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Boiling heat transfer on porous single layer brass meshes

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Boiling heat transfer on porous single layer brass meshes

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Abstract. Heat transfer enhancement has been a crucial issue in recently developed research. The article presents the possibility of increasing the heat flux values exchanged during boiling of water and ethanol on surfaces with meshes. Single layer brass meshes were tested and the results indicate a considerable potential of such structures to improve boiling heat transfer. The comparison of the experimental data with selected models indicate large differences that might be linked with different experimental conditions and sample treatment methods. Various experimental conditions found in literature concern different pressure values, various angles of heater surface inclination as well as different sources of heat (electrical heaters, laser beam, hot fluid).

1. Introduction

Energy generation (including renewables) is a crucial issue in the modern world. However, another important problem is its proper transfer. In the case of thermal energy, phase - change heat exchangers are often used due to high thermal loads and efficiencies of such systems. Thus, there is a need for the development of novel heat exchangers working in boiling and condensation modes. Boiling is a phase – change process that makes it possible to transfer large heat fluxes from the surface to the boiling liquid. The presence of any cavities and microstructures on the heater surface might lead to elevated heat fluxes. The enhancement of boiling can be significant and it depends on the kind of surface and its morphology.

A researcher Mertz et al [1] investigated the boiling of propane on the outer surface of steel pipes with an outer diameter of 20 mm covered with heat sprayed stainless steel structures. The density of the generated structures ranged from 0.1 to 0.3 mm and the pore size from 4 to 17%. The tests indicated that the heat transfer coefficient of a pipe with a porous coating was 2.5 to 3 time greater than that of a pipe with a plane surface. The biggest heating intensity was provided by a layer with a thickness of 0.2 mm. It has been noticed for the studied samples that the heat transfer coefficient increases with increasing porosity, which may prove the existence of an optimum of this parameter. Both Liang and Yang [2] examined the boiling of pentane on horizontally oriented surfaces made of copper and aluminium substrate with graphite fibres of 8 - 10 μm height and 50% porosity. The researchers state that heat flux density from copper surfaces with graphite fibres and aluminium surfaces with graphite fibres was greater than that of the plain copper and aluminium surfaces by up to more than 8 times. The same enhancement of heat transfer at boiling on graphite-coated material surface was also found by Parker and El-Genk [3]. Ujereh et al [4] examined boiling of FC-72 on silicon and copper surfaces covered with carbon nanotubes. The experts also investigated the result of coating a pretreated copper surface with nanotubes, i.e. with rectangular microcavities of 0.25 mm height and width. For this configuration, a decrease in the critical heat flux density was witnessed.

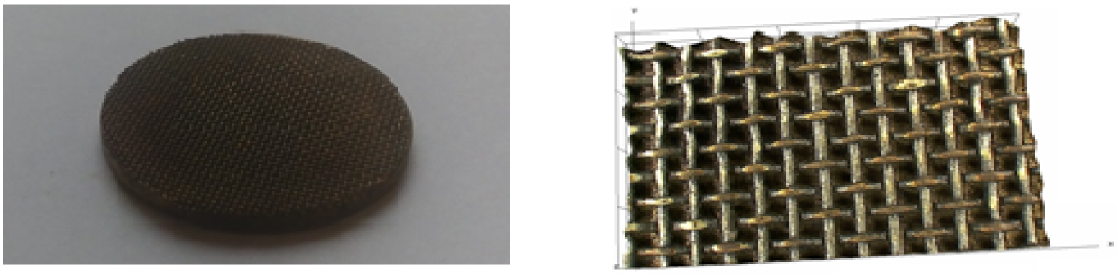
Highly efficient are also fins and microfins. It is generally considered that fins are referred to as having dimensions in the macro scale, while the height of microfins is expressed in the microscale (up to a few milimeters). Kovalew et al. [5] analysed a finned element covered with a glue layer of various thickness. It was stated that the thicker layer led to lower heat fluxes in the nucleate boiling region, but a different phenomenon was observed for higher superheats of over 60 Kelvin.

In addition to the above mentioned boiling intensifying surfaces, mesh structures were also investigated. These are fabricated from small diameter meshes and applied to heating surfaces. The researchers Brausch and Kew [6] explored the heat transfer of distilled water while boiling on mesh wicks made of stainless steel. The sampling had between 1 and 5 such meshes located on one another. They found that a single layer increased the heat flux value compared to a surface without eyelets for small temperature differences. In the work of Franco et al. [7], the R141b refrigerant solution was subjected to pool boiling conditions. The mesh type of material was copper, but also aluminum and brass as well as stainless steel. Structures with small holes improved boiling for small temperatures. The authors confirmed also the favourable effect of the number of layers on heat transfer because of a higher number of active nucleation points. An analysis of the influence of the mesh material was carried out in [8]. The researchers came to the conclusion that the finest parameters can be achieved for meshes with high thermal conductivity. Orman [9] conducted experiments of water and ethanol boiling on horizontal samples made of single layers of meshes from phosphor bronze and commercial copper. The higher and lower microstructures were analysed, while their wire diameter ranged from 0.20 to 0.32 mm. The obtained results indicate a clear influence of the height of the mesh on the heat transfer rate. His later work [10] was focused on the possible impact of the wire mesh aperture for the same boiling agents. It was stated that meshes containing smaller wire apertures exchanged higher heat flux values. The copper mesh test results of the aperture of up to 1.5 mm were presented and compared with the smooth surface data. Also a large augmentation of heat flux over the smooth reference surface was reported. It also needs to be added that meshes and various other kinds of porous coatings can also be very effective in enhancing heat transfer in the flow boiling modes - as shown, among others, by [11-14], and also in pool boiling on ribs [15-19].

The present article focuses on the experimental analysis of boiling on brass meshes sintered on copper discs. Such samples are tested in nucleate boiling mode. The literature data indicate that often researchers obtain different results even for similar types of microstructures. Thus, the findings of this study can lead to the clarification of this phenomenon and the differences reported by various authors regarding boiling on meshes. Additionally, meshes are often tested as attached to heaters by mechanical means (e.g. [6]) rather then sintering without oxygen (as in the present paper), while the impact of proper contact between the mesh and the base seems to be important. The processes occurring within the meshes during boiling are not fully solved and the current paper can provide new information on this issue.

2. Material and method

The tests of boiling were made using the brass meshes of wire diameter 0.10 and 0.25 mm and distance between the neighbouring wires: 0.16 and 0.40 mm, respectively. The specimen production technology was based on the use of a special oven, where specimens consisting of the copper base and brass meshes were placed at the temperature close to the melting temperature (in the atmosphere without oxygen). The brass meshes were composed of copper (65%), nickel (12%) and lead (23%). The thermal conductivity of this material amounted to λ = 138 W/(mK). Figure 1 presents the sample of wire diameter 0.25 mm and distance between the wires of 0.40 mm.



(a) (b)

Figure 1. Copper sample with sintered brass layer: a) photo, b) optical microscopic image of the brass mesh.

The testing was made on the experimental stand, which main element is the cylindrical electric heater within a copper cylinder, on which samples were attached. Above it the vessel with boiling liquid was attached. The generated vapour was condensed in the cooling coil with the cold tap water acting as coolant. The details of this set – up have been presented in [9]. The liquids used in the experiments were distilled water (produced in the university laboratory) and commercial ethyl alcohol. The composition of the latter is 99.8% C_2H_5OH, while the rest are impurities (mostly H_2O). Boiling occurred under ambient pressure and the experimental data points for each sample and boiling liquid were recorded for the rising heat flux (set by an autotransformer). The temperature was measured using K-type thermocouples fitted to a data logger that transferred the obtained data to the computer for further processing. All the thermocouples used within the experimental stand were of K-type. They had the diameter of up to 1 mm. The data logger was set to record the readings at the interval of 1 second. The reading was considered complete when the steady state was reached (the values did not change further after the power was increased). The error of temperature measurement was considered to be 0.2K. The data were recorded simultaneously from all the thermocouples.

The heat flux values were calculated considering the temperature difference between the thermocouples located in the heating block. Because the heat is conducted from the heater to the sample, it is possible to use the Fourier law of conduction and determine the heat flux based on the difference between the thermocouple readings as well as their distance from each other in the heating block (about 1.5 cm) and also taking into account the value of thermal conductivity of copper In this way, the heat flux is calculated for each power value supplied to the heater according to the equation:

$$q = \frac{\lambda_{Cu}}{d_{T_2 - T_1}} \left(T_2 - T_1 \right) \tag{1}$$

where λ_{Cu} represents thermal conductivity of the copper heater, T_1 and T_2 are temperature values within the copper heater at the locations (1) and (2), while d is the distance between the locations (1) and (2) where the thermocouples were installed.

3. Test results

Boiling on meshes might be a very efficient heat exchange process, as discussed in the introduction on the example of various microstructural coatings. The process itself is based on the generation of vapour bubbles within or on the meshes. However, at small heat fluxes supplied to the sample not all the surface is covered with bubbles and they typically grow and depart from the sample sites, as evidenced by the fast camera tests given in figure 2 for the time interval of 0.006 seconds. At higher temperatures the process becomes very intense and the bubbles might join together right at the mesh where they are formed. Thus, large bubbles are created. At the same time, bubbles grow at a larger number of locations on the mesh. This leads to the intensification of the heat exchange process and heat fluxes are bigger.

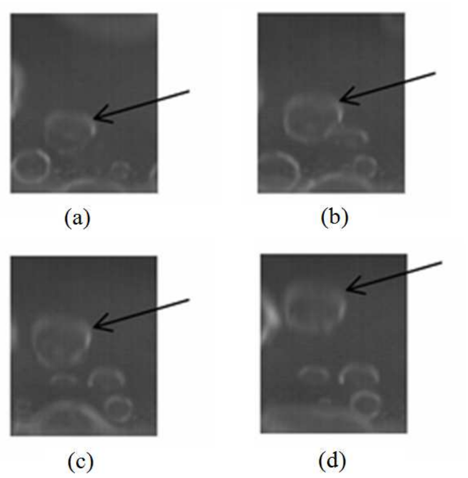


Figure 2. The growth and departure of a bubble from the mesh:
a) t =0, b) t = 0.006 s, c) t = 0.012 s, d) t = 0.018 s.

Vapour bubbles are created at "nucleation sites", which are usually some irregularities on the surface (or sites created artificially such as applying the mesh or microfins). The bubbles are very small at first and grows with time as more liquid is evaporated. At a certain moment, as it becomes large enough and buoyancy is high, it leaves the surface. The diameter of the bubbles largely depends on the boiling liquid properties – in the case of water bubbles are large, while in the case of ethanol – small. Sometimes bubbles can join with the other bubbles. Thus, very large bubbles can be created.

During boiling large heat fluxes are transferred due to two most important reasons that are characteristic of this phenomenon. First of all, it is a process when a change of phase occurs (from the liquid to vapour phase) and the values of heat of evaporation are typically large. Moreover, vapour bubbles that leave the surface create motion and this convection movement intensifies the heat transfer from the surface (higher heat transfer coefficients are observed in this case). The use of meshes offers additional benefits, because they contain many nucleation sites that are not present on the smooth surface in such large numbers.

The tests of boiling were done under atmospheric pressure and during the measurements the level of liquid was constant (2 cm above the samples). The experimental data were recorded for increasing heat flux (at certain steps regulated with an autotransformer). The results of the investigations into thermal performance of each sample have been presented below as the relationship of the heat flux (q) and the temperature difference (ΔT), which is calculated as the surface temperature minus the saturation temperature. The heat flux was determined as the temperature difference multiplied by thermal conductivity of copper and divided by the distance between the thermocouples in the heater block. The error analysis indicated that the largest errors occur for low heat fluxes, while the smallest for the high heat flux values.

Figure 3 presents the experimental data for water, while figure 4 for ethanol. Mesh no 1 is the fine mesh (wire diameter of 0.10 mm and distance between the neighbouring wires 0.16 mm), while mesh no 2 has the wire diameter of 0.25 mm and distance between the wires of 0.40 mm.

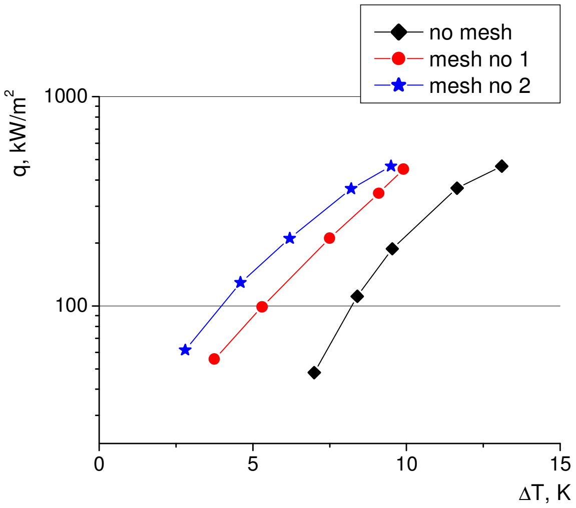


Figure 3. Heat flux vs. temperature difference for water.

As can be seen in both these graphs the application of metal meshes improved the performance of the samples in comparison to the surface without the mesh. At the same temperature difference it is possible to exchange higher heat fluxes (more heat can be dissipated to the liquid), which can lead to better overall efficiency of the heat exchangers. The mesh with larger distance between the wires provided more improvement than the fine mesh – this phenomenon can be more visible in the case of ethanol. The improvement might be caused by a larger heat exchange area for the bigger mesh.

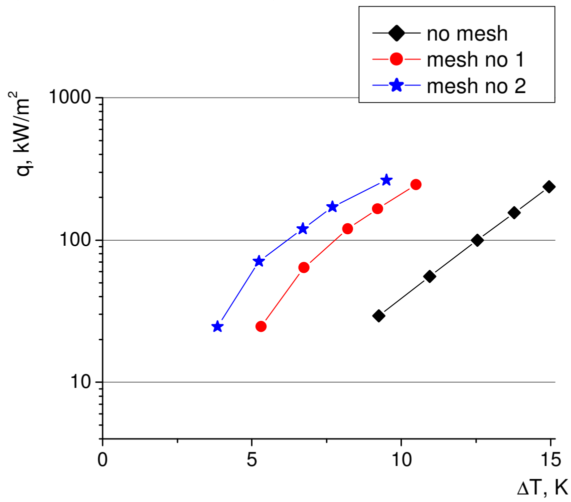


Figure 4. Heat flux vs. temperature difference for ethanol.

The details of the improvement caused by the application of the mesh over the surface without it can be more clearly visible in figure 5, which presents the ratio of heat fluxes dissipated from the mesh of wire diameter 0.25 mm to the heat fluxes from the surface without any mesh. The data have been shown for the same temperature differences.

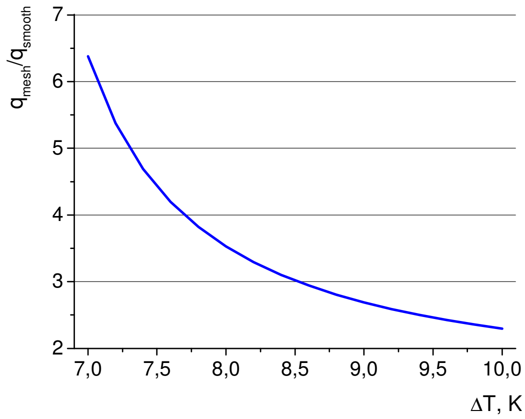


Figure 5. Ratio of heat flux for the surface with the mesh and without it (smooth) - data from figure 4.

The highest improvement with the application of the brass mesh can be seen for the range of low temperature differences (namely below about 8 K). On the other hand at larger values of heat flux the mesh might not be very effective, which might be caused by the phenomenon of vapour generation in the considered porous layer. This might lead to the occurrence of conditions that indicate thermal insulation. Thus, meshes are most efficient for small heat fluxes.

A different but equally important problem that must be considered in the case of mesh heaters is the correct determination of heat flux values as a function of heater parameters (material and geometry of the considered porous coatings). The issue of modelling of the boiling phenomenon is a crucial problem that can be solved with a number of modern data treatment methods (discussed for example in [20, 21]). Figures 6 and 7 present the comparison of the experimental results for the mesh of 0.25 mm wire diameter (as presented earlier in figures 3 and 4) with the calculation results of the models selected from literature, namely: Nishikava et al [22] and Rannenberg and Beer [23] models.

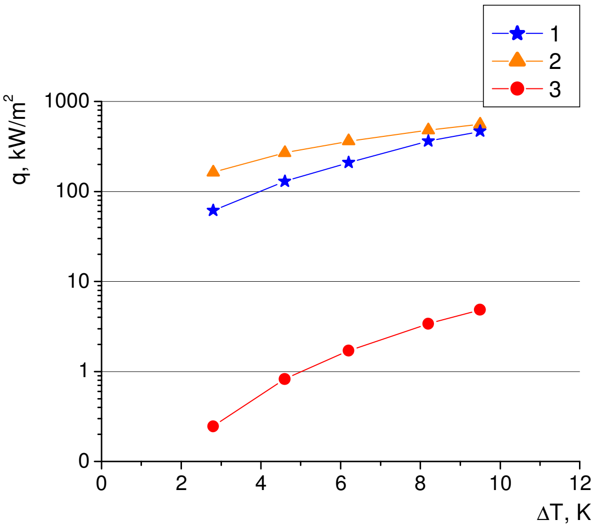


Figure 6. Comparison of the test and calculation results for water (1 – test results, 2 – calculations according to Nishikava et al. [28], 3 - calculations according to Rannenberg and Beer [29]).

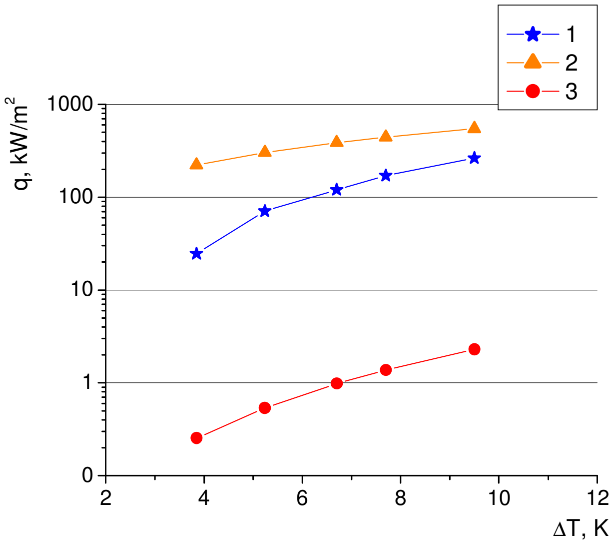


Figure 7. Comparison of the test and calculation results for ethanol (1 – test results, 2 – calculations according to Nishikava et al. [28], 3 - calculations according to Rannenberg and Beer [29]).

As can be seen in the above graphs the results obtained during the present experiment are located between the calculation results for both considered models. None of the models has been very effective for this type of coatings, however the Nishikava et al. model provides quite correct results for water at high temperature differences. A more general model – that might include all kinds of regular geometry structures – might be welcome and could be developed if more experimental data are available for various types of samples. Such models are easier to develop for the surfaces without any coatings, but if the surface morphology is changed, many new factors and parameters are introduced and development of the more general model becomes more difficult. Consequently, in order to create a new, more reliable model of boiling on porous layer a wider experimental base is necessary to be obtained.

A different problem that requires attention is corrosion due to the action of boiling agents on brass. The current experiments have been done on “fresh” samples and the impact of fouling or corrosion on heat transfer has not been studied, but it can unfavorably influence the performance of heat exchangers. Such tests can be done in the future with the view of analyzing the corrosion and fouling processes with the use of SEM image technology.

4. Conclusions

Brass meshes are an effective method of the improvement of boiling heat transfer. They can dissipate more heat than the surface without any mesh – heat fluxes can be even several times larger. In the present study about 6.5 times larger heat fluxes can be exchanged at the same temperature differences if meshes are applied. However, this phenomenon is clearly visible especially for small values of the temperature differences. This might be explained by the extension of heat transfer area and more nucleation sites present on the meshes. It can be concluded that although meshes improve heat transfer, they are not equally effective for all temperature differences, which is a disadvantage and a severe limitation if the favorable conditions prevail only for a few Kelvin range. At high temperatures the differences of thermal performance between the meshes tend to decrease. This can suggest that other mechanisms of heat transfer occur at low and high heat fluxes. The selected models of boiling on porous coatings have proved to be inaccurate for the brass mesh tested in this study, especially in the case of ethanol and for the low ranges of temperature differences. Thus, the physical mechanisms of boiling assumed by the considered models taken from literature might be erroneous. Consequently, a new model would need to be made in the future to provide more accurate solutions for various kinds of porous coatings.

List of abbreviations
Cu – copper
d – distance, m
q – heat flux, kW/m^2
T – temperature, K
λ – thermal conductivity, W/(mK)
ΔT – temperature difference, K

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