the largest ethanol boiling heat flux was also observed for this heat exchanger, while in the case of water boiling the sample made of pure copper provided the highest heat exchange rate (although the differences between all the samples were small). In both of the above mentioned papers ([13, 14]), the best overall thermal performance was provided by the pure copper specimens, which also manifested itself in a significant shift of the boiling curves into an area of small temperature differences by several degrees Celsius (with smaller values being recorded for water and larger for ethanol). A modified design of a composite heat exchanger, but operating with the same boiling agents, was presented in [15]. In this paper, composite heat exchangers made of bronze meshes of the same wire diameter, but different apertures (0.40 mm and 0.63 mm) covered with fine copper fibers of 50 μm in diameter were investigated. The sintering process was used to create durable bonds between the meshes and the fibers as well as the copper base. It was reported that the samples consisting of the meshes and fibers outperformed the smooth reference surface and the surface with the meshes in the whole range of heat flux values. The heat flux dissipated from the sample with the mesh and fibers was over seven times higher than that of the smooth reference surface – which was observed at low heat fluxes. As the heat flux rose, the improvement quickly became weaker. On the other hand, the ratio of the heat flux dissipated from the sample with the mesh and fibers to the heat flux dissipated from the sample with the mesh only was quite constant in the analysed range of heat flux values and amounted to about 1.8.

Porous microstructures are often used as components of heat pipes, which are very efficient heat exchangers. Franchi and Huang [16] experimentally analysed the thermal performance of heat pipes made of composite wicks (composed of fine nickel powders sintered onto a copper mesh). It was reported that the composite samples exhibited better performance (even over three times higher) than the conventional heat pipes (without the investigated composite material of the wick). The authors provided a possible explanation for the enhancement, which could be caused by improved evaporation heat transfer attributed to an increased evaporating meniscus density and/or a rise in capillary pumping of the wick. Moreover, the use of nickel/copper wicks immersed in water might have created a galvanic cell. Thus, non-condensable gasses could have been generated. Yeh et al. [17] focused their study on the biporous nickel wicks of heat pipes (whose evaporator was made of stainless steel). The performance of the biporous wick proved to be enhanced about 60% in relation to a monoporous wick. The authors claimed that a smaller particle size (74 – 88 μm) and higher sintering temperature (750oC) could be more beneficial. The impact of the particle size seemed to be related to the evaporating menisci area, while the sintering temperature impacted the pore size in the biporous wick.

With regard to the modelling of composite strength properties, Charkviani et al. [18] conducted an experimental investigation of the interlaminar strength and stiffness of layered composite materials. Additionally, a new method was proposed which could determine the ultimate strength of composites under shear and their manufacturing technology. It was reported that the final result of the design process is considerably dependent on setting reliable initial data on the mechanical characteristics of the composites. In [19], a non-destructive technique for the determination of a laminated composite's properties was considered. The authors employed a combined numerical–experimental method to determine the elastic characteristics of the composite monolayer. The technique was based on the concept of combining the results of experimental tests with numerical modelling methods (using optimization). According to the authors, high accuracy of the calculation results was achieved. Bazhina et al. [20] developed a layered composite material made of boron, titanium and aluminium. It was reported that combustion as well as subsequent high-temperature shear deformation led to composite ceramic and intermetallic macrolayers being oriented along the direction of material flow, while perpendicular to the applied load. Crack propagation was studied and the impact of the orientation of microvolumes in the material on the stress intensity factor was determined. Frącz et al. [21] considered the prediction of the strength properties of composites produced with polyester resin and glass fibers. Modelling was based on the numerical homogenization method, considering the geometrical features as well as the properties of the components of the composite samples. The calculated properties were used in strength simulations considering three composite reinforcement variants. In [22] the results regarding selected strength properties of an aluminium composite reinforced with carbon fibers were presented. It was reported that a lack of cohesive connection of the fibers with the matrix as well as a considerable number of internal defects within the structure of the composite reinforced with one type of fiber caused a reduction in its strength in comparison to the reference alloy. Additionally, it was also shown that chopped carbon fibers contributed to a large rise in the elastic properties of the composites with an AlSi matrix; however, those properties were not impacted by the reinforcing phase surface preparation or the pressing pressure.

The strength of metallic composite layers strongly depends on the sintering quality, namely the adhesion of the joints between the components. Metallic composites of a uniform structure are able to transfer stress more effectively [14]. On the other hand, local unevenness or a low level of bonding may lead to premature cracking during thermal and mechanical stress [23]. The mechanical properties of porous composites (layers in packages as laminates or layered composites produced by sintering) usually deteriorate with rising porosity and the number of layers [24, 25]. Thus, porosity acts as stress concentrator and reduces material stiffness.

The previous papers of the present authors also considered the material properties of composite heat exchangers used for boiling heat transfer enhancement. In [13] strength tests of samples with sintered copper fibers and composite samples reinforced with glass and carbon fibers were presented. Moreover, the quality of the bonds between the components was also investigated. It was reported that the composite specimens outperformed the copper structure (the adhesion strength increased significantly – even almost twofold). On the other hand, the assessment of the adhesion strength of a copper base with meshes of different material (pure copper, bronze, brass) presented in [14] indicated that the strength value obtained for the copper-brass sample was slightly lower that for the copper-bronze and much lower than for the copper-copper configuration. The authors stated that destruction of the mesh occurs first (alloys earlier, followed by pure copper).

Recently, Lipatnikowa et al. [26] focused on metal-intermetallic composites. It was reported that the multi-layered composite exhibited an advantage regarding strength properties as well as a more uniform strain distribution. Furthermore, the layered composite material containing a small number of layers exhibited greater resistance to intermetallic interlayer fracture. Nowadays, modelling is supported by adequate software tools [27], while the future might lie in the application of machine learning [28] or artificial intelligence methods. On the other hand, it needs to be emphasized that the strength properties of various structures are closely linked with safety issues and risk management [29, 30].

The application of composite heat exchangers for boiling heat transfer enhancement is very promising. The results reported in the literature indicate significant improvement in the heat flux, if such devices are used. Another, but very complex problem is developing reliable models regarding both the thermal and strength properties of such composite systems. The present paper aims to address this issue, especially with regard to more precise heat flux determination, which is the main research gap to be bridged. Thus, the present paper's contribution is mostly focused on developing a more reliable equation for heat flux regarding boiling on metal composite mesh layers. Moreover, it also proposes a calculation procedure for selected strength properties of such structures.

DEVELOPMENT OF MODIFIED HEAT TRANSFER MODEL

The experimental data of distilled water and ethyl alcohol boiling heat transfer published by the current authors [13, 14] are now used to create a modified model of heat flux. The studies took place on an experimental stand whose main component is an electric heater, on which samples are soldiered and immersed in a pool of boiling liquid. The samples consist of a copper base covered with fine meshes made of copper, phosphor bronze, and brass (each sample contains a single layer of a given mesh). A durable attachment of these two elements is obtained during the sintering process. The details of this process were presented in [14]. All the samples had the same aperture (distance between the wires) of 0.50 mm, while the value of the wire diameter was 0.28 mm (presented in [14]) and 0.32 mm (presented in [13]). The experimental database covers in total sixty measurement points, which is now considered for the calculations. The nucleate boiling heat transfer model presented by Rannenberg and Beer [12] was selected for the analysis. The reason behind it is that this model was developed for meshed microstructures (the same type as those analysed in this paper).

The calculations were made with a focus on obtaining the closest possible match between the experimental and theoretical values of heat flux.

Each experimental point refers to a value of heat flux dissipated at a certain temperature difference. In total 60 measurement points were considered (30 points for water boiling and 30 for ethanol boiling). With the use of computer software tools, a procedure was applied to ensure that the difference between the experimental and calculated values of heat flux was kept to the minimum for all the measurement points. In comparison to the original model, the developed modification is based on changing the value of one constant, namely 12719.08, and adding the exponent 0.088 to the thickness of the microstructure. Thus, the modified formula for the pool boiling heat flux dissipated from composites – based on [12] – takes the following form:

$$q = \left(12719.08 \left(T_{sur} - T_{sat}\right) \frac{\lambda_l^{0.13} c_{pl}^{0.59} \lambda_{eff}^{0.28}}{D_h^{0.41} \varepsilon^{0.91} r^{0.59}} \left(\frac{R_{ef}^2 (1-\varepsilon)^2}{d^2} \right)^{0.16} \frac{w}{\delta^{0.088}} \right)^{1/0.41} \tag{1}$$

where the value of hydraulic diameter D_h can be obtained from [12]:

$$D_h = d \frac{\varepsilon}{1-\varepsilon} \tag{2}$$

Effective radius R_{ef} is half of hydraulic diameter D_h. The other elements in (1) and (2) are: λ_l – thermal conductivity of the liquid (in the present study: water and ethanol), λ_{eff} – effective thermal conductivity (which takes into account the thermal conductivity values of the material of the composites: copper, brass, bronze as well as porosity), ε – volumetric porosity, δ – height of the layer, c_{pl} – specific heat of the liquid, r – heat of vaporization.

Figure 1 presents a comparison of the experimental results of composite heat exchanger samples adopted from the papers by the present authors [13, 14], with the calculation results according to the model originally proposed by Rannenberg and Beer [12] – Figure 1a, and according to this model, but modified with two constants – as in Equation 1. The dashed red line in the figures means the line of ideal matching where $q_{calc} = q_{exp}$, while the green lines show the ±100% error band.

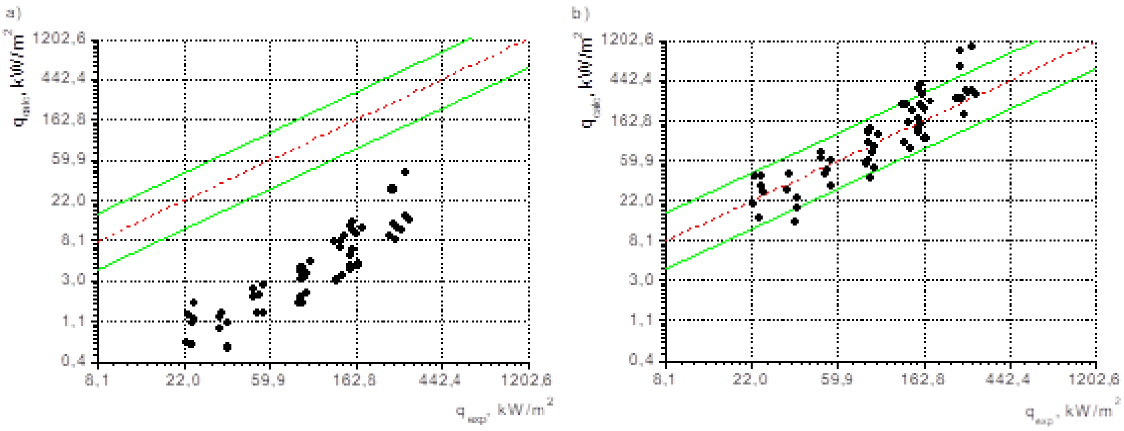

Fig. 1. Comparison of experimental data of boiling heat flux (qexp) dissipated from composite heat exchangers (adopted from [13, 14]) with calculation results of heat flux (qcalc) determined according to original model [12] – (a), and according to model in [12] modified in accordance Equation 1 – (b). Dashed red line represents ideal match of heat flux values (qcalc = qexp), green lines show ±100% error band.

The application of the original model (Fig. 1a) quite significantly underestimated the values of heat flux in comparison to the experimental results (even by about one order of magnitude). It might result from the fact that in [12] different boiling liquids were utilised (namely, refrigerants no longer employed in modern refrigeration systems). A modified model (Fig. 1b) provides much better agreement with the experimental data. Almost all the measurement points are situated within or close to the ±100% error band. Now, it might be vital to verify if modified Equation 1 can be successfully used to predict the heat flux values of other composite heat exchangers tested with distilled water and ethyl alcohol as boiling agents. Figure 2 presents the comparison of the experimental results provided by Białek et al. [11] of the distilled water and ethyl alcohol boiling heat transfer on bronze microstructures covering a copper base. The wire diameter of the mesh was 0.25 mm, while its aperture was 0.40 mm.

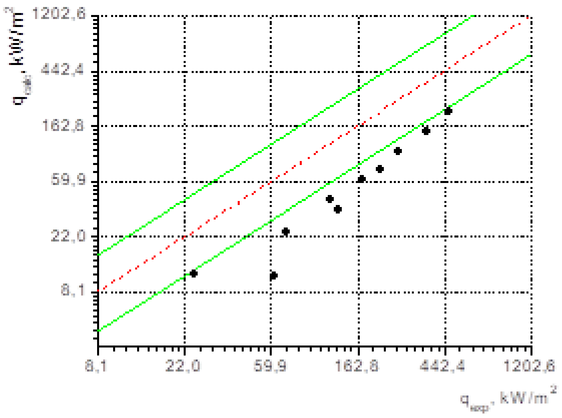

Fig. 2. Comparison of experimental data of boiling heat flux (qexp) dissipated from composite heat exchangers (adopted from [11]) with calculation results of heat flux (qcalc) determined according to model in [12] modified in accordance with Equation 1. Dashed red line represents ideal match of heat flux values (qcalc = qexp), green lines show ±100% error band.

The results demonstrate that the modified model provided moderate agreement with the experimental data. Although none of the measurement points was located in the error band of ±100%, they were situated relatively close to it and they group along a straight line with the rising heat flux. The discrepancy here could be related to different experimental conditions.

The modification of the model presented above was developed for metal wire meshes. Nevertheless, such a microstructure can be reinforced with fine fibers of a different material. In [15], composite heat exchangers made of bronze meshes of an 0.20 mm wire diameter and apertures of 0.40 mm and 0.63 mm, on which fine copper fibers 50 um in diameter and a length of ca. 1 mm were applied. A verification of Equation 1 was conducted for such a composite structure. In order to conduct the calculations according to Equation 1, which was developed for meshes only, the presence of fibers was not considered at all (denoted as “1” in the figure) and accounted for with a reduced value of porosity (denoted as “2” in the figure).

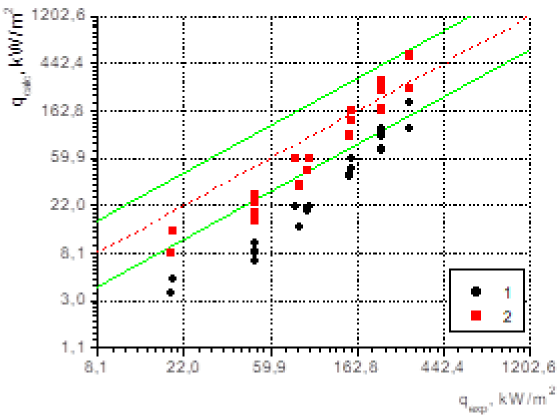

Fig. 3. Comparison of experimental data of boiling heat flux (qexp) dissipated from “mesh+fibres” composite heat exchangers (adopted from [15]) with calculation results of heat flux (qcalc) determined according to model in [12] modified in accordance with Equation 1; where: 1 – presence of fibers in sample was not considered, 2 –presence of fibers in sample was considered with reduced porosity. Dashed red line represents ideal match of heat flux values (qcalc = qexp), green lines show ±100% error band.

A simplification of not considering the presence of copper fibers properly might be behind the discrepancies of the results denoted as “1”. The model was not developed for such a microstructure (consisting of both mesh and fibers) and should be modified accordingly to account for the additional conduction heat transfer within the fibrous structure. Nonetheless, even one modification of the calculation procedure, namely with a smaller value of porosity caused by the presence of fibers (denoted as “2” in the figure), led to considerably higher accuracy. Naturally, a more complex composite structure was created as a result of incorporating fine fibers into the mesh layer and, thus the mechanism of heat transfer within such a microstructure should be more carefully studied. However, the calculation results provided in Figures 2 and 3 indicate that the modification of the model seems to be quite successful in determining the heat flux dissipated from composite heat exchangers during boiling.

MODELLING STRENGTH PROPERTIES OF METALLIC MATRIX COMPOSITE COMPONENTS

The sintering process increased the contact area between the copper substrate and the mesh of various copper alloys, as well as the temperature and time of the process. Diffusional bonding of the contacting particles, because of the pressure difference between the convex and concave pairs of the structure, was caused by the mobility of the absorbed atoms. The self-diffusion coefficient plays a significant role, depending on factors such as the diameter of the junction neck, which depends on the temperature and relates to the distance from the wire diameter to the contact edge. Equally important are the diffusion joints. They were analysed by Chatys and Orzechowski [31] by measuring randomly selected i-th volumes of the investigated microsections of the structures. The result was the measured value of the bridge width of randomly selected connections in order to determine the distribution function. The bridge diameters (i.e. the distribution of connections) were approximated by normal distribution with a mean value of 14.294 μm and a standard deviation of 5.158 μm. In the areas of greatest deformation, i.e. at the fiber contact points where the wire cross-sections are the smallest (convex and concave structure pairs) and the forces are the highest, recrystallization (healing) processes begin. A new crystalline grain arrangement is formed, different from the initial one. New areas with fresh grains and a significant number of previously separated pores are created. The diffusional connections of fibers (wires) are determined by the adhesion value, which was estimated by means of the peel-off method for the fiber structures on different substrates (i.e. structures of intersintered wires and a copper substrate). The highest adhesion values were estimated at the sintering temperature and time of 950°C and 20-25 min, respectively.

Naturally, the properties of the final products and system depend on the properties of the individual elements that they are made of (e.g. [32, 33]). In terms of the analysed composite heat exchangers, material constants such as Young's modulus influence the quality and strength value.

The sintering process is intensified with the increased contact area between the copper base and the mesh (made of brass, bronze) and with rising temperature and sintering time [13]. The highest adhesion values of the porous structures (considered as a system of the copper base and the mesh) are recorded for the bronze mesh.

The modelling of the strength properties was based on the assumption that the components are perfectly bonded during sintering and the stresses act uniformly across the entire sample surface. Consequently, the concept of weighted average strength can be utilised, taking into account the volume fraction of the individual layers in the metal matrix composite. The composite can be treated as a series of layers where the strength of the entire system is limited by the weakest layer (in our case, the mesh). Then the composite strength can be calculated as:

$$\sigma_c = \sum_i \frac{\sigma_i V_i}{V_i} \tag{3}$$

where: σ_i – strength of the i-th layer, V_i – volume fraction of the i-th layer in the entire sample.

The same equation applies to Young's modulus. The analysis can take into account the local stress coefficient at the wire contact points or apply FEM analysis for the entire microstructure of the mesh and capillary layer.

The estimation of the strength properties of the analysed system, consisting of a copper base (2 mm in height) and a mesh layer (of the maximal height of about 0.6 mm, which consists of overlapping wires of diameter 0.28–0.32 mm), was based of the following values of Young's modulus: about 120 GPa for copper, about 110 GPa for bronze and about 100 GPa for brass. The following strength values were used for the same materials: 69 MPa, 32 MPa, 27 MPa, respectively. The volume fraction of the mesh was calculated based on the geometry of the samples and amounts to 0.08, while for the solid copper base it is 0.92. Thus, the effective values of Young's modulus and the strength of the analysed specimens can be estimated (Table 1).

TABLE 1. **Effective values of Young's modulus and strength of composite samples**

Sample composition	Young modulus, GPa	Strength, MPa
copper – bronze	119.2	66.04
copper – brass	118.4	65.64

After reaching the maximum load (cohesive strength), the sinter is destroyed. Deformation of the wires (fibers) increases the stress in a given volume, causing failure first in the weakest wire (fiber), and then at the porous structure (fibers, mesh) – substrate interface. This is a consequence of the combined action of forces applied within the component structures (wire, fiber, base), meaning that both the fiber, mesh, and base are subject to equal stress, in accordance with Hooke's law.

The bond value, in the form of the bridge (connection) width as the critical length of the sintered mesh component (wire) with the substrate, particularly brass or bronze, depends on the shear stresses, which are lower than for copper alone and can transfer the lower stresses to adjacent components of this structure.

CONCLUSIONS

The application of composite heat exchangers can be highly advantageous in terms of improving heat transfer conditions. The modification of a boiling heat transfer model (selected from literature based on the similarity of the microstructural material) conducted with the use of 60 measurement points proved to be quite successful, even for a different type of surface microgeometry (composed of a mesh reinforced with fine fibers).

With regard to the samples composed of a copper base and copper/brass/bronze meshes, the original model underestimated the heat flux values – even by about an order of magnitude. The application of the modified formula led to almost all the measurement points being situated within or close to the ±100% error band. The modification included the introduction of one constant and the modification of another one.

The estimation of the strength properties provided the Young's modulus values of the composite made with a copper base and copper/bronze/brass mesh. They all proved to be smaller in comparison to the system composed of pure copper nevertheless, different engineering applications could require different materials. Thus, such an estimation might prove to be of practical importance.

Owing to the significant advantages provided by composite heat exchangers during boiling, future studies could be focused on the application of other boiling agents commonly used in the refrigeration industry. Additionally, different mesh materials (for example stainless steel) might be considered for sample preparation.

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Data Availability Statement

The data that support the findings of this study are openly available in [Zenodo] at https://doi.org/10.5281/zenodo.21019264 [34].

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