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Composite Heat Exchangers for Boiling Heat Transfer Enhancement

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1. Introduction

Phase – change heat exchangers are commonly used in many industrial applications such as refrigeration systems, electronics cooling, and etc. In terms of boiling, this heat transfer mode is highly efficient in dissipating significant heat fluxes at small temperature differences. Considerable improvement in the value of heat fluxes can be achieved by the application of heat enhancing microstructures on heat exchangers such as metal wire meshes and metal – fibrous structures. These porous structures will be considered in the present paper.

Metal wire meshes can be successfully used for the production of high performance phase – change heat exchangers. In (Liu et al. 2001) tests of boiling heat transfer of methanol and HFE-7100 on a stainless steel mesh coating were described, while in (Brausch & Kew 2002a, Brausch & Kew 2002b, Brausch & Kew 2003) water and R-141b boiling was investigated – also on stainless steel mesh wicks. The coatings consisted of one, three and five layers of mesh. It was reported that the use of a single layer resulted in elevated heat fluxes in comparison to the smooth surface at low superheats. The paper (Franco et al. 2006) presents the research results of boiling heat transfer of R141b on different wire meshes that were made of stainless steel, aluminum, copper and brass. The application of the microstructure of a proper geometry enabled to obtain higher values of the critical heat flux (even 40% higher than for the smooth surface). The work (Li et al. 2006) deals with water boiling on surfaces covered with two to nine mesh layers. All meshed surfaces proved to enhance boiling in comparison with the smooth surface. A similar finding was reported in (Li & Peterson 2006), where test results of water boiling on a copper surface with a copper mesh can be found. In (Wong & Kao 2008) attention was given to heat pipes containing two – layered mesh wick coating. The authors reported that the fine mesh provids more nucleation sites. Also in (Liou et al. 2010) investigations were focused on multi-layer copper meshes sintered to the heat pipe surface with water as the working fluid. The paper (Diao et al. 2014) contains test results of evaporation/boiling on copper mesh of height 0.6-1.0 mm under different pressures. The highest enhancement of heat transfer with the application of the mesh reached about 32%.

Equally advantageous might be the use of porous metal – fibrous coatings. They are produced from metal fibers sintered to surfaces in the reduction atmosphere. In the monograph (Poniewski 2001) extensive test results for water, ethanol and R-113 on surfaces covered with copper fibrous microstructures of fiber diameter 50 μm and length 3 mm were provided. It was stated that the parameters of the porous layer significantly impact heat transfer performance. Other works (Wójcik 2004, Wójcik 2005, Wójcik 2009) focused on experimental investigations of water boiling on a tube covered with a copper – fibrous layer of 40% porosity. A significant enhancement was recorded for the porous microstructures. In (Kalawa et al. 2017) research results of pool boiling of distilled water on heater surfaces covered with coatings produced with stainless steel fibers were given. It was stated that the coating enhanced heat transfer in relation to the smooth surface (heat flux for the superheat of 10K was ca. 3.5 higher than for the smooth surface).

Currently, phase – change processes attract much scientific interest (Pavlenko & Koshlak 2019) including the thermal properties of porous media (Koshlak & Pavlenko 2019). In terms of heat transfer enhancement, literature provides much data on heat exchangers produced from the same material as presented in the above sections. The current paper experimentally analyses and compares composite elements made of two types of microstructures. The first ones consist of the copper base and the single bronze meshes of different aperture (distance between the wires). The second one is made of the copper base with the bronze meshes, on which copper fibers have been sintered. The aim of the paper is the determination of the thermal performance of such composite phase – change heat exchangers.

2. Material and method

The tests have been conducted on samples made of the copper base (a disk of 3 cm diameter), on which porous structures have been applied. The layers consist of a single mesh (Fig. 1) made of bronze.

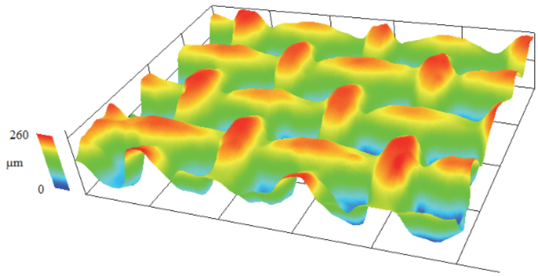

Fig. 1. 3-D image of the example mesh

Two kinds of meshes have been used – both have the wire diameter of 0.20 mm, while their aperture (distance between the wires) amounted to 0.40 and 0.63 mm. The bronze mesh surfaces have been reinforced with fine copper fibers. The diameter of the wires was 50 µm, while their length ca. 1 mm. Thus, samples of the copper base with bronze meshes of 0.40 and 0.63 mm with sintered copper fibers on top have been developed and investigated. All the specimens were sintered in the reduction atmosphere of hydrogen and nitrogen. During this process durable bonds are developed between joined elements.

The tests of boiling heat transfer have been performed on the experimental stand, whose main element has been presented in Figure 2.

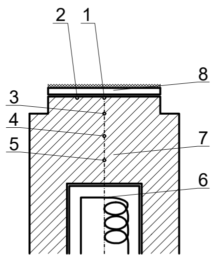

Fig. 2. Main unit of the experimental set-up: 1, 2 – thermocouples under the sample, 3, 4, 5 – thermocouples in the axis of the heating block, 6 – electric cartridge heater, 7 – copper block, 8 – sample with the mesh

The produced specimens in the form of copper discs, on which microstructural coatings have been sintered, were soldered to the copper heating block. An electric resistance heater was located in it to produce heat, which was later conducted to the samples (the block was insulated from the surroundings with high temperature insulation). The power of the heater was increased during the measurements using the autotransformer with given steps to provide a few data points which enabled to draw the boiling curves (which are a visual representation of the thermal performance of each sample).

The boiling curve is a dependence of heat flux vs. superheat (defined as the difference between the surface and saturation temperature of the liquid). The heat flux transferred to the samples was calculated using temperature readings recorded in the axis of the copper heating block (Fig. 2) with the Fourier's law of heat conduction. The temperatures under the sample were also recorded. As a result, the boiling curves could have been drawn. Boiling occurred in the thermally – resistant glass vessel located above the sample on the teflon plate. The generated vapour underwent condensation in the condenser located above it and was returned to the vessel gravitationally so that the liquid level above the sample was kept constant. The liquid temperature in the vessel was measured with a thermocouple. In the tests all thermocouples were of K type.

3. Results and discussion

The experimental analysis has been focused on determining the thermal performance of the designed samples in the nucleate boiling mode of heat transfer. Figure 3 presents the dependence of heat flux vs. superheat for the smooth copper surface and the copper samples with bronze meshes of different aperture of 0.40 mm and 0.63 mm. The meshes had the same wire diameter of 0.20 mm (thus, the same height).

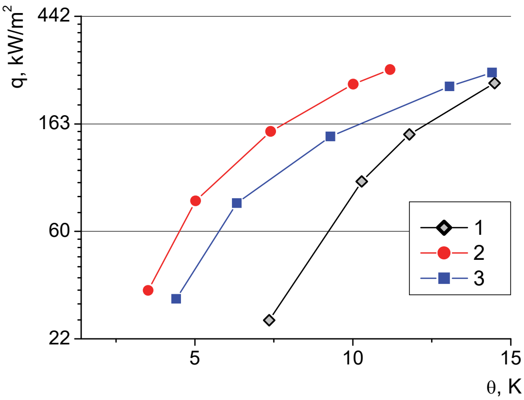

Fig. 3. Boiling curves for distilled water; 1 – smooth copper surface, 2 – bronze mesh of 0.63 mm aperture on the copper base, 3 – bronze mesh of 0.40 mm aperture on the copper base

As can be seen the application of the bronze meshes sintered to the copper base significantly improved heat transfer, leading to elevated heat flux values in comparison to the smooth surface test results. For the same superheat, the heat flux can be much higher than for the surface without any coating. The coarser mesh of larger distance between the wires (aperture of 0.63 mm) proved to be more effective in dissipating heat than the finer mesh of 0.40 mm aperture. It might be related to better removal of the vapour phase. The finer mesh probably hampers vapour and liquid flow in the area of high heat fluxes and the data points come close to the ones obtained for the smooth surface.

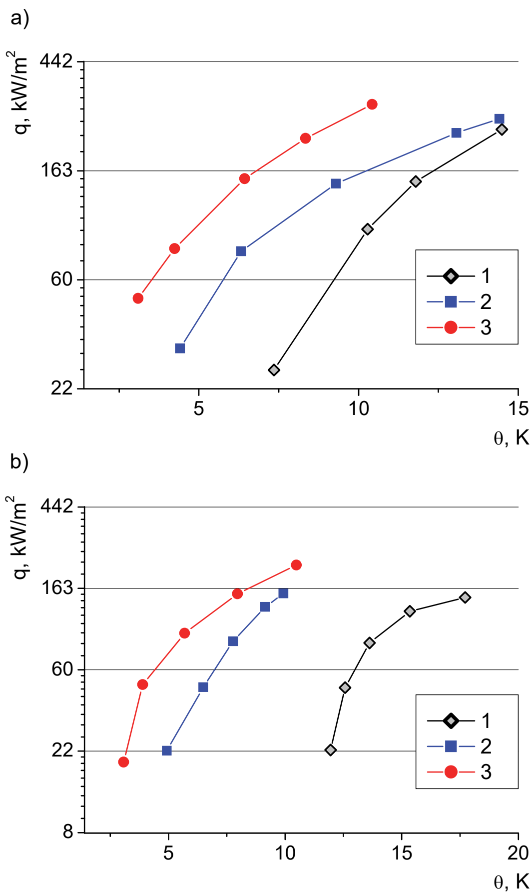

Fig. 4. Boiling curves for distilled water (a) and ethyl alcohol (b); 1 – smooth copper surface, 2 – bronze mesh of 0.40 mm aperture on the copper base, 3 – bronze mesh of 0.40 mm aperture on the copper base with copper fibers on top

Further enhancement of heat flux might be possible if additional passive techniques are used for the production of the heat exchangers. The porous microstructures consisting of the bronze meshes, on which fine copper fibers of 50 μm diameter were applied. A combination of the bronze mesh and copper metal – fibrous structure have proved to be even more efficient as indicated in Figures 4a and 4b for distilled water and ethyl alcohol, respectively.

As indicated in the above figures, the combined effect of the mesh and the fibers provided the most advantageous heat transfer conditions. The heat flux values for both boiling liquids are highest if copper fibers are sintered onto the bronze mesh of 0.40 mm aperture. The same phenomenon can be observed for the mesh of larger aperture as presented in Figures 5a and 5b.

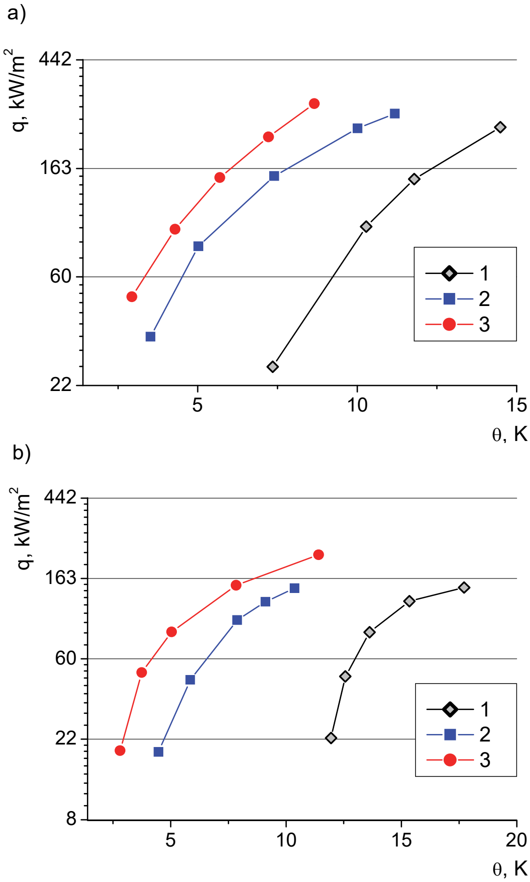

Fig. 5. Boiling curves for distilled water (a) and ethyl alcohol (b); 1 – smooth copper surface, 2 – bronze mesh of 0.63 mm aperture on the copper base, 3 – bronze mesh of 0.63 mm aperture on the copper base with copper fibers on top

The application of porous coatings might considerably increase heat flux transferred from the phase – change heat exchangers. It might be related to the combination of two effects. The first one is linked with the higher density of active nucleation sites (locations were vapour bubbles are grown) on the surface. Additional porous coverings increase the number of such sites and, thus, enhance heat transfer. The other factor might be the extension of the heat exchanger area due to the larger surfaces in the form of meshes and fibers covering the heaters. The nature of this phenomenon might be more visible if the enhancement factor is considered as the function of the superheat. It has been presented in Figure 6 (based on the heat flux data from Fig. 4a) as the enhancement ratio (ER). It is defined as the ratio of the heat flux transferred from the meshed surface of aperture 0.40 mm to the heat flux from the smooth surface (1), the ratio of the heat flux transferred from the surface with the mesh of aperture 0.40 mm and the fibers to the heat flux from the smooth surface (2) and the ratio of the heat flux transferred from the surface with the mesh and the fibers to the heat flux from the surface with the mesh only (3).

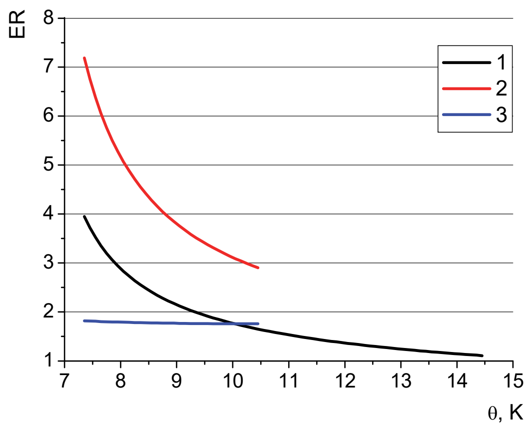

Fig. 6. Enhancement radio (ER) for distilled water – explanation of (1), (2), (3) in the text

The enhancement of heat transfer caused by the application of the porous microstructures resulted in heat fluxes over seven times higher – in the case of the bronze mesh layer covered with copper fibers. This effect diminishes as the superheat rises. It might be related to the fact that more nucleation sites become active on the smooth reference surface while the number of active nucleation sites on the microstructural surfaces is constant. Moreover, is it worth noting that the sample with both mesh and fibers performed much better than the specimen with the mesh only. The ratio of the heat flux transferred from the sample with the mesh and the fibers to the heat flux values of the meshed sample is almost constant (curve no 3 on Figure 6) and equals ca. 1.75. Thus, the additional effect of sintering the fibers, which extend the heat transfer area, is very advantageous. It slightly diminishes with increased superheat. This could be caused by more vapour being generated as temperature rises, which hampers the vapour and liquid flow within the produced porous layer.

4. Conclusions

The application of the investigated composite phase – change heat exchangers significantly enhanced heat transfer in comparison to the smooth surface without any coating. Particularly promising is the combined use of the mesh and the porous layer consisting of fine fibers. Sintering the components of the microstructures to each other and to the copper base reduces the thermal resistance and provides the development of the durable bonds between the jointed elements. It is especially important if the heat exchangers are located in vehicles or machines, which are subject to vibrations. The thermal performance of the tested heat exchangers with the porous layers is highest for small superheats and diminishes with rising heat flux. This phenomenon is also known for other microstructural coatings and should be considered during the design stage of new heat exchangers. Future works in this area need to cover high performance boiling agents such as nanofluids.

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References

Brausch, A. & Kew, P.A. (2002). Examination and visualisation of heat transfer processes during evaporation in capillary porous structures. *Applied Thermal Engineering*, *22*, 815-824.

Brausch, A. & Kew, P.A. (2002). The effect of surface condition on boiling heat transfer from mesh wicks. *Proc. of 12th Int. Heat Transfer Conf., Grenoble, France*, *3*.

Brausch, A. & Kew, P.A. (2003). Heat transfer mechanisms during the nucleate boiling process from woven mesh screen structures: identification of enhancing and limiting effects. *Proc. of 5th Int. Conf. Boiling Heat Transfer, Montego Bay, Jamaica*.

Diao, Y.H., Liu, Y., Zhao, Y.H., Wang, S. (2014). Evaporation/boiling heat transfer performance in a sintered copper mesh structure. *J. of Heat Transfer*, *136*, 1502-1502.

Franco, A., Latrofa, E.M., Yagov V.V. (2006). Heat transfer enhancement in pool boiling of a refrigerant fluid with wire nets structures. *Exp. Thermal and Fluid Science*, *30*, 263-275.

Kalawa, W., Wójcik, T.M., Piasecka, M. (2016). Heat transfer research on enhanced heating surfaces in pool boiling. *Proc. of Int. Conf. Exp. Fluid Mechanics 2016, Mariánskè Lázně, Czech Republic, EPJ Web of Conferences*, *143*, 02048.

Koshlak, H. & Pavlenko A. (2019). Method of formation of thermophysical properties of porous materials. *Rocznik Ochrona Środowisk*a, *21*, 1253-1262.

Li, C., Peterson, G.P., Wang, Y. (2006). Evaporation/boiling in thin capillary wicks (I) – wick thickness effects. *J. of Heat Transfer*, *128*, 1312-1319.

Li, C. & Peterson, G.P. (2006). Evaporation/boiling in thin capillary wicks (II) – effects of volumetric porosity and mesh size. *J. of Heat Transfer*, *128*, 1320-1328.

Liou, J.-H., Chang, C.-W., Chao, C., Wong, S.-C. (2010). Visualization and thermal resistance measurement for the sintered mesh-wick evaporator in operating flat-plate heat pipes. *Int. J. of Heat and Mass Transfer*, *53*, 1498-1506.

Liu, J.W., Lee, D.J., Su, A. (2001). Boiling of methanol and HFE-7100 on heated surface covered with a layer of mesh. *Int. J. of Heat and Mass Transfer*, *44*, 241-246.

Pavlenko, A., & Koshlak, H. (2019). Heat and mass transfer during phase transitions in liquid mixtures. *Rocznik Ochrona Środowiska*, *21*, 234-249.

Poniewski, M.E. (2001). *Wrzenie pęcherzykowe na rozwiniętych mikropowierzchniach*, Kielce, Wydawnictwo Politechniki Świętokrzyskiej.

Wong, S.-C. & Kao, Y.-H. (2008). Visualization and performance measurement of operating mesh-wicked heat pipes. *Int. J. of Heat and Mass Transfer*, *51*, 4249-4259.

Wójcik, T.M. (2004). Boiling on cylindrical surfaces with thick-layered porous covering. *Proc. of X Int. Symp. Heat Transfer and Renewable Sources of Energy, Szczecin – Miedzyzdroje, Poland*, 653-660.

Wójcik, T.M. (2005). Pool boiling heat transfer on horizontal tubes with metal, fibrous porous coverings. *Proc. of 4th Int. Conf. on Transport Phenomena in Multiphase Systems HEAT2005, Gdansk, Poland*, 535-542.

Wójcik, T.M. (2009). Experimental investigations of boiling heat transfer hysteresis on sintered, metal – fibrous, porous structures. *Exp. Thermal and Fluid Science*, *33*, 397-404.

Abstract

The paper deals with the development of high-performance composite heat exchangers made of different metals. The samples made of meshes and fine fibers have been sintered to the copper base in the reduction atmosphere to prevent oxidation. The test of boiling heat transfer performance have been carried out under ambient pressure with distilled water and ethyl alcohol as working agents. The obtained data indicates significant enhancement of heat flux of such composite heat exchangers in comparison to the smooth surface without any coating. The maximum heat flux for the microstructure covered heater has been several times higher than for the smooth surface. The enhancement has been observed to decrease as the temperature difference become higher.

Keywords:
composite heat exchanger, enhancement, porous layers

Kompozytowe wymienniki ciepła do intensyfikacji wrzenia pęcherzykowego

Streszczenie

Artykuł dotyczy badań wysokowydajnych, kompozytowych wymienników ciepła wykonanych z różnych metali. Próbki wykonano poprzez spiekanie w atmosferze redukcyjnej (w celu uniknięcia utlenienia) warstw siatkowych i drobnych włókien metalu z podstawą miedzianą. Badania przeprowadzono pod ciśnieniem atmosferycznym dla dwóch cieczy roboczych tj. wody destylowanej i bezwodnego alkoholu etylowego. Uzyskane wyniki wskazują na znaczące możliwości zwiększenia wymienianych gęstości strumienia ciepła dla wymienników kompozytowych w porównaniu do powierzchni gładkiej bez pokrycia. Maksymalne wartości gęstości strumienia ciepła odbieranego z powierzchni z mikropokryciem nawet kilkakrotnie przewyższały te, odbierane z powierzchni gładkiej. Intensyfikacja wrzenia zmniejszała się jednak w miarę wzrostu przegrzania.

Słowa kluczowe:
kompozytowy wymiennik ciepła, intensyfikacja, warstwy porowate