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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 $1.4 \times 10^{-5}$ to $3.5 \times 10^{-5}$ $m^3 \cdot s^{-1}$) 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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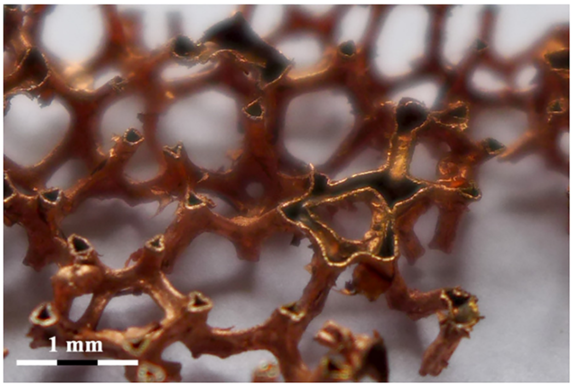


**Fig. 1.** Detail view of cut-off after machining of the used 10 PPI metal foam with clearly visible hollow ligaments.

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