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# HEAT TRANSFER ENHANCEMENT IN PHASE-CHANGE HEAT EXCHANGERS

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**Abstract.** The paper presents the results of boiling heat transfer enhancement due to the application of additional mesh on the heat exchanger surface. The copper mesh of porosity of 75% was sintered to the copper heater producing strong bonds between the elements. The results indicate a possibility of significant improvement of heat transfer conditions in comparison to the smooth surface. The heat flux was found to be almost six times higher for the same superheat if the mesh structure was applied. Distilled water and ethanol were the working fluids. The investigations were performed under atmospheric pressure.

**Keywords:** boiling, heat exchangers.

## 1. Introduction

Heat exchangers are part of almost every mechanical device. They are used in vehicles, planes and many other kinds of transportation systems. Aviation engineering requires low weight equipment as well as significant efficiency and phase-change heat exchangers offer a possibility to transfer considerable heat fluxes at low temperature differences.

Boiling is an effective mode of heat transfer, which is able to dissipate significant heat fluxes. However, this process can be enhanced even further by the application of specially prepared coatings on heat exchanging surfaces. Many kinds of such coverings might be used. Some improve the conditions of boiling in relation to the smooth surface, while others might produce the opposite effect. Currently, there is no successful model for describing the boiling process on surfaces covered with additional structures.

Enhancement of boiling heat transfer due to the application of metallic powder coating of 30–75% porosity was analysed in (Afgan *et al.* 1985). The authors investigated boiling of water, ethanol and refrigerant 113. The powder was sintered to the surface and created a porous layer of 0.53–2.2 mm thickness. The obtained results indicated that heat transfer was improved for smaller temperature differences in relation to the smooth surface. Another possibility of heat transfer augmentation is the use of wire mesh coatings. The test results of water boiling on a horizontal smooth and rough surface covered with a single stainless steel mesh layer were presented in (Tsay *et al.* 1996). The aperture (distance between the wires) and wire diameter were indicated as: 1.2875 mm/0.3 mm, 0.5083 mm/0.55 mm and 0.338 mm/0.17 mm. It was found that the application of a single mesh layer resulted in enhanced heat transfer in comparison with the smooth reference surface at temperature differences above 6 °C. The experimental tests of refrigerant R141b boiling conduced on the heating surface covered with copper, aluminium, brass and stainless steel mesh structures, analysed in (Franco *et al.* 2006), showed that mesh layers of small aperture enhance heat transfer in comparison with the smooth surface for low heat fluxes. According to the authors, heat transfer performance is influenced by structure thickness (number of layers). On one hand it increases active nucleation site density, on the other hand hydraulic resistance of vapour flow rises. However, according to experimental investigations in (Rannenberg, Beer 1980) on R11 and R113 boiling on surfaces covered with 2–9 layers of mesh, there is no apparent impact of the number of layers on heat transfer. Similar conclusions can be found in (Smirnov, Afanasiev 1982). Recently, an analysis of multi-layer copper meshes sintered to the heat pipe surface was performed with water as the working fluid in (Liou *et al.* 2010).

## 2. Experimental set-up

Heat transfer measurements were conducted on the experimental unit whose main element is a horizontal copper fin located on the side of the vessel (Fig. 1). The fin employed can be without any coating (reffered to as smooth surface) or it can be covered with a porous metallic microstructure. This structure was sintered to the fin at the temperature of ca. 900 °C in the atmosphere of hydrogen and nitrogen to prevent oxidation. The wire three-layer mesh was used in this study. The applied microstructure changes the morphology of the surface and can improve heat transfer conditions. Inside the vessel liquid is boiled under ambient pressure. The fin contacts the liquid from one side (the one with the microstructure) and air from the other – this part is observed with an infrared camera. The heater located on one side of the sample enables the fin to warm up to temperatures over saturation temperature. Due to the fact that heat is provided from one side of the fin, a temperature gradient is created along the fin. The temperature distribution is measured by a long – wave (8–14 μm) thermovision camera equipped with a detector of 384×288 pixels of thermal resolution of 0,08 K and located at about 40 cm from the experimental set-up. The condenser serves as the cooling equipment in order to condense the liquid and return it to the pool. The thermocouple, type K, measures temperature of the liquid.

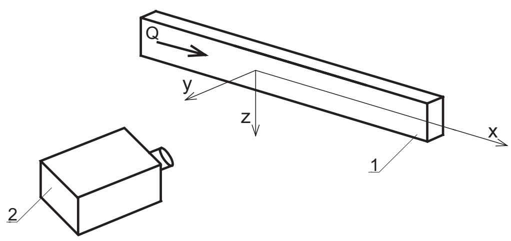


**Fig. 1.** Schematic picture of the measurement unit: 1 – copper fin; 2 – infrared camera

The application of the thermovision camera enables to determine the temperature distribution along the fin and, after performing adequate calculations (numerical differentiation and data fitting), draw boiling curves according to the method presented in (Orzechowski 2003). In this methodology boiling heat transfer is assumed to depend exponentially on superheat (which is defined as a difference between the wall temperature of the heater and the saturation temperature of the liquid):

$$\alpha = a\,\theta^{n}\,. \qquad (1)$$

The experimental determination of constants *a* and *n* leads to the formula for the boiling curve. According to the methodology (Orzechowski 2003) the equation for superheat gradient along the fin in logarithmic coordinates takes the form of:

$$\ln\left(\frac{d\theta}{dx}\right)^{2} = \ln\left(\frac{2m^{2}}{n+2}\right) + (n+2)\ln\theta\,. \qquad (2)$$

Here $n \neq 2$ and $m^2$ is defined as the ratio:

$$m^{2} = \frac{a\,P}{\lambda F}, \qquad (3)$$

where P and F indicate the circumference and surface area of the analysed fin, respectively, while $\lambda$ is the thermal conductivity of its material.

The obtained temperature distribution along the fin (after numerical differentiation) enables determination of constants *a* and *n* from fitting of the experimental data. Consequently, the boiling curve can be drawn as a function of local values of the heat transfer coefficient (or heat flux) and wall superheat from equation (1). In order to more precisely determine heat transfer coefficients in cases when the dependence is not linear, the measurement results can be analysed with a modified method, assuming the non-linear dependence of the heat transfer coefficient, as presented in (Orzechowski 2007):

$$\alpha = a_1 + a_2\theta + a_3\theta^{2} + a_4\theta^{3} + \ldots\,. \qquad (4)$$

## 3. Test results and discussion

The tests have been carried out on copper wire mesh coating of 75% porosity and thickness of 0.75 mm. Three mesh layers were used to produce this structure. They were sintered to each other and to the copper fin. The applied technology ensures that strong bonds between the joined elements are created. In this way contact resistance is eliminated. The coating is on the fin's surface. The measurements of this fin are: 4 mm thickness, 12 mm height and 90 mm length. The tests have been performed for distilled water and ethanol chosen as boiling liquids at atmospheric pressure. The smooth surface of the fin has been used for reference. The details of the measurement technique, testing errors as well as results have been presented in (Orman 2008).

At the beginning of the tests, temperature distribution along the fins with the use of the thermovision camera was recorded. Figure 2 presents the temperatures for three different levels ($W_1$, $W_2$ and $W_3$) of electric power supplied to the heater with the same wire mesh coating.

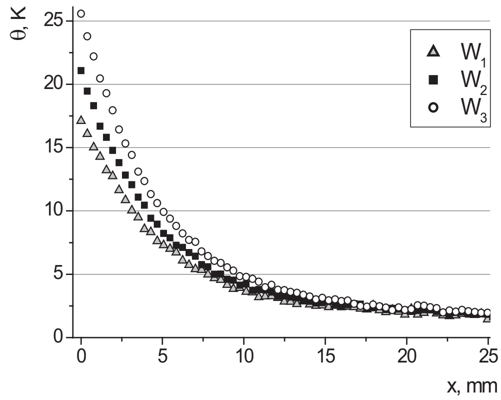


**Fig. 2.** Temperature distribution along the fin for three power levels (W) supplied to the heater during boiling of distilled water

Boiling is highly effective in dissipating heat and temperature drops and approaches the saturation temperature within a small distance from the fin's base.

Based on the numerical differentiation of the results from figure 2, it is possible to produce a dependence of temperature gradient as a function of superheat from three levels of power supplied to the heater. The results are illustrated in figure 3.

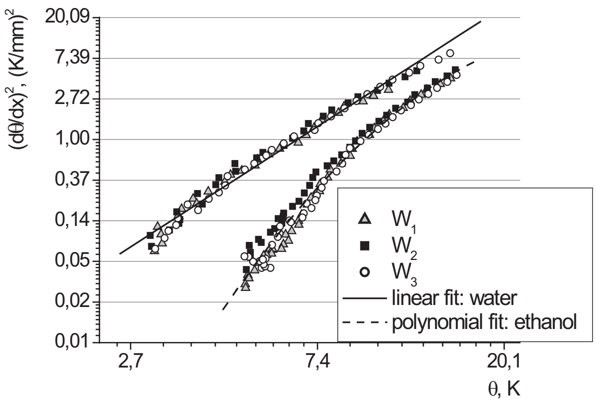


**Fig. 3.** Superheat gradient vs. superheat for three power levels (W) supplied to the heater; data for distilled water and ethanol

The fitting procedure (either linear or polynomial) enables to obtain the constants, which are necessary to draw boiling curves (Eqs 1 and 4). They could be presented in the form of dependency of heat transfer coefficient or heat flux, as presented in figure 4. Therefore, the results obtained for the meshed surface can be compared with the data for the smooth surface, taken from (Orman, Orzechowski 2009).

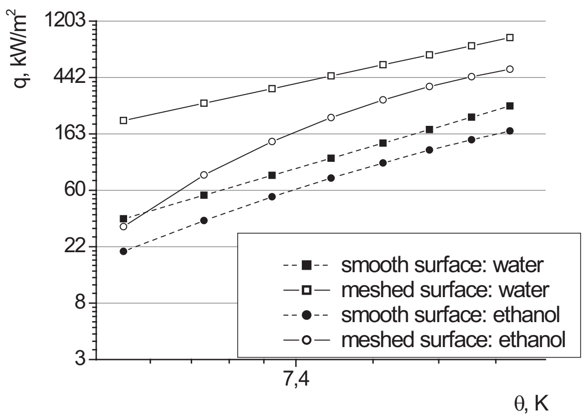


**Fig. 4.** Boiling curves for smooth and meshed surfaces. Data for the smooth surface as in Ł. J. Orman and T. Orzechowski (2009)

The results indicate that the application of the mesh microstructure enhances boiling heat transfer in comparison to the smooth surface (dashed lines in Fig. 4). It makes it possible to produce heat exchangers with a smaller surface area (and consequently lighter). The heat flux values proved to be a few times higher for the same superheat. The details of the improvement of the heat flux are presented in the table.

**Table.** Ratio of the heat flux for the surface with the mesh layer ($q_m$) and the smooth surface ($q_s$) – data from figure 4

| Superheat [K] | $q_m/q_s$ | |
|---|---|---|
| | distilled water | ethanol |
| 5 | 5.7 | 1.55 |
| 6 | 5.11 | 2.24 |
| 7 | 4.66 | 2.67 |
| 8 | 4.3 | 2,92 |
| 9 | 4.01 | 3.06 |
| 10 | 3.76 | 3.08 |
| 11 | 3.55 | 3.07 |
| 12 | 3.37 | 2.98 |

The highest improvement was recorded for water. In this case heat flux can be almost six times higher if the mesh layer is applied. For water there was less improvement with rising superheat, while for ethanol the opposite effect was observed. This might be related to different surface tension characteristics of both fluids.

## 4. Conclusions

The application of mesh structures in heat exchangers that work under boiling mode may result in considerable improvement of heat transfer rate. If such more efficient and smaller exchangers are used in vehicles, less fuel consumption might be anticipated. They would require less space and transfer much higher heat fluxes. Here, apart from heat transfer data mechanical properties should be considered since such exchangers can work in unfavourable conditions (be subject to vibrations, etc.). However, this issue should be investigated by a different study.

## References

Afgan, N. H.; Jovic, L. A.; Kovalev, S. A., *et al.* 1985. Boiling heat transfer from surfaces with porous layers, *International Journal of Heat Mass Transfer* 28(2): 415–422. http://dx.doi.org/10.1016/0017-9310(85)90074-2

Franco, A.; Latrofa, E. M.; Yagov, V. V. 2006. Heat transfer enhancement in pool boiling of a refrigerant fluid with wire nets structures, *Experimental Thermal and Fluid Science* 30(3): 263–275. http://dx.doi.org/10.1016/j.expthermflusci.2005.07.002

Liou, J.-H.; Chang, C.-W.; Chao, C., *et al.* 2010. Visualization and thermal resistance measurement for the sintered mesh – wick evaporator in operating flat – plate heat pipes, *International Journal of Heat and Mass Transfer* 53(7–8): 1498–1506. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2009.11.046

Orman, Ł. J. 2008. *Wymiana Ciepła Przy Wrzeniu na Nieizoetrmicznych Powierzchniach Wymiennikowych z Pokryciem Siatkowym*: Praca doktorska. Kielce: Kielce University of Technology (in Polish).

Orman, Ł. J.; Orzechowski, T. 2009. Analysis of boiling heat transfer on the non-isothermal surface covered with selected wire mesh structures, in *7th World Conference on Experimental Heat Transfer ExHFT-7*, June 28 – July 03, 2009, Krakow, Poland, 2159–2166.

Orzechowski, T. 2003. *Wymiana Ciepła przy Wrzeniu na Żebrach z Mikropowierzchnią Strukturalną* [Heat Exchange at this Boiling Ribs from the Structural Interfaces]. Kielce: Wydawnictwo Politechniki Świętokrzyskiej (in Polish).

Orzechowski, T. 2007. Local values of heat transfer coefficient determination on fin's surface, *Experimental Thermal and Fluid Science* 31(8): 947–955. http://dx.doi.org/10.1016/j.expthermflusci.2006.10.005

Rannenberg, M.; Beer, H. 1980. Heat transfer by evaporation in capillary porous wire mesh structures, *Letters in Heat and Mass Transfer* 7(6): 425–436. http://dx.doi.org/10.1016/0094-4548(80)90019-3

Smirnov, G. F.; Afanasiev, B. A. 1982. Investigation of vaporisation in screen wick – capillary structures, in *Proc. VI Int. Heat Pipe Conf. "Advances in Heat Pipe Technology"*, 7–10 September, 1981, London, UK, 405–413.

Tsay, J. Y.; Yan, Y. Y.; Lin, T. F. 1996. Enhancement of pool boiling heat transfer in a horizontal water layer through surface roughness and screen coverage, *Heat and Mass Transfer* 32(1–2): 17–26. http://dx.doi.org/10.1007/s002310050086