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Experimental heat transfer analysis of open cell hollow ligament metal foam at low Reynolds number

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A B S T R A C T

Paper deals with the evaluation of the heat transfer characteristic of metal foam. The novelty of work lies in the use of metal foam with hollow ligaments made by metallic deposition method and evaluation conducted in the conditions of low Reynolds number based on the mean pore diameter. The low flow velocity of the heat transfer medium has been chosen with intent to include the operating conditions of the devices utilizing metal foams in the thus defined conditions such as electronics cooling, low flow rate heat exchangers or solar thermal applications. The evaluation was carried out on two samples of a copper metal foam with a pore density of 10 and 20 PPI (pores per inch) by comparing the Nusselt number at four values of volumetric flow rate of the heat transfer medium (from 1.4×10^{-5} to 3.5×10^{-5} $m^3 \cdot s^{-1}$) and at four values of the used heat flux (from 200 to 575 W) on the authors designed and manufactured measuring apparatus. The resulting Nusselt number comparison showed an approximately double increase for the same Reynolds number in a sample with a pore density of 20 PPI, compared to a sample of 10 PPI. The given correlation of the Nusselt number numerically quantifies the effect of the Reynolds number based on the mean pore diameter on its total value and hence on the overall efficiency of the heat transfer process. Presented results have a considerable application potential, especially due to the small number of published works dealing with research of metal foams of a similar type and conducted with such defined flow conditions.

1. Introduction

Metal foams belong to the group of so-called cellular materials. These materials are formed of cell structure, which may take the form of honeycombs, or three-dimensional array of polyhedral cells formed by the interconnection of the ligaments (fibers), while a substantial part of its bulk volume is occupied by the void volume (filled with air). The unique physical properties of the metal foam allow their use in a wide range of technical applications such as heat exchangers [1], electronics coolers [2], electrodes in lithium-ion batteries [3], shock absorbers [4] or as a fire protection element [5]. In the field of thermal technology are metal foams most often used in the form of heat exchangers, due to its high values of the heat transfer coefficient and the specific surface area (area of interaction between the solid wall and fluids). Currently used technologies can create cellular materials from several materials, such as polymers, ceramics, glasses, composites or metals. The configuration of the properties of the metal foams is dependent on its manufacturing process, which does not affect only the apparent properties as pore diameter, pore density or relative density but also the shape and cross-section of the ligaments forming the cellular structure. In conventional technical applications are mostly used metal foams with full metal ligament cross-section, hollow ligament cross-sections or precursor-filled ligament cross-section.

Metal foams with precursor-filled ligaments are produced using the metallic deposition method, which is widely used, in particular, due to the high uniformity and exceptional porosity of the resulting metal foams. In the desired cases, the precursor may be removed by pyrolysis processes which ensure that the ligament is subsequently filled with air only (see Fig. 1). The hollowness of the ligament varies with the thickness of the metal coating, type of material or thickness of the ligaments of the precursor matrix [6,7]. Metal-filled ligaments are produced in the manufacturing of metal foams by powder metallurgy methods.

The cross-sectional area of the metal foam ligament directly influences the thermal conductivity, heat transfer, and reduces or increases the cross-section of the metal involved in heat exchange [7]. From this point of view, it is important to define the type of metal foam accurately, respectively the type of the ligament already in the initial description of the metal foam in research dealing with its thermal analysis.

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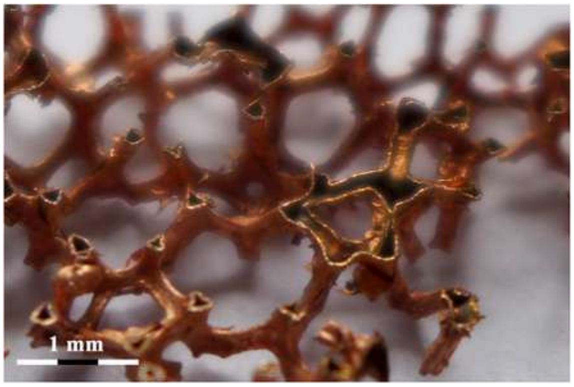

Fig. 1. Detail view of cut-off after machining of the used 10 PPI metal foam with clearly visible hollow ligaments.

Research activities dealing with the properties of metal foams are quite extensive and include, in particular areas related to the thermal, mechanical and flow parameters. Recently, the results of the research on metal foams have been published by a large number of authors who have mainly dealt with heat transfer analysis of metal foams. However, the authors used different measurement procedure, flowing media, experimental apparatuses and samples of foams. Also in some published works, authors not clearly defined manufacturing process of the metal foam specimen or the type of ligament into one of the above category and thus the direct application possibility of this research is partially limited.

Boomsma et al. in [8] published comprehensive research of fluid and energy processes in metal foams. The authors conducted measurements on experimental apparatus, which used as flow medium water, respectively a mixture of ethylene glycol and water. A sample of the metal foam was placed in a channel, and the heat flux was fed from the top of the sample. The authors used four samples of 6101-T6 aluminum alloy metal foams with a porosity of 60, 70, 80 and 90%, which were manufactured by the casting method, which results in metal-filled ligaments of metal foams. The results of the measurements, i.e. the suitability of the use of metal foams as high-efficiency heat exchangers, were presented using a Nusselt number for different flow rates, respectively different Reynolds numbers.

Hsieh et al. in [9] used a similar method in which metal foam samples were placed in a channel and the heat flux was fed to metal foam through a heating tape located at the bottom of the experimental apparatus. The authors have again used metal foam with 10, 20 and 40 PPI, information characterizing its properties is narrowed only to the used base metal, aluminum, the production method as well as the description of the ligament structure absent.

Mancin et al. in [10] experimentally measured the heat transfer coefficient for the seven samples of the aluminum metal foam with 5, 10, 20 and 40 PPI. The sample description lacks the method of manufacture as well as a more detailed specification of the structure of the ligaments (in paper is used figure of metal foams with metal-filled ligaments, but the authors did not state whether the figure is merely illustrative or is a picture of the used sample). As a flow medium was used air, heat flux to metal foam was fed from the base heater plate.

Kamath et al. in [11] dealt with the evaluation of the influence of metal foam thickness on the overall heat transfer coefficient. In the experiment, the authors used a vertical wind tunnel where samples of the copper and aluminum metal foams were axially placed with the heater in the center. As a flow medium was used air. The object of the study was two types of metal foam with 10 and 20 PPI, as in other cases, the authors did not precisely define the structure of the ligaments, which in this case can be seen from the used figure of metal foam specimen and indicate metal-filled ligament.

Zaragoza and Godall in [12] evaluate the thermal properties of metal foams on the proposed experimental apparatus. The structurally simple apparatus consists of three parts, a circular cross-sectional test chamber, through which the heat flow is passed from the electric heater, and two flow straightener chambers located before and behind the test chamber. Experimental measurements were carried out on samples of metal foams with a porosity of 5 and 10 PPI, the paper does not contain a precise description of the structure of ligaments. The properties of the ligaments in view of its cross-section can be obtained only from the picture showing individual samples showing metal-filled ligaments.

Guarino et al. in [13] evaluate pressure loss and heat transfer coefficient on three samples of metal foam with 5, 10 and 20 PPI. The humid air was used as the flow medium. The description of the used samples is narrowed to the base material – Aluminum alloy. Information on the structure of the ligaments cannot be obtained even from the used image of the test sample placed in the measuring apparatus.

Park et al. in [14] investigate the heat exchange efficiency of the heat exchanger constructed of three types of nickel metal foams with a 20, 40 and 80 PPI. The production method is not specified, but the graphical assessment of surface area density shows the hollow ligaments of the used metal foam.

The flow velocity, the properties of the metal foam and the hydrodynamic properties of the heat transfer medium have a fundamental influence on the flow regime, which can be characterized by the value of the Reynolds number. In case of the metal foam flow regime ranges from pre-Darcy, Darcy, Forchheimer to turbulent flow (from low to high value of Reynolds number). Shen et al. in [15] investigated water-cooled microchannel heat sinks with various structured metal foams, where local flows and heat transfer with and without porous foams were clarified. Bağcı et al. in [16] examined hydrodynamic properties in metal foams, working with pre-Darcy to turbulent flow. Arbak et al. in [17] evaluated influence of pore density on thermal development in open-cell metal foam, where authors show effect of Reynolds number on thermal entry length. From above mentioned papers, it is clear that at the high value of the Reynolds number the effects of turbulence on heat exchange properties are decisive.

The presented paper deals with the evaluation of the heat transfer properties of copper metal foam with hollow ligaments by quantification of the Nusselt number value. Experimental evaluation was carried out at low velocities of the heat transfer medium, which was characterized by a low Reynolds number. The low flow velocity of the heat transfer medium has been chosen with intent to include the operating conditions of the devices utilizing metal foams in the thus defined flow conditions. The low flow velocity of the heat transfer medium has been chosen with intent to include the operating conditions of the devices utilizing metal foams in the thus defined flow conditions. For example, the concept of using metal foam within natural convection flow regime for the purposes of electronics cooling was dealt by Bayomy et al. in [18] or Rachedi et al. in [19]. The rapidly developing application possibility of metal foams is the area of the renewable energy sources, where many devices work in the field of natural convection. Saedodin et al. in [20] presented a proposal for the use of metal foam as a thermal absorber of a flat-plate solar collector. Other options for the design of heat exchangers based on metal foams, respectively study of natural convection in metal foam are mentioned for example by Chiappini in [21] or Feng et al. in [22].

Huisseune et al. in [23] with the use of CFD analysis evaluated the heat transfer coefficient of various heat exchangers made of metal foams with using air for heat transfer medium. As the equivalent diameter in the calculation of Reynolds number was used the hydraulic diameter of flow channel where metal foam samples were placed, thus calculated Reynolds number was always less than 2000. Park et al. in [14] in assessing of the thermal properties of the metal foams conducted measurements on apparatus using as a heat transfer medium water whose flow velocity was up to 0.17 m.s^{-1}, which resulted in achieving a relatively low values of Reynolds number (up to 250) which equivalent diameter based on the metal foam permeability and porosity. Hsieh et al. in [9] evaluated the metal foams regarding heat transfer at low Reynolds numbers based on equivalent spherical diameter (regarding to mean pore diameter), where this value ranged from 5 to 35, as a heat transfer medium was used air.

2. Materials and methods

Experimental analysis of the heat exchange process of hollow ligaments metal foam in low Reynolds numbers regime was carried out on two samples of open cell metal foam with a pore density of 10 and 20 PPI made of copper. Each sample had width 100 mm, length 200 mm and thickness 4 mm. Samples from manufacturer were made by the metallic deposition method. According to Kennedy [24] this method uses a polyurethane template, carrying the essential shape and dimension characteristics of the future metal foam. In this process the polyurethane foam template is coated with a powder metal performed by immersion or by spraying. Excess powder metal is removed by squeezing the foam by passing it through rollers. After coating and drying, the polyurethane foam template is removed by thermal degradation, mostly by pyrolysis. Manufacturing process is completed by a re-increasing of the temperature to sinter the metal powder particles and forming a rigid cellular metal structure. The relative density of these samples was determined to 96.5%. All dimensional and geometric characteristics of the samples required for further calculations were determined by using computer tomography on Zeiss METROTOM 1500 with measurement uncertainty (9 + L/50) µm (see Fig. 2).

The average pore diameter d_P for a metal foam with 10 PPI has a value of 2.120 mm, a ligament length of 2.312 mm and a thickness of 0.505 mm. For metal foam with 20 PPI, were these parameters found at 0.858 mm, 1.021 mm and 0.304 mm. From the individual section view cuts of the metal foam specimens were calculated that metal foam with 10 PPI has 92.33% of the void volume, which is open to medium flow, 7.11% takes volume of metal and 0.56% volume of the hollow in ligaments. For metal foam specimen with 20 PPI was these values found at 89.89%, 0.53% and 9.58%. The specific surface area (A_{SF}) was determined for both samples with the use of computer tomography 3D scan (i.e., the interface between the solid material and the flow medium) to 0.08815 m^2 for metal foam with a pore density of 10 PPI and 0.112 m^2 for metal foam with a pore density of 20 PPI.

The basic principle of the experiment was to fed the heat flux to the metal foam structure through the heater body. This heat was then drained by the flowing heat transfer medium (water) in metal foam structure. The heat exchange process for the described metal foam samples was evaluated on the basis of the temperature difference of the heat transfer medium at the inlet and outlet and the temperature of the solid/fluid interface.

The experiment was carried out on the authors designed and constructed measuring apparatus that consisted of a test section and a hydraulic circuit. The test section was designed and constructed in a way that two samples of metal foam (with the same pore density) could be placed axially, separated by a 600 W micathermic resistive heater of our construction. For a more uniform heat distribution from the heater, 0.5 mm thick copper plates were attached to its body. The homogeneity of the supplied heat flow was analyzed by the FLIR T335 thermal camera which did not show a significant reduction in the area of the used micathermic resistive heater. During the described test, the heater's input was controlled so that the heater reached a maximum temperature of 100 °C. The partial reduction occurred only around the periphery of the heater, which can be seen in Fig. 3.

The test section was made by combining peripheral parts made of recycled polypropylene, borosilicate glass forming the top cover and MDF boards (in hydrophobic surface treatment) forming a base and a top casing. In this part of the measurement apparatus were also flow channels and flow straightener whose task were to stabilize the flow of the heat transfer medium from turbulent to the laminar flow regime, which was required for the experiment. The flow straightener was made of brass pipes with small diameter (2 mm). The dimensions, configuration, and location of the each part of the test section are schematically shown in Fig. 4.

During the experiments was whole apparatus thermally insulated with mineral wool blocks to ensure minimal impact on the results due to thermal losses of the measuring apparatus. To simplify processes during the experiment, metal foam samples were placed in the test section without using a heat conducting adhesive or soldering. Absence of adhesives or solder joints degrades heat exchange performance as is mentioned by Guarino et al. in [25] however the top cover pressure provided sufficient contact between the metal foam and the heating element to ensure the desired thermal conductivity as is stated in Kamath et al. in [11]

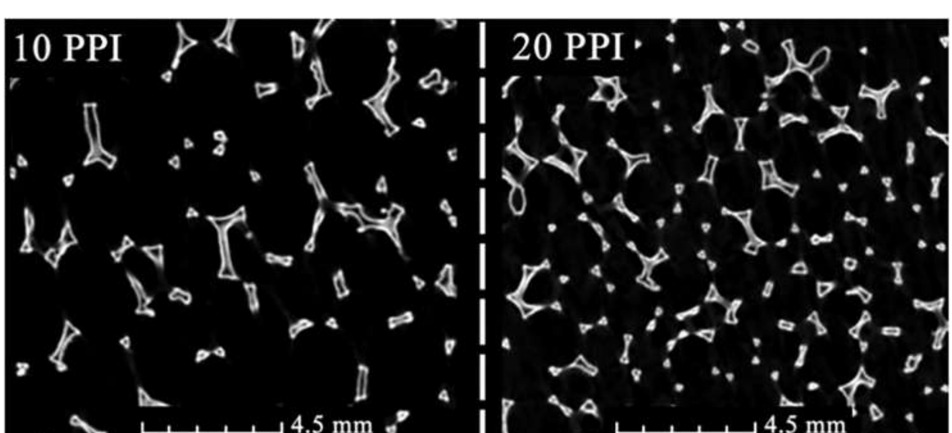

Fig. 2. Scan of used metal foam specimens from computer tomography analysis with visible hollow cross-section ligaments.

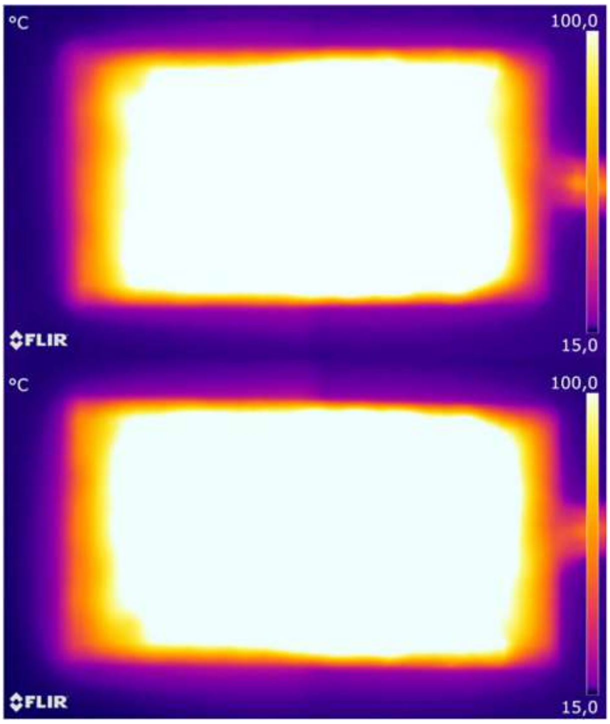

Fig. 3. Thermal image of used micathermic resistive heater from top side (up) and bottom side (down).

or Zaragoza and Godall in [12]. The uniformity of the pressing force within the area as well as within the each measurement repetition was secured by using a torque wrench.

Test section also included thermocouple probes that were placed in the axis of the entire device at the positions shown in Fig. 4, these probes recorded the temperature of the metal/water interface at three locations (for the upper and lower samples) as well as the temperature of the heat transfer medium at the inlet and the outlet of the test section. The probes were introduced into the test section with thin holes, the hydraulic tightness was ensured by using silicone sealant.

The test section was supplemented by the other components of the hydraulic circuit and the measuring instruments as is shown in Fig. 5. The hydraulic circuit consisted of a laboratory constant supply of the heat transfer medium, in this case, water, whose flow rate was adjusted with a control valve and rotameter. The heat transfer medium with the required flow rate and velocity flowed into the test section where its temperature increased due to the heat flux from the micathermic resistive heater and then left the measuring apparatus and was drained to the laboratory waste disposal system. Because of the low flow rates used during measurements, no circulating hydraulic system has been built, what greatly simplifies the used measuring apparatus. The pressure loss of a measuring apparatus with installed block of metal foam with pore density 10 PPI varied according to used volumetric flow rate from 95 to 320 Pa and from 200 to 580 Pa for metal foam with 20 PPI. These relative low values of pressure loss are given especially by the extremely low values of volumetric flow rates of heat transfer medium as well as by the compact dimensions of the measuring

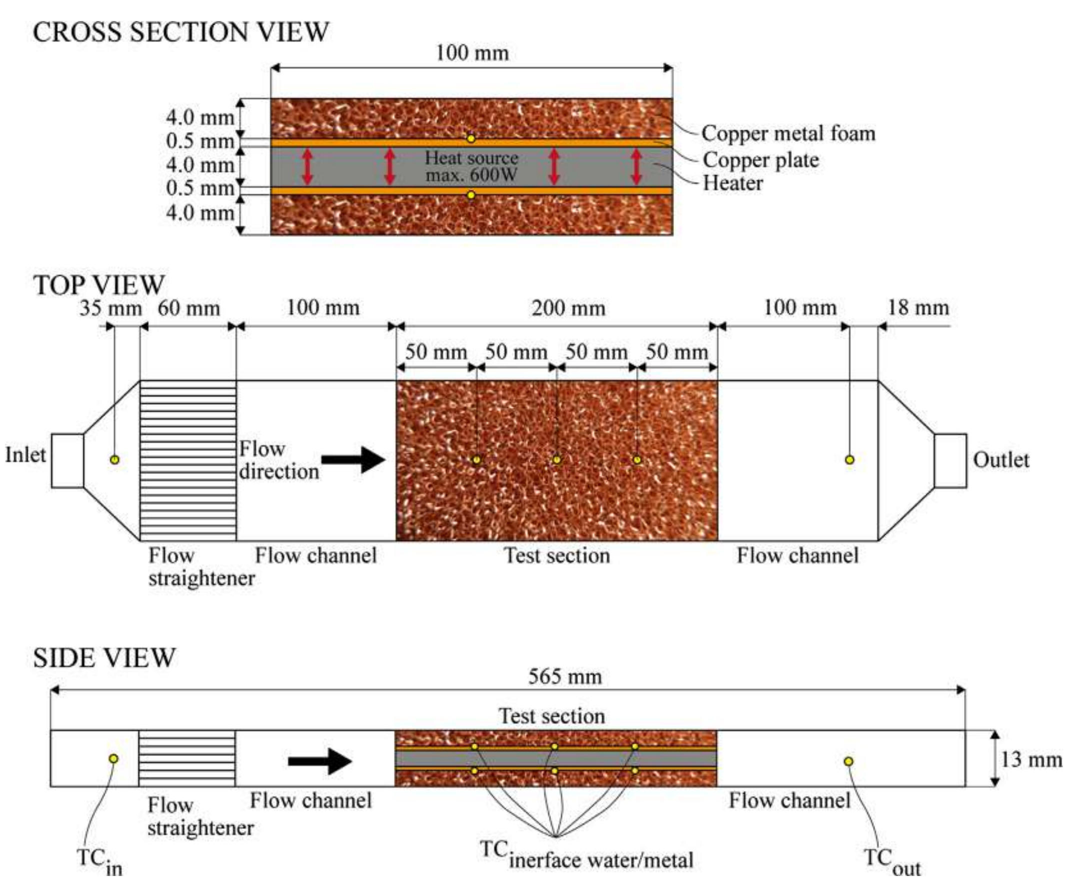

Fig. 4. Schematic view of the test section and depicted position of the thermocouple probes (TC) and flow direction of the heat transfer medium.

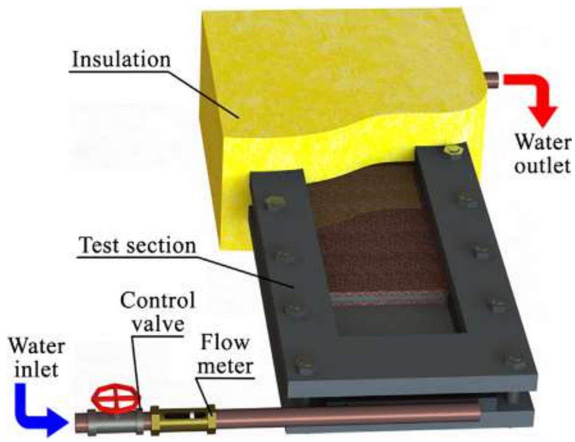

Fig. 5. Rendered 3D model of measuring rig (without depicted thermocouple and heater wiring).

apparatus. All pressure characteristics were measured by the KIMO AMI 300 data acquisition system with pressure module MPR 2500.

The used measuring instruments consisted of a TACOSETTER 100 rotameter with a measurement uncertainty of ±5% (F.S.) which was used to accurately determine the required flow rate of heat transfer media. The temperature of the heat transfer medium, as well as the temperature of water/metal interface, was recorded using the KIMO TTKE-363 thermocouples probes (uncertainty ± 0.4 °C) and the KIMO AMI 300 data acquisition system with thermocouple module with uncertainty ± 0.8 °C. Heat flux of the micathermic resistive heater was controlled by a Triac controller and a UNI-T UT171B multimeter with an AC voltage uncertainty of ±0.4% and AC current uncertainty of ±0.75%. The vernier caliper with a measurement uncertainty of ±0.02 mm was used in the calculation of the required dimensions of samples of metal foams and micathermic resistive heater (width, length). The experimental measurements were performed using four values of the heat transfer medium flow rates – 1.4×10^{-5}, 2.1×10^{-5}, 2.8×10^{-5} and $3.5 \times 10^{-5}\ m^3 \cdot s^{-1}$ (what is approximately 50, 75, 100 and 125 $l \cdot h^{-1}$) and four values of supplied heat flux at 200, 325, 450 and 575 W. The temperature of the heat transfer medium at the inlet to the measuring apparatus was about 13 °C. The values of the evaluated parameters were recorded only after their stabilization, which occurred in most cases within 30 min of setting the desired values. Three series of measurements were performed for the higher accuracy of the experiment. Changes in flow rate and heat flux were made only after the metal foam sample reached the initial temperature after switching off the supplied heat flux.

The output of the experiment was the temperature of the heat transfer medium at the inlet (T_{IN}), the outlet (T_{OUT}), the interface metal/water temperature ($T_{INTERFACE}$) and the volumetric flow rate of the heat transfer medium (Q). The evaluation of the heat-exchange process of the used metal foams was carried out using Nusselt number Nu. The Nusselt number is broadly defined and expresses the function of several variables affecting the heat exchange process. In the presented work, was the Nusselt number defined according to Eq. (1), this definition is suitable for the described experiment, is generally accepted and has been published for example, in [8,26,27]. In Eq. (1) is q drained heat by heat transfer medium (according to Eq. (2)), $A_{INTERFACE}$ is the area of the heat exchange surface, which is in this case related to the area of the micathermic resistance heater and specific surface area of metal foam determined by computer tomography (and since the metal foam samples are placed on both sides of micathermic resistance heater is multiplied by two), ΔT is temperature difference between the interface surface temperature ($T_{INTERFACE}$) and the temperature of the heat transfer medium at the inlet (T_{IN}) according to Eq. (3), D_{HYD} is hydraulic diameter representing the characteristic channel size (determined according to Eq. (4), where A_{CS} is the cross-section of the flow channel and L_P is the wetted perimeter), k_C is the thermal conductivity of the heat transfer medium.

$$Nu = \frac{q}{A_{INTERFACE} \cdot \Delta T} \cdot \frac{D_{HYD}}{k_C} \tag{1}$$

$$q = \dot{m} \cdot c \cdot (T_{OUT} - T_{IN}) \tag{2}$$

$$\Delta T = (T_{INTERFACE} - T_{IN}) \tag{3}$$

$$D_{hyd} = \frac{4A_{CS}}{L_P} \tag{4}$$

The flow characteristics of the experiment can be determined by the flow velocity of the heat transfer medium or by determining the Reynolds number Re. Within the issue of determining the Reynolds number are considered a number of methods that are different from the used equivalent diameter (e.g. particle diameter, pore diameter, capillary tube diameter, etc.), respectively the Reynolds number can be calculated by the use of permeability, porosity or frontal velocity. In the presented work was used Reynolds numbers based on mean pore diameter of metal foam Re_P according to Eq. (5). This method is mentioned by the authors in [9,14,28,29] where as the equivalent diameter was chosen mean pore diameter d_P with intent to take account of the specific fluid conditions of the medium flowing in the metal foam structure. In the Eq. (5) is U_D a darcian velocity, ρ is fluid density and μ is dynamic viscosity. The darcian velocity U_D (Eq. (6)) was calculated by the ratio of the volumetric flow rate in the channel (Q) and the area open to the flow of the heat transfer medium given by the product of the cross-section of the channel and the void fraction of the metal foam ($A_{CS} \cdot \varepsilon$).

$$Re_P = \frac{\rho \cdot U_D \cdot d_P}{\mu} \tag{5}$$

$$U_D = \frac{Q}{A_{CS} \cdot \varepsilon} \tag{6}$$

Uncertainty and error propagation for the results was analyzed using the method of Kline-McClintock [30] according to Eqs. (7) and (8). The analysis included the thermocouple probe uncertainty (±0.4 °C), the data acquisition system (±0.8 °C), the uncertainty of reading and the regulation of the mass flow rate (±5% F.S. according to the manufacturer), the uncertainty of computer tomography in determining the basic geometric parameters (±9 + L/50) μm) and the vernier caliper uncertainty used in the measurement of metal foam samples dimensions (±0.1 mm) (See Table 1).

Table 1
Summary of the sources of uncertainties in measurements.

Source	Uncertainty
Flow meter	±5% (F.S.)
Thermocouple	±0.4 °C
Data acquisition system	±0.8% of reading
Vernier Caliper	±0.02 mm
Measurement of d_P and A_{SF} (Zeiss Metrotom 1500)	±(9 + L/50) μm
Multimeter	±0.4%
AC voltage	
AC current	±0.75%

$$\frac{\Delta Nu}{Nu} = \sqrt{\left(\frac{\Delta \dot{m}}{\dot{m}}\right)^2 + \left(\frac{\Delta T_{IN}}{T_{IN}}\right)^2 + \left(\frac{\Delta T_{OUT}}{T_{OUT}}\right)^2 + \left(\frac{\Delta T_{INTERFACE}}{T_{INTERFACE}}\right)^2 + \left(\frac{\Delta A_{INTERFACE}}{A_{INTRERFACE}}\right)^2 + \left(\frac{\Delta D_{HYD}}{D_{HYD}}\right) + \left(\frac{\Delta q}{q}\right)^2} \tag{7}$$

$$\frac{\Delta Re_P}{Re_P} = \sqrt{\left(\frac{\Delta \dot{m}}{\dot{m}}\right)^2 + \left(\frac{\Delta A_{CS}}{A_{CS}}\right)^2 + \left(\frac{\Delta d_P}{d_P}\right)^2} \tag{8}$$

Based on Eqs. (7) and (8), the results errors were determined for a sample of the metal foam with a pore density of 10 PPI for a Nusselt number at an average of 7.01% and for 20 PPI at an average of 7.13%. The Reynolds number error was calculated at 5.68% and 5.22%. All experiment scenarios are summarized in Table 2.

3. Results and discussion

The aim of the experiment was to quantify the heat exchange process of hollow ligaments metal foam at low Reynolds number based on mean pore diameter. During the experiment, the flow velocity of the heat transfer medium was controlled so that the resulting Re_P ranged from 1.55 to 4.07 for metal foam with a pore density of 20 PPI and 3.79–9.76 for a metal foam with a pore density of 10 PPI. The course of the Reynolds number in relation to the flow velocity is shown in Fig. 6. According to Lage et al. [31] and Dukhan [32], are the boundaries that determine the flow regime for the Re_P parameter, in the range 0–1 for Darcy or viscous-drag dominated laminar flow regime, 1–10 for Forchheimer, or form-drag dominated laminar flow regime, 150–300 for post-Forchheimer unsteady laminar flow regime, and above 300 for fully turbulent flow.

From the graph in Fig. 6 is clear that the experimental evaluation was carried out at very low Reynolds numbers Re_P in ranges characteristic for Forchheimer, or form-drag dominated laminar flow regime. The results of the three repetitions of the experimental measurement for both types of considered metal foams are shown in Fig. 7. The graph depicts the curse of the Nusselt number depending on the heat transfer medium volumetric flow rate which is expressed by the value of Reynolds number based on the mean pore diameter.

In both cases is visible clustering of measured values of Nusselt number Nu into four regions according to the four used volumetric flow rates expressing by the Reynolds number Re_P. Slight variation within the Re_P value is caused by a deviation in the flow rate of the heat transfer medium due to the sensitivity issues of the control valve. However, there is an increase without major fluctuations in the y-axis, indicating the consistency of the measured results.

The metal foam with a pore density 10 PPI, which Nusselt number curve has a flatter course showed values: for volumetric flow rate 1.4×10^{-5} m^3·s^{-1} and thus Re_P 3.81 is Nu 4.08 (with standard deviation value of 0.16), for volumetric flow rate 2.1×10^{-5} m^3·s^{-1} and thus Re_P 5.60 is Nu 5.84 (with standard deviation value of 0.54), for volumetric flow rate 2.8×10^{-5} m^3·s^{-1} and thus Re_P

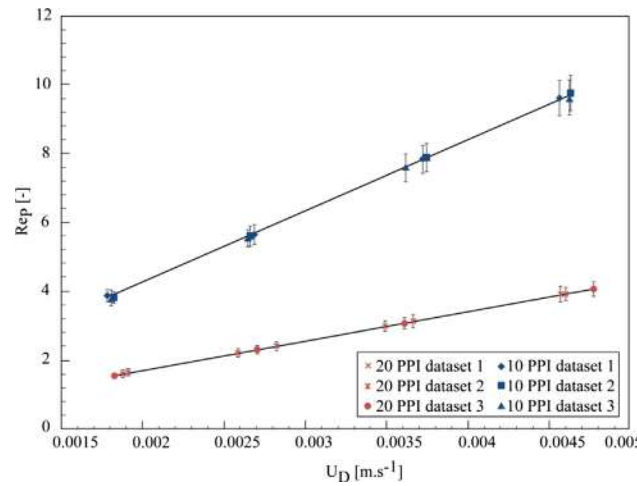

Fig. 6. Relation between the flow velocity of the heat transfer fluid and the Reynolds number Re_P with displayed error bars.

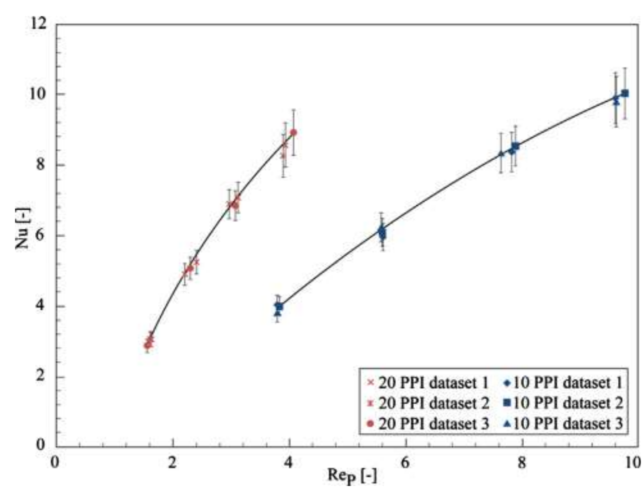

Fig. 7. The course of the Nusselt number for the metal foam with a pore density of 10–20 PPI with the displayed error bars.

Table 2
Summary of the experiment scenarios.

Experiment scenarios	Metal foam pore density [PPI]	Flow rate of heat transfer media [m^3·s^{-1}]	Heat flux [W]	Time [min]	Number of replications
1	10	1.4×10^{-5}	200–325–450–575	120	3
2		2.1×10^{-5}	200–325–450–575	120	3
3		2.8×10^{-5}	200–325–450–575	120	3
4		3.5×10^{-5}	200–325–450–575	120	3
5	20	1.4×10^{-5}	200–325–450–575	120	3
6		2.1×10^{-5}	200–325–450–575	120	3
7		2.8×10^{-5}	200–325–450–575	120	3
8		3.5×10^{-5}	200–325–450–575	120	3

7.73 is Nu 7.85 (with standard deviation value of 0.28) and for volumetric flow rate $3.5 \times 10^{-5}\ m^3 \cdot s^{-1}$ and thus Re_P 9.66 is Nu 9.80 (with standard deviation value of 0.64).

For a metal foam with a pore density of 20 PPI whose Nusselt number curve has a significantly steeper course were calculated these values for volumetric flow rate $1.4 \times 10^{-5}\ m^3 \cdot s^{-1}$ and thus Re_P 1.59 is Nu 2.99 (with standard deviation value of 0.22), for volumetric flow rate $2.1 \times 10^{-5}\ m^3 \cdot s^{-1}$ and thus Re_P 2.30 is Nu 4.54 (with standard deviation value of 0.34), for volumetric flow rate $2.8 \times 10^{-5}\ m^3 \cdot s^{-1}$ and thus Re_P 3.05 is Nu 5.88 (with standard deviation value of 0.52) and for volumetric flow rate $3.5 \times 10^{-5}\ m^3 \cdot s^{-1}$ and thus Re_P 3.96 is Nu 8.50 (with standard deviation value of 0.47).

Fig. 7 shows an increase in the Nusselt number with an increasing Reynolds number. This increase is mainly caused by a higher convective heat transfer with the rise of the volumetric flow rate of the heat transfer medium. The influence of the difference of the used metal foam samples is particularly evident in the Reynolds number of approximately four where the Nusselt number for the sample with a pore density of 20 PPI is approximately twice that of the sample with the pore density of 10 PPI. This increase at the same volumetric flow rates (and very similar values of the flow velocities of the heat transfer medium) is caused by an increase of the heat exchange surface that participates in heat transfer from micathermic resistance heater to heat transfer medium, greater values of heat transfer caused an increase of temperature difference at the inlet and outlet of the measurement apparatus. The increased Reynolds number leads to a higher local heat transfer coefficient, and in turn, this enhances the heat transfer between the solid and fluid. It can be concluded that the overall heat transfer coefficient of metal foam test samples at the described flow regime is combinations of conduction heat transfer through the ligaments of the metal foam and convection heat transfer from the specific surface area to the heat transfer medium.

3.1. Nusselt number correlation

Correlation of the results describing heat transfer in systems employing metal foam as the heat exchange surface is a relatively complicated task, in particular, because of the microscopic nature of the process taking place at the level of metal foam cells. Another important factor influencing the correlation accuracy with other authors is the difficulty resulting from the measurement uncertainty of the whole experimental system as well as metal foams. Regarding the used heat transfer medium, the type of samples of metal foams and flow regime conditions at which presented measurements have conducted, the results published by other authors varied in different conditions and therefore it is not possible to make a relevant comparison in full extent. For example, Hsieh et al. [9] conducted similar experiment, but authors used air as a heat transfer medium during the experiments. For samples of metal foam with the almost same parameters, the authors achieved lower Nusselt numbers, which is, however consistent with the differences in the thermal properties of air and water, but the course of the curve showed a similar character to the presented data.

In general, a suitable form of presentation of data in engineering applications is the correlation of the Nusselt number using Dittus and Boelter method [33], whose general form is expressed in (Eq. (9)) where Prandtl number Pr expresses the ratio of the kinematic diffusivity to thermal diffusivity of the heat transfer medium.

$$Nu = C \cdot \mathrm{Re}^m \cdot \mathrm{Pr}^{1/3} \tag{9}$$

Despite the initial use of this correlation exclusively for tubular heat exchangers, this method is currently generally accepted for use in the correlation of the Nusselt number related to metal foam systems, as is published in scientific journals [11,34,35,36,37]. Based on the experimental data presented in Fig. 7, the correlation of the Nusselt and Reynolds numbers was obtained using the least-square fitting method. The correlation for the used metal foams shows the equations (Eqs. (10) and (11)) with a standard correlation error for a metal foam sample with a pore density of 10 PPI with a value of 0.0677 and a 20 PPI with a value of 0.107.

$$Nu_{10PPI} = 0,59 \cdot \mathrm{Re}_P^{0,94} \cdot \mathrm{Pr}^{1/3} \tag{10}$$

$$Nu_{20PPI} = 0,87 \cdot \mathrm{Re}_P^{1,16} \cdot \mathrm{Pr}^{1/3} \tag{11}$$

From the presented correlation, it is obvious that the value of the coefficient C and m increases with the increase in the pore density value of the metal foam sample, which is consistent with the data presented in the past [9]. From the correlation results, it is possible to note the significant influence of the Reynolds number on the total value of the Nusselt number, which is expressed by the magnitude of the coefficient m.

4. Conclusions

In the presented paper were experimentally evaluated thermal properties of samples of copper metal foams with hollow ligaments with a pore density of 10 and 20 PPI by comparing the Nusselt number at very low values of the Reynolds number based on the mean pore diameter, using water as the heat transfer medium. The comparison was conducted on the authors proposed and manufactured measurement apparatus, which is characterized by axial symmetry conditions and placement of two identical samples of metal foams on both sides of the heating element. The resulting comparison of the Nusselt number showed an almost double increase in this parameter at the same Reynolds number for a sample with a pore density of 20 PPI (compared to a sample of 10 PPI). This increase, as well as the steeper curve of Nusselt number, can be attributed to a larger heat exchange area. The resulting Nusselt number correlation shows the significant effect of the Reynolds number based on the average pore diameter on the total Nusselt number and hence on the overall efficiency of the heat exchange process under the conditions of a very slow flow of heat transfer medium. The presented results provide an overview of the thermal properties of hollow ligaments at low Reynolds numbers, whose application is especially relevant for electronics cooling, low flow rate heat exchangers or solar thermal applications. Presented results have a considerable application potential, especially due to the small number of published works dealing with research of metal foams of a similar type of such defined flow conditions.

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