COPPER METAL FOAM AS AN ESSENTIAL CONSTRUCTION ELEMENT OF INNOVATIVE HEAT EXCHANGER

Paper deals with creation of the innovative heat exchanger - manifold header for the heat pipe evacuated tube solar collector, which essential functional element is heat exchange chamber made of the copper metal foam. Design of the heat exchanger is based on effective utilization of the unique properties of the metal foam which makes it possible to design highly effective and space saving devices. Inner volume of heat exchanger was reducing from 0,00045 m³ to 0,000135 m³ and heat exchange surface was increase from 0,0104 m² to 0,1403 m² at proposed prototype, what drastically increase heat exchange efficiency. The proposal itself is based on the unique physical properties of the metal foam, which was described by computational analysis.

Key words: copper metal foam, solar collector, heat exchanger, computational fluid dynamics

INTRODUCTION

Materials with cellular structure are used by nature in construction of the largest and strongest natural objects, whether there are bones, wood or corals, cellular structure provides unique properties of this material [1]. Industrial use of materials with cellular structure has been recently very limited with the level of technological development, as to the latest knowledge and advanced manufacturing technology allowed "copying" the nature and deployment of these materials in various industries and applications. [2-4].

Metal foams also have huge economical or marketing potential in the field of metallurgy.[5] The most important group of cellular material consists from various types of the metal foams. Metal foams are unique material with cellular structure consisting of void spaces in basic metal material.

METAL FOAM PROPERTIES

Key characteristics of the metal foam are given in the metallurgical process.

The basis of the manufacturing process lays in creations of suitable condition in which void spaces (gas microbubbles) are forming in melted metal due to foaming of melt.

Under normal circumstances gas microbubbles will tend to rise due to buoyancy forces on the surface of the melt. This rise can be, according to [6] limited by increasing the melt viscosity or adding alloying elements to melt, which create stabilizing components. Range of conditions directly affect the final properties of metal

foam. At present metallurgy of metal foams prevails three methods of manufacturing - injection of gas to the melt from external source, adding foaming agent that produces gas bubbles in situ and merging gas microbubbles, which were diffused in the melted metal. In case of the gas injection, resultant metal foam can have infinite width and length (depending only on foundry machinery) and thickness 0,1 m maximum. Relative density of metal foam is from 69 to 540 kg.m⁻³ (for most used aluminium alloy metal foam) and pore diameter varies from 3 to 25 mm, wall thickness is 0,05 do 0,085 mm (in case of metal foam with closed cell structure) [7]. In the process, when foaming agent (e.g. titanium hydride TiH_2) [8] is added to the melt (foaming agent due to increased temperature of the melt starts to decompose and released gas component), the resulting metal foam is a highly homogeneous and average density range from 180 to 240 kg.m⁻³ (when aluminium alloy is used). Average pore size is 2 to 10 mm [6].
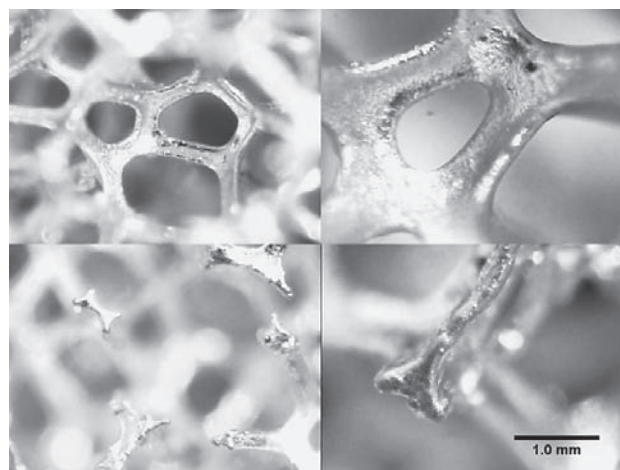

Figure 1 Microscopic view of metal foam with 20 pores per inch produced by foaming agent method

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The resulting pores morphology of the foam metal which was prepared by the method of merging gas micro-bubbles dispersed in melt, is given by the content of the gas, the pressure of the melt, velocity and the solidification direction, and the chemical composition of the melt. Usually prevail the elongated shape pores oriented towards to the direction of the solidification. The pores have a diameter 0,010 mm to 10 mm, a length from 100 µm to 30 mm, and porosity values range from 5 % to 75 % [6]. In general, metal foams can be divided into two main group - metal foam with open cell structure and closed cell structure. Open cell structure allow to flow media through structure, closed cell structure not. In thermal applications, such as heat exchangers, solar absorbers, coolers are mainly used open cell metal foams [9].

Main characteristics of open cell metal foam from view of application in form of heat exchanger are mean pore diameter D_p, specific surface area A_{sp}, porosity ε, thermal conductivity k_{mf} and heat transfer coefficient h_c [10-11].

These properties determine possible use of metal foam in terms of heat exchange efficiency, inertial flow resistance and pressure drop. Mean pore size diameter D_p affects pressure drop of flown media, density of foam metal block and strength (tensile, compressive, flexural and shear). Average size of mean pore diameter varies from micrometers to millimetres. Value of mean pore diameter D_p is possible control in the manufacturing process by changing of metallurgical inputs of above mentioned methods. The size of D_p proportionally affect all the other characteristic of the metal foam. Mean pore diameter can be determined directly from the manufacturing documentation, or by using micro and macroscopic photogrammetry (Figure 1 and Figure 2).

Specific surface area A_{sp} of a metal foam is the amount of the surface area within a given volume of foam. It is a surface where is ongoing thermal exchange
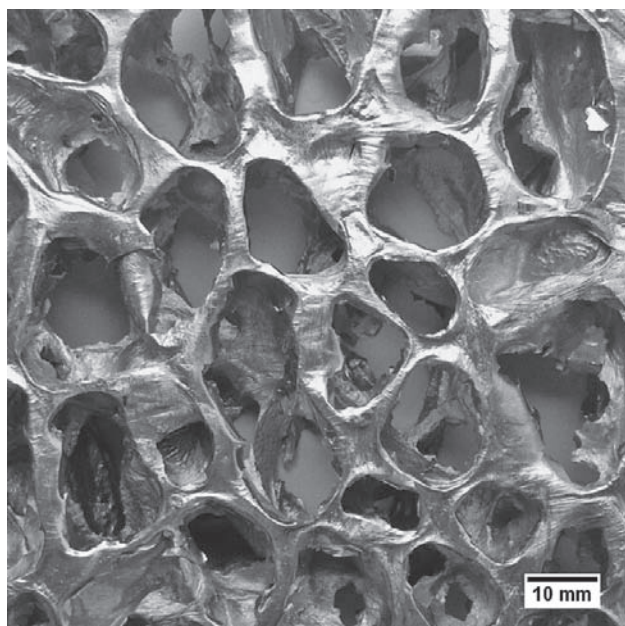

Figure 2 Macroscopic view of metal foam with 5 pores per inch produced by method of merging gas microbubbles

process between fluid (thermal transport medium) and solid (metal foam). Most used method for calculating specific surface area is proposed by Amiri-Vafai [12].

$$A_{sp} = \frac{6(1-\varphi)}{D_p} \qquad (1)$$

Value of the specific surface area affects heat exchange efficiency, higher value of the specific surface area caused higher efficiency and opposite. Specific surface area varies from 500 to 3 000 $m^2 \cdot m^{-3}$, in extreme cases up to 10 000 $m^2 \cdot m^{-3}$ [13]. Overall thermal conductivity of metal foam is defined by porosity, thermal conductivity of solid material, and fluid medium [1].

$$k_{mf} = \varepsilon.k_f + (1-\varepsilon).k_s \qquad (2)$$

Most important thermodynamic properties of metal foam is overall heat transfer coefficient h_{mf}, which affect total heat exchange efficiency or Nusselt number of proposed (or designed) heat exchanger. Measurement and expression of heat transfer coefficient is a dynamically changing area in field of research and development of the metal foam, but generally accepted expression of heat transfer coefficient in the open cell metal foam according to [14] is shown at Equation (3).

$$h_{mf} = 0,4181.Re^{0,5318}.Pr^{0,333}.\frac{k_f}{t} \qquad (3)$$

$$Re = \frac{G.t}{\varepsilon.\mu_f} \qquad (4)$$

$$Pr = \frac{\mu_f.c_f}{k_f} \qquad (5)$$

Heat transfer coefficient according to Equation (3) is function of Reynolds and Prandtl number, which are affected by fluid properties and porosity of the metal foam.

DESIGN OF HEAT EXCHANGER

Innovative design of the heat exchanger is based on effective utilization of the unique properties of the metal foam which makes it possible to design highly effective and space saving devices. Proposed prototype design of the heat exchanger has key role in heat pipe evacuated tube solar collector and is based on the previous studies involved in study of metal foam and foam glass properties and their use in solar technology by authors [15-17]. Heat transfer medium entering into manifold body via inlet fitting and flows in flow canals, which are created by combination of permeable and impermeable porous materials. Impermeable materials are represented by foam glass, whose hydrophobic capability defines flow canals and separates each heat exchange chamber made from metal foam. Heat chamber tightly enclose condenser casing of vacuum tube. Specific sur-
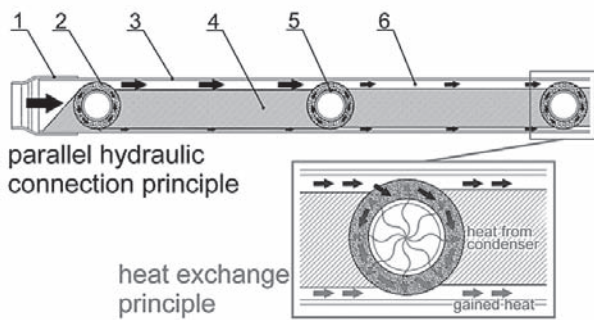
Figure 3 Working principle and main parts of proposed heat exchanger - solar collector manifold header, 1 - inlet fitting, 2 - heat exchange chamber made from metal foam, 3 - manifold body, 4 - hydraulic spacer from glass foam block, 5 - condenser casing, 6 - flow canal (between foam glass and manifold body)

face of metal foam increase heat exchange surface compared to common design. Heat transport medium flows through metal foam inner structure and gains accumulated heat from condenser, this heat is finally transported for further usage.

COMPUTATIONAL FLUID DYNAMICS ANALYSIS OF HEAT EXCHANGER

Final version of prototype have been tested in Ansys Fluent software, for optimal design of the shape and size of the component itself. Special attention was paid to reduce the inner volume of heat transport media in manifold header compare to common designs. Presented prototype reduce inner volume about 70 % from 0,000450 m³ at common designs to 0,000135 m³. Inner
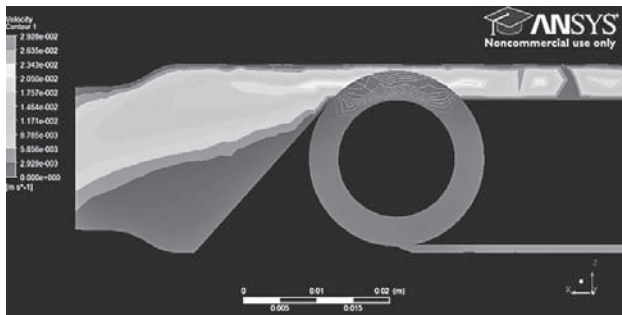

Figure 4 Velocity contours for two-dimensional model of manifold header (inlet fitting and first heat exchange chamber - up, complete manifold - down)
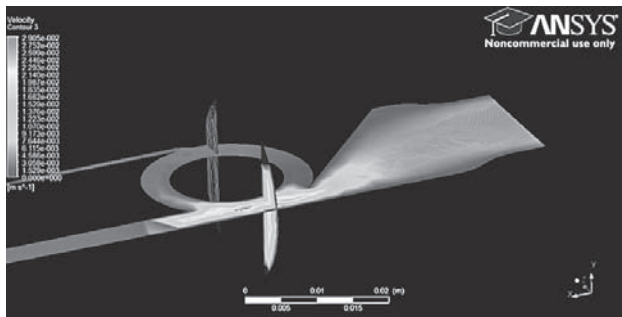

Figure 5 Velocity contours for three-dimensional model - heat exchange chamber in section view at X - Z and Y - Z plane

volume affects to heat inertia of solar collector. The topographic computer aided design model and unstructured mesh with 240 000 cells have been created. Model was separated to fluid and porous region. This model solves velocity and outlet pressure for a specified mass flow rate at the inlet. The pressure based solver and SIMPLE algorithm has been used and the discretization of second order. Pressure equation was solved by using PRESTO scheme. The simulations considered the characteristics of metal foam, which is already proven in previous experiments dealing with the heat exchangers made of foam metal: porosity $\varepsilon = 0,9$; pore diameter $D_p = 1,1$ mm; specific surface area $A_{sp} = 2\ 700$ m²·m⁻³. Heat transfer medium is water with the temperature at the input to the manifold header of 313,15 K. The flow of the media via the manifold header was $2,2.10^{-6}$ to $2,2.10^{-5}$ m³·s⁻¹, which corresponds to $2,77.10^{-7}$ to $2,77.10^{-6}$ m³·s⁻¹ for a single heat exchange chamber. Velocity and pressure contour for 2D and 3D view of model are shown in Figure 4 and Figure 5. Visual quality is affected by low computing power.

CONCLUSION

Presented prototype of parallel manifold header represents unique combination of porous material and innovative approach to construction of solar collector manifold header, which allows parallel hydraulic connection of condensers. Advantage of presented prototype is modifiability in terms of numbers of vacuum tube, shape, dimensions and material of condenser or main body of manifold header. One of the main essential improvement is reducing of inner manifold volume, what affects thermal inertia of solar system. Inner volume was reducing from 0,00045 m³ at common designs to 0,000135 m³ at proposed prototype. Heat exchange surface was increase from 0,0104 m² at common designs to 0,1403 m² at proposed prototype, what drastically increase heat exchange efficiency of proposed manifold header. Concept of manifold prototype will be tested in series of experiments in next part of development, including joint operation of commercial vacuum tube solar collector and collector with proposed manifold.

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LIST OF SYMBOLS, ABBREVATIONS AND ACRONYMS

A_{sf} specific surface of the metal foam,
c_f specific heat of fluid,
D_p mean pore diameter,
G volumetric flow rate of fluid,
h_{mf} heat transfer coefficient of metal foam,
k_f thermal conductivity of fluid,
k_{mf} thermal conductivity of metal foam
k_s thermal conductivity of solid,
Pr Prandtl number,
Re Reynolds number,
t foam ligament thickness,
ε porosity of metal foam,
φ metal foam density,
μ_f dynamic viscosity of fluid

Note: The responsible translator for English language is Jarmila Bandžáková, M.A., Agency-ETC