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EFFICIENT SURFACES FOR BOILING HEAT TRANSFER ENHANCEMENT

WYDAJNE POWIERZCHNIE WYMIENNIKOWE DLA WYMIANY CIEPŁA PRZY WRZENIU

Abstract

The paper discusses the use of efficient surfaces for heat transfer enhancement during a nucleate boiling heat transfer. Distilled water under ambient pressure was the working fluid in the presented experiment. The application of a brass mesh of 0.63 mm aperture and 0.20 mm wire diameter on the surface of a copper heater led to considerable improvement in the value of heat flux at low temperature differences of a few Kelvin, where the enhancement ratio exceeded 2. Such modified surfaces could be used in the design of more efficient heat exchangers e.g. in refrigeration systems.

Keywords: *boiling heat transfer*, *microstructures*

Streszczenie

Artykuł dotyczy wykorzystania wydajnych powierzchni do intensyfikacji wrzenia. Czynnikiem roboczym w badaniach była woda destylowana. Zastosowanie siatki mosiężnej o prześwicie 0,63 mm i o grubości drutu 0,20 mm na powierzchni wymiennikowej skutkowało znacznym wzrostem gęstości strumienia ciepła w obszarze małych przegrzań, gdzie stopień intensyfikacji wymiany ciepła przekroczył 2. Takie modyfikowane powierzchnie mogą być wykorzystywane do projektowania bardziej wydajnych wymienników ciepła, np. w systemach chłodniczych.

Słowa kluczowe: *wymiana ciepła przy wrzeniu*, *mikropowierzchnie*

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1. Introduction

Boiling mode is a phase-change process which is characterised by significant heat flux values being exchanged at relatively low temperature differences. Such heat exchangers are commonly used for example in refrigeration or electronics. Smooth heat exchangers can be covered with additional structures and the morphology of the heater surface itself can also be changed by means of various techniques e.g. through roughening or machining. Different kinds of microstructures can also be applied on heaters in order to enhance boiling. Such enhancement means elevating the exchanged heat fluxes in a device at the same temperature difference or enabling the same heat flux to be dissipated at a lower temperature difference.

One common kind of structures used for boiling augmentation are metal meshes. They are cheap to produce and easy to attach to heaters with different methods. Asakavičjus et al. [1] considered boiling of R-113, ethanol and water inside a heat pipe with an internal coating of up to 12 mesh layers. It was given that mesh layers enhance boiling heat transfer in comparison to the smooth surface and boiling on microstructures proved to occur at much lower heat fluxes. Vasil'yev [2] experimentally analysed water boiling on a horizontal heater with a single stainless steel mesh layer. The wire diameters of the meshes were 0.055 mm, 0.09 mm, 0.15 mm and 0.26 mm, while aperture (distance between the wires): 0.08 mm, 0.14 mm, 0.40 mm and 0.73 mm, respectively. It was reported that the heat transfer coefficient increased as the aperture value became smaller. The most significant augmentation was observed for the mesh of 0.055 wire diameter and aperture 0.08 mm. The investigations performed by Li et al. [3] concentrated on water boiling under ambient pressure on a copper heater covered with meshes. The wire diameter was 0.056 mm, while the number of layers was up to 9, producing a structure of the height up to 0.82 mm and porosity 0.693–0.737. All of the meshed surfaces improved boiling in comparison with the smooth surface. Li and Peterson [4] were experimentally analysing water boiling under ambient pressure on a horizontal copper surface with a copper mesh coating. The authors found out that the application of such meshes enhanced boiling heat transfer in comparison with the smooth surface. The meshes had a wire diameter of $d = 56$ μm and aperture (distance between the wires) $a = 119.3$ μm, $d = 114$ μm and $a = 139.7$ μm as well as $d = 191$ μm and $a = 232.8$ μm. The observations revealed that for smaller apertures higher heat flux values could be dissipated from the surface. In order to determine the impact of volumetric porosity, samples of 6 mesh layers were produced and compacted to various porosity values. Only a low influence of porosity was detected. Other kinds of structures can be applied on heaters in order to enhance boiling heat transfer. Danilova et al. [5] analysed boiling of R-22 and R-717 on steel tubes with aluminum porous coating made with the flame spraying technique. Heat transfer coefficient of the porous covering was observed to be 2 to 5 times higher in comparison to the smooth surface. The paper by Cieśliński [6] experimentally considers water boiling heat transfer on horizontal heaters produced with copper with electrochemically deposited microstructures. The height of such aluminum, copper and silver coverings was 0.3–1.1 mm. It was reported by the author that the heat transfer coefficient value of the copper layer was the highest – about four times larger than the one noted for the smooth surface. Yang et al. [7] experimentally analysed boiling of water on foams of the height

1 mm, 2 mm, 3 mm, 4 mm and 5 mm. Heat transfer coefficients of foam layers were reported to be two to three times higher than those of the smooth surface.

2. Material and method

There are many types of microstructures, however mesh layers seem to be very efficient as given in the literature and they have been chosen for the analysis. The tests have been performed on the non-isothermal surface of a 3 mm thick fin with a brass mesh of 0.63 mm aperture and 0.20 mm wire diameter. Such a mesh is a commercially available product applied, for example, for filtering purposes. Sintering at the temperature of ca. 900°C was used to produce durable bonds between the copper fin (base) and the attached brass mesh. This process occurred in the oxygen-free atmosphere (with nitrogen and hydrogen) so that oxidation of the elements could be avoided.

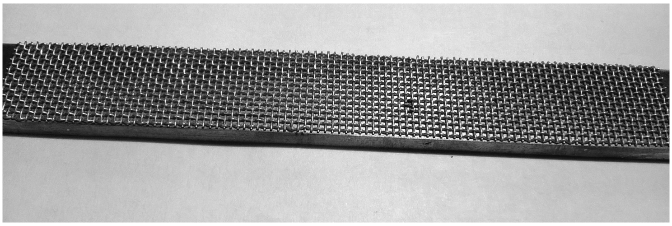

Fig. 1. Photo of the sample – copper base with the brass mesh

Figure 1 presents a photograph of the sample. The fin is placed and sealed in the vessel with boiling water. Its surface open to the atmosphere is observed with a thermovision camera system to determine the temperature gradient along it with heating power being regulated by means of an autotransformer. The inner surface is in contact with distilled water that is boiled in the vessel. Here, the methodology presented by Orzechowski [8] has been used. This technique is based on the assumption of exponential dependence of the heat transfer coefficient on the difference between the surface and saturation temperatures – called superheat (θ). As a result of the application of numerical differentiation procedure of the obtained temperature distribution along the length of the investigated element, it is possible to determine the local values of the heat transfer coefficient (and, consequently, heat flux) through the application of the linear fitting of the experimental results.

3. Results and discussion

The experiments have been performed under ambient pressure with distilled water as the boiling fluid. The surface that was observed with the infrared camera was covered with a special black paint in order to reduce possible errors caused by the incorrect value of emissivity and the influence of the surroundings on the measurements. The results of the superheat gradient were used to produce numerically the first derivative values. Then the heat flux was determined. The results of both surfaces are particularly different in the range of small superheat values. However, as the temperature differences become larger (the surface becomes hotter and more bubbles are created), the impact of the additional porous metal layer gets smaller and the obtained results seem to approach those that were recorded for the smooth surface. It is very visible in Fig. 2, where the heat flux (determined using procedure described in [8]) has been presented vs. wall superheat.

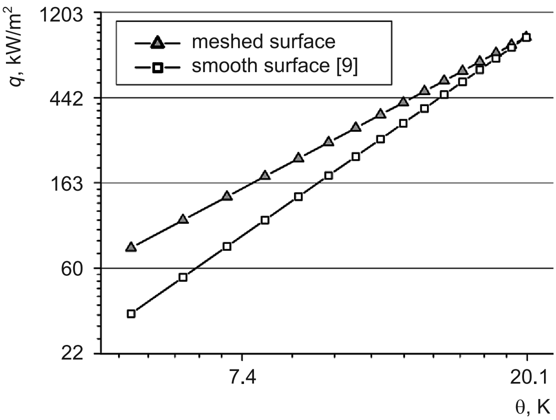

Fig. 2. Heat flux vs. wall superheat

Based on the above figure of changes of the hear flux values as a function of superheat in logarithmic coordinates, it can be stated that the boiling process is enhanced mainly for low temperature differences. This may be attributed to the fact that the mesh microstructure offers additional locations where vapour bubbles can be grown. The overheating of the mesh provides favourable conditions for efficient heat transfer. Here, the contact surface between the extended surface with the mesh and the fluid is much larger than in the case of a technically smooth surface. Nevertheless, a constant growth in temperature leads to the increased vapour production of superheats over 15 K. As a consequence, vapour seems to accumulate within the surface. This phenomenon is more pronounced in the case of the mesh layer, because vapour removal and liquid inflow is hampered due to increased resistance. This might be the prime reason behind worsening of heat transfer conditions for considerable superheat values. If temperature is increased even further, the burn-out of the heater can take place. Very large accumulation of vapour may lead to the occurrence of a permanent vapour blanket on the heater surface that acts as a thermal insulation. Here, a transition to film boiling occurs, which is an unfavourable phenomenon due to lower heat fluxes and large temperatures. Figure 3 summarises the results of heat transfer enhancement due to the application of an additional mesh layer. A steady deterioration of heat dissipation conditions can be easily observed for the analysed type of coating.

It is worth noting that the application of the analysed brass mesh can result in elevated heat fluxes. For the superheat of 5 K ,the enhancement ratio was almost 2.2 as given in Fig. 3. The heat flux dissipated from the meshed surface can, thus, be over twice higher than that from the smooth reference surface without any layers for the same superheat value.

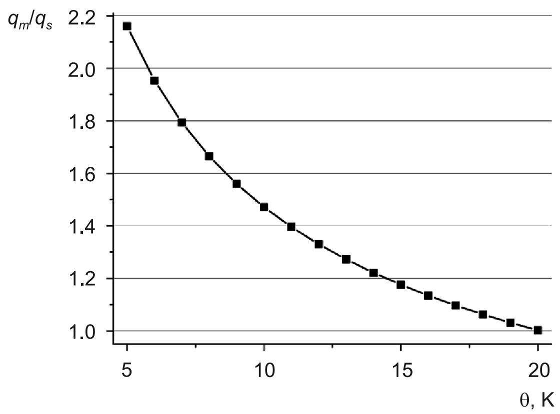

Fig. 3. Ratio of the heat flux for the surface with the meshed layer (q_m) and the smooth surface (q_s) – data from Fig. 2

This indicates better heat transfer conditions and can also be used to produce smaller heat exchangers that are still able to remove the same heat flux.

4. Summary and conclusions

There are many different techniques to enhance boiling. The majority are passive (e.g. application of additional microstructures). Here, metallic coatings seem to be the most favourable – including steel of different types [10, 11]. However, some involve the use of electrostatic field for boiling of dialectic fluids, which could be inferred from [12, 13]. The presented results indicate significant possibilities in heat transfer enhancement with the use of mesh layers. However, microstructures can also be used in flow boiling (as considered in [14, 15]). Generally, they tend to augment boiling in the range of low temperature differences. At higher heat fluxes more vapour is produced and gets accumulated within the additional coating, which hampers heat and mass transfer conditions.

Further work of the authors can be directed to search for new types of coatings – including those that are produced as a combination of a microstructure (e.g. meshes) and a modification of the surface with laser or electrospark deposition. This could further enhance boiling heat transfer. What is more, different boiling fluids, such as commercial refrigerants, nanofluids or new cooling agents can be used instead of water.

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References

[1] Asakavičjus I.P., Žukauskas A.A., Gajgalis V.A., Eva V.K., *Teplootdača freona-113, etilovogo spirta i vody v setčatych fitiljach*, Lietuvos TSR Moksly akademijos darbai, B serija, vol. I **104**, 1978, 87-93.

[2] Vasil'yev A.A., *Heat transfer and critical heat flux densities in boiling of water under a vacuum on walls covered with a single layer of mesh*, Heat Transfer Research, vol. **24** (7), 1992, 913-921.

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

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

[5] Danilova G.N., Dyundin V.A., Bosishanskaya A.V., Soloviyov A.G., Vol'nykh Yu.A., Kozyrev A.A., *Effect of surface conditions on boiling heat transfer of refrigerants in shell-and--tube evaporators*, Heat Transfer – Soviet Research, vol. **22** (1), 1990, 56-65.

[6] Cieśliński J.T., *An experimental study of nucleate pool boiling heat transfer from a flat horizontal plate covered with porous coatings*, Archive of Thermodynamics, vol. **12** (1–4), 1991, 69-76.

[7] Yang Y., Ji X., Xu J., *Pool boiling heat transfer on copper foam covers with water as working fluid*, Int. J. of Thermal Sciences, vol. **49**, 2010, 1227-1237.

[8] Orzechowski T., *Wymiana ciepła przy wrzeniu na żebrach z mikropowierzchnią strukturalną*, Wyd. Politechniki Świętokrzyskiej, Kielce 2003 [in Polish].

[9] Orman Ł.J., *Nucleate boiling heat transfer on a smooth surface of a fin*, XII Int. Symp. „Heat Transfer and Renewable Sources of Energy", Międzyzdroje 2008, 363-369.

[10] Ulewicz R., Mazur M., Bokuvka O., *Structure and mechanical properties of fine-grained steels*, Periodica Polytechnica Transportation Engineering, vol. **41**, 2013, 111-115.

[11] Mazur M., Ulewicz R., Novy F., Szataniak P., *The structure and mechanical properties of domex 700 MC steel*, Komunikacie, vol. **15** (4), 2013, 54-57.

[12] Radziszewski L., *The influence of the surface load exerted by a piezoelectric contact sensor on testing results: Part I, The displacement field in the solid*, Archives of Acoustics, vol. **28**, 2003, 71-91.

[13] Radziszewski L., *The influence of the surface load exerted by a piezoelectric contact sensor on testing results: Part II, The electrical transients generated by piezoelectric sensor*, Archives of Acoustics, vol. **28**, 2003, 93-100.

[14] Piasecka M., *An application of enhanced heating surface with mini-reentrant cavities for flow boiling research in minichannels*, Heat and Mass Transfer, vol. **49** (2), 2013, 261-275.

[15] Hożejowska S., Piasecka M., Poniewski M., *Boiling heat transfer in vertical minichannels. Liquid crystal experiments and numerical investigations*, Int. J. of Thermal Sciences, vol. **48** (6), 2009, 1049-1059.