AN EXPERIMENTAL STUDY ON THE DETERMINATION OF THERMAL CONDUCTIVITY, HEAT CAPACITY AND THERMAL DIFFUSIVITY OF A POROUS METAL FOAM

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ABSTRACT : Porous metal foams are novel heat transfer surfaces with the potential use as heat sinks and heat exchangers. In the presented study, thermal characteristics of porous metal foams which are modeled as bulk micro-channel patterns in relevance to the material characteristics are the main topic of discussion given in this paper. An experimental investigation based upon a modeling approach through the measurements of local temperatures along the x-y-z axis of the porous copper foam samples was conducted. A variety of plate type copper foam samples with a size of 150 mm (L), 30 mm (W) and 3 mm, 4 mm, 5 mm (t) with 95 % porosity are tested and physical analysis is presented at heating surface temperatures of T_H = 50 ˚C for ϴ = 10 min.. Effects of the cooling time is also given at T_H = 80 ˚C for ϴ = 10 min. Time dependent thermal views of the samples are taken by usage of thermal imaging camera. Experimental results compared with copper foil reference items are presented to see the various effects of the porous medium on heat transfer. Scanning electron microscopy (SEM) device is used for analyzing the micro-structure of the samples. Local changing of the thermal conductivity, k heat capacity, C and thermal diffusivity, α are calculated as a function of different parameters.
The experimental results showed that, k, C and α values of the porous copper foams and copper foil reference items change between 250 W/m.K ≤ k ≤ 517 W/m.K and 40 W/m.K ≤ k ≤ 120 W/m.K, 250 J/K ≤ C ≤ 710 J/K and 255 J/K ≤ C ≤ 715 J/K, 5 mm^2/s ≤ α ≤ 42 mm^2/s and 0.1 mm^2/s ≤ α ≤ 0.8 mm^2/s depending on the T_H, t and ϴ.

Key words: Copper Foam, Temperature, Porous Medium, Porosity, Thermal Conductivity, SEM

INTRODUCTION

The concept of porous media is used in many areas of applied science and engineering. Using porous media to extend the heat transfer area, improve effective thermal conductivity, mix fluid flow and thus enhance heat transfer is an enduring theme in the field of thermal fluid science. According to the internal connection of neighbouring pore elements, porous media can be classified as the consolidated and the unconsolidated. For thermal purposes, the consolidated porous medium is more attractive as its thermal contact resistance is considerably lower. Especially with the development of co-sintering technique, the consolidated porous medium made of metal, particularly the metallic porous medium, gradually exhibits excellent thermal performance because of many unique advantages such as low relative density, high strength, high surface area per unit volume, high solid thermal conductivity, and good flow-mixing capability [1] (Xu et al., 2011b). It may be used in many practical applications for heat transfer enhancement, such as catalyst supports, filters, biomedical implants, heat shield devices for space vehicles, novel compact heat exchangers, and heat sinks, et al. [2-5] (Banhart, 2011; Xu et al., 2011a, 2011b, 2011c). In the last decade, open cell metal foams both stochastic and periodic have been largely studied through experimentation and analysis. New and innovative heat transfer techniques are needed for heat transfer enhancement and pressure drop research and development studies.

In this view, porous metal foams are good candidate for these purposes. There are many studies to analyse the material characteristics of metal foams. Calmidi [6] proposed the use of cubic unit cell model to approximate the metal foam structure and proposed a relationship of pore diameter (d_{pore}) as a function of porosity (ε) and pore density (PPI). Du Plessis et al. [7] presented a model for evaluating permeability (K) and inertia coefficient for metal foams which was derived by experimental results of foam samples of small pore size (45-100 PPI) and porosity of 0.973-0.978 with water and glycerol as fluid phase. Kurtbas et al. [8] conducted an experimental study for investigating the heat and exergy transfer characteristics of forced convection in a horizontal rectangular channel with inserted aluminum open cell metal foam under constant heat flux, using different pore densities (10, 20, 30 PPI). They found that the aluminum open cell metal foam has a considerable effect on the thermal performance when they compare their results with the empty channel. Ghosh [9] performed a systematic study to give an overview related to heat transfer in a metal foam and asked ''How good is open-cell metal foam as a heat transfer surface?''. In his study, the effect of area density as functions of pore size and strut diameter were discussed. He concluded that foams are a promising alternative for compact heat exchangers due to the ideal thermodynamic characteristics. Literature reviews show that there are very limited data and studies are available on thermal characteristics of porous copper foams. Performance of copper foams for heat transfer enhancement purposes should be studied.

As a result, analysis of micro / mini channels as porous structures are studied as a function of different parameters for future scopes of enhancing thermal performance of channels.

EXPERIMENTAL METHODOLOGY

Porous Medium: Porous media with high thermal conductivity have emerged as an effective method of heat transfer enhancement due to their large surface area to volume ratio and to intense mixing of the flow. Porosity can be calculated depended of volume of both sample and solid [10] Kaviany :

$$\varepsilon = 1 - (V_{solid} / V_{sample}) \quad (1)$$

Use of porous metal foams in heat transfer applications is novel. Consequently, numerous investigations have been carried out on this subject in the recent past. For the experimental studies, different shapes, sizes and thicknesses copper foams are used as a test sample listed in the Table 1.

Table 1. Properties of The Copper Foam Samples

Shape	Dimension (mm)	Porosity (%)	PPI	Density (g/cm3)
Plate	150*30* 3	95	40	0.45
	150*30*4			
	150*30*5			

Copper foams are produced with specified dimensions and properties by manufacturing company, Beijing Shunyuan Wangda Trade Co., in China. To perform and analyze the local temperature variations in porous medium, a heater unit is used as a heat source.
Copper foams are located on it with different thicknesses. Heater temperatures (T_H) are T_H = 50 ˚C which are used as case temperatures to analyze the thermal characteristics of the copper foams. Thermal image views of the copper foams are taken periodically for ϴ = 10 min. by Testo 875-2i thermal image camera and temperature variations along the selected region or directions are taken as a case measurement.
The thermal camera provides thermal imaging with a high level of thermal sensitivity, outstanding image quality and allowing hot and cold spots to be quickly visible. Hence, the smallest temperature differences can be seen. To describe the effects of the micro-structure of the copper foams on heat transfer performance, scanning electron microscopy (SEM) device is used. The key parameters for this research: heater temperatures, geometry of the copper foam samples, porosity, pore size and time periods.

Heating And Cooling Experiments

Two different experiments are considered. These are called as heating and cooling experiments. In the heating experiments, test samples are located on to the heater unit with a specified T_H of 50 ˚C are shown in Figure 1 and are waited for ϴ = 10 min.

Thermal camera views of the test samples are taken at the end of the time period from the upper surface of the samples and also from the contact surfaces by reversing the sample upper surface. These thermal views are used for analysing the thermal behaviour of the test samples. In the cooling experiments, test samples' contact surfaces, which exposed to a T_H = 50 ˚C through heating process for ϴ = 10 min. time period, are located on reference plate of white paper at room temperature until the contact surface temperature comes to room temperature, T_R values. Thermal views of the contact surfaces are taken periodically for ϴ = 0, 3, 6 and 10 min.

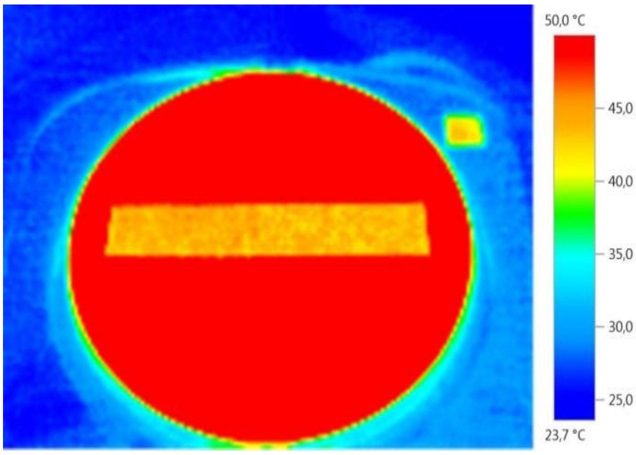


Figure 1. Location of The Samples on The Heater Unit

Temperature Measurements on The Tested Copper Foam Samples

Defining the thermal characteristics of the porous copper foam materials along the all surface points, use of the temperature measuring device with high sensitivity plays important and critic role for certain and precise experimental results.
Settings of the thermal imaging camera with respect to material properties before taking the thermal views of the copper foams are also key points. Especially setting of the heater temperatures, emissivity value of the material, quality of the thermal views and correct position of the measuring device are also critical points for taking the correct results.
As a case study, plate type copper foam samples with different thicknesses, t which t = 3 mm, t = 4 mm and t = 5 mm shown in the Figure 2, are arranged on heater surface at T_H = 50˚C for 10 min. and temperature variations on the upper and contact surfaces of the copper foams are measured by thermal camera instantly. Thermal camera focused precisely on copper foam material at same distance and position. Image clarity set by manually. After taking the thermal image views of the material, all image views are transferred to the computer for thermal analysis. Thermal images are analyzed with testo software program shown in the Figure 3. Thermal analysis results are given in the Figure 4.

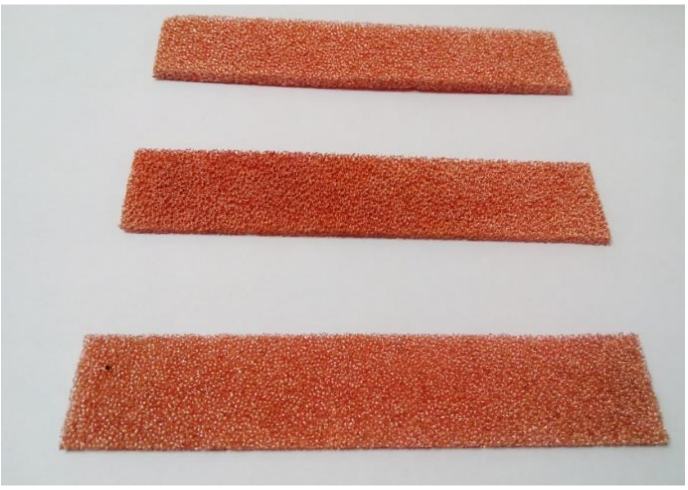


Figure 2. Plate Type Copper Foam Test Samples

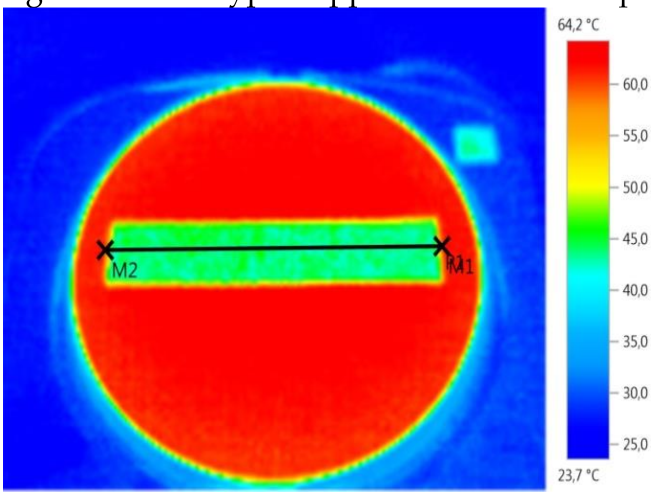
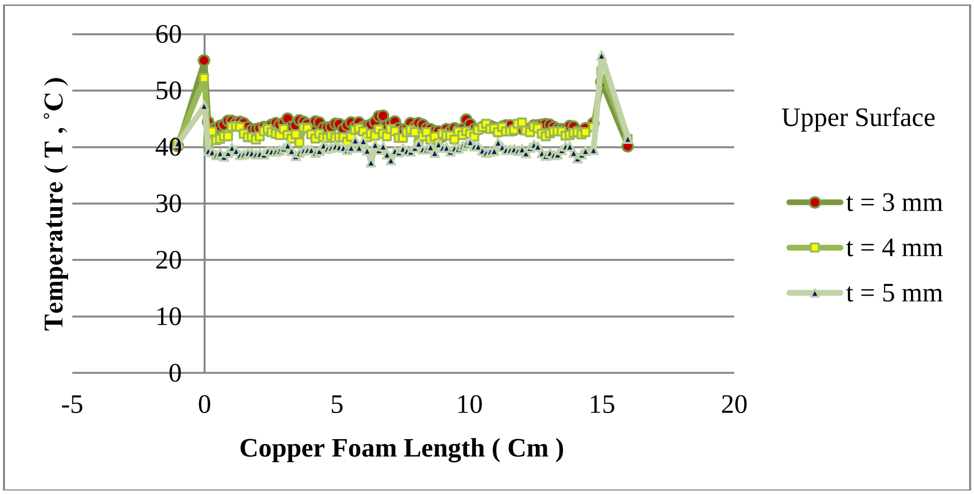


Figure 3. Thermal View and Temperature Distribution of The Copper Foam Sample



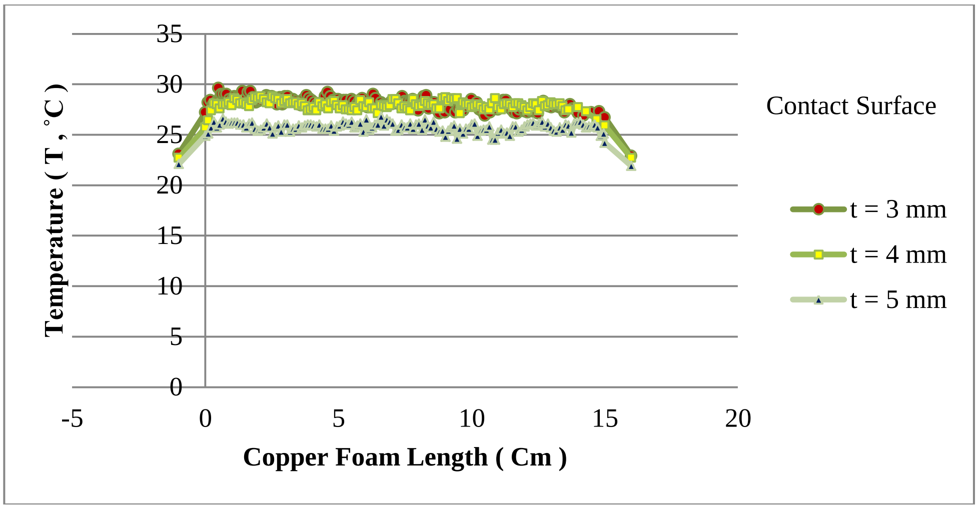


Figure 4. Copper Foam Upper and Contact Surface Temperature Profiles

It is seen from the Figure 4 that, upper surface temperature values of t = 5 mm Cu foam sample are lowest compared with other sample thicknesses. Mean temperature values for t = 3 mm Cu foam sample, 42.5 ˚C, for t = 4 mm Cu foam sample, 41.5 ˚C and for t = 5 mm Cu foam sample, 39 ˚C. Similarly, contact surface temperature values of t = 5 mm Cu foam sample are lowest compared with other sample thicknesses. Mean temperature values for t = 3 mm Cu foam sample, 28 ˚C, for t = 4 mm Cu foam sample, 27.9 ˚C and for t = 5 mm Cu foam sample, 25.7 ˚C

SEM Analysis of The Copper Foam Sample

Micro-structure of the copper foam from a heat transfer point of view, a scanning electron microscope (SEM) device is used. Micro-structure of the copper foam specimens observed at a wide range. Figure 5 and Figure 6 show the micro-structure of the copper foam material.

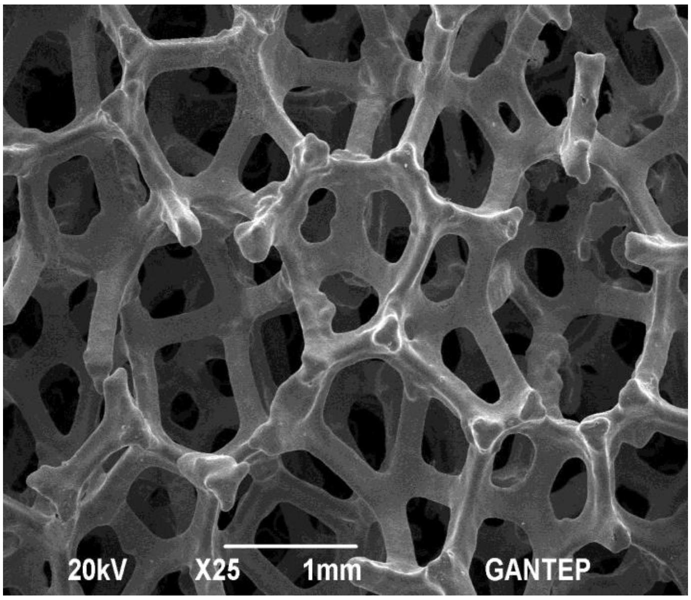


Figure 5. SEM Image of The Copper Foam

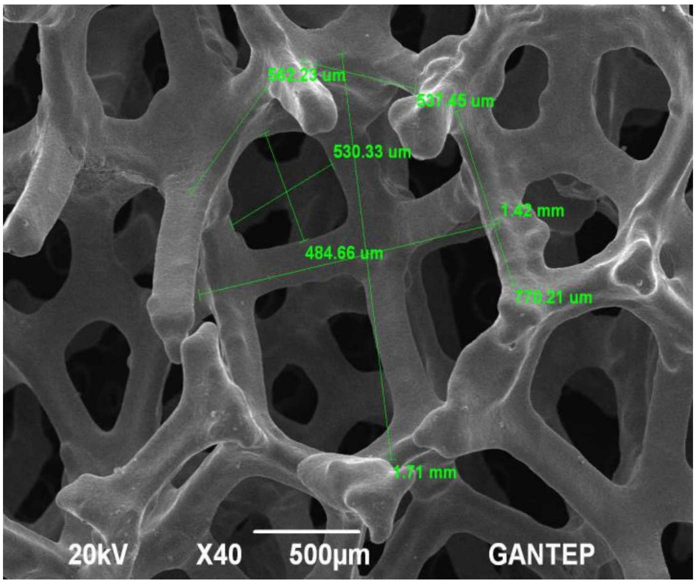


Figure 6. Unit Cell Image with Measured Dimensions

Scope investigations of the research listed as:

Effects of the micro-structure on heat transfer performance of the copper foam.

Observe and define the effects of pore shape, size, and directions on heat transfer

Defining the thermal behaviour of the material by means of thermal conductivity and heat capacity as well as thermal diffusivity.

THERMAL CHARACTERIZATION OF THE POROUS COPPER FOAM SAMPLES

Many different research groups have studied the heat transfer characteristics of these porous medium, experimentally and analytically. It is a widely held view that metal foams are still incompletely characterized because of their specific structure. The information repository is improving with time whereas the widespread use of the high porosity media in modern technological devices makes the need for fully characterizing them more urgent. Developments on this issue would certainly help engineering researchers, especially in terms of heat transfer [11,12]. In this study, thermal characteristics of the copper foam samples observed by means of thermal conductivity, heat capacity and thermal diffusivity. Changes of the k, C and α values of the Cu foam samples and Cu foil reference items at T_{H} = 50˚C for ϴ = 10 min. are given in the Figures 7, 8 and 9.

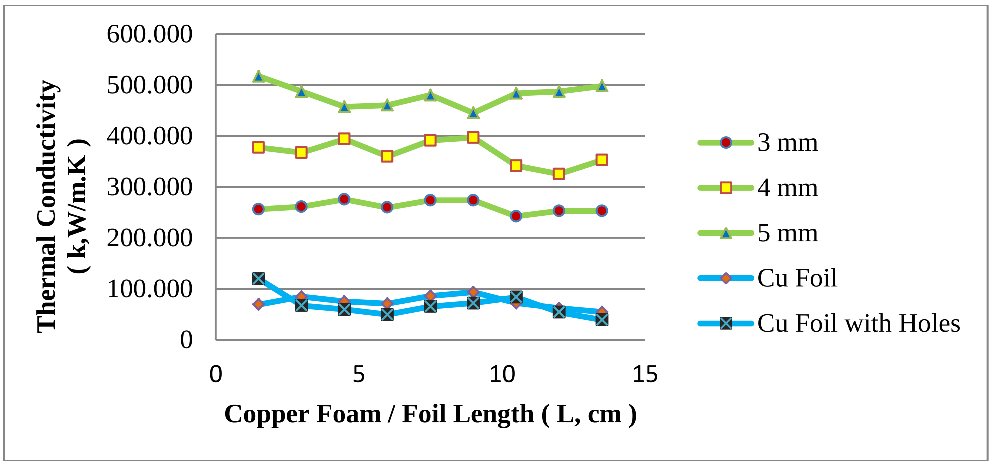


Figure 7. Variations of The Thermal Conductivity of The Cu Foams / Foil Samples at T_H = 50 ˚C

Results from the Figure 7 give some informations; k values of the Cu foam and Cu foil samples change from point to point and depend on the ϴ which can be seen along the surface. It is clear from the figures that if thicknesses of the Cu foam increase then k increases. This situation shows the effects of the porous medium on k. It is seen from the Figure 7 that, t = 5 mm Cu foam sample has higher k than the other thicknesses of the samples. Values of the k change between the (250 W/m.K – 275 W/m.K) for 3 mm, (320 W/m.K – 400 W/m.K) for 4 mm and (440 W/m.K – 517 W/m.K) for 5 mm Cu foam sample. On the other hand, Cu foil reference samples k values change between the (50 W/m.K – 93 W/m.K) for Cu foil and (40 W/m.K – 120 W/m.K) for the Cu foil with holes.

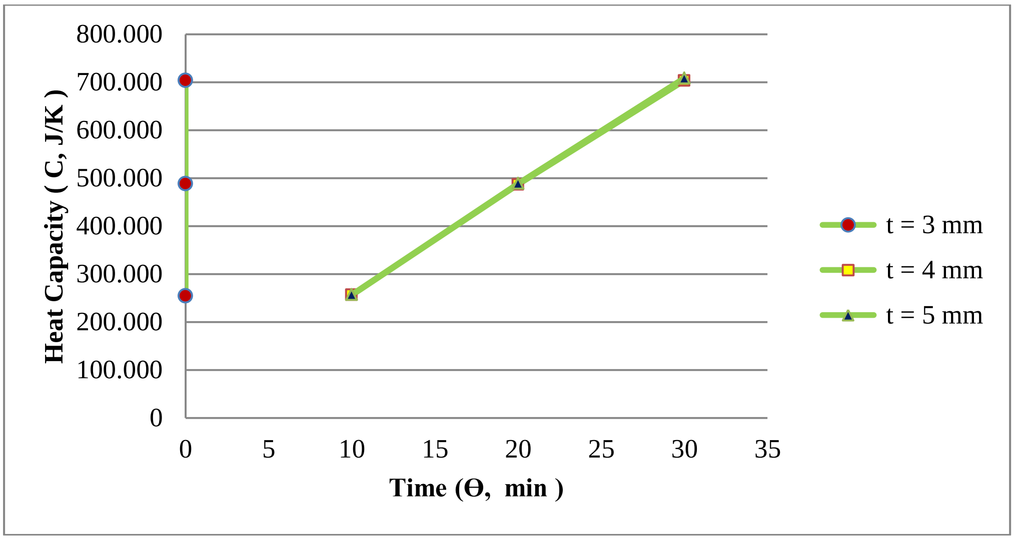


Figure 8. Time Dependent Heat Capacity Variations of The Cu Foams at T_H = 50 ˚C

As can be seen from the Figure 8 effects of the t are low for the specified T_H. Time dependent variations of C values of t = 3 mm Cu foam sample change between 254

J/K ≤ C ≤ 704 J/K, 250 J/K ≤ C ≤ 703 J/K for t = 4 mm Cu foam and 256 J/K ≤ C ≤ 709 J/K for t = 5 mm Cu foam.

Heat capacity values of the porous copper foam samples change between 250 J/K ≤ C ≤ 710 J/K and 255 J/K ≤ C ≤ 715 J/K for copper foil reference item samples depending on the different parameters of T_H, t and Θ. Results show that there is a little difference between the test samples.

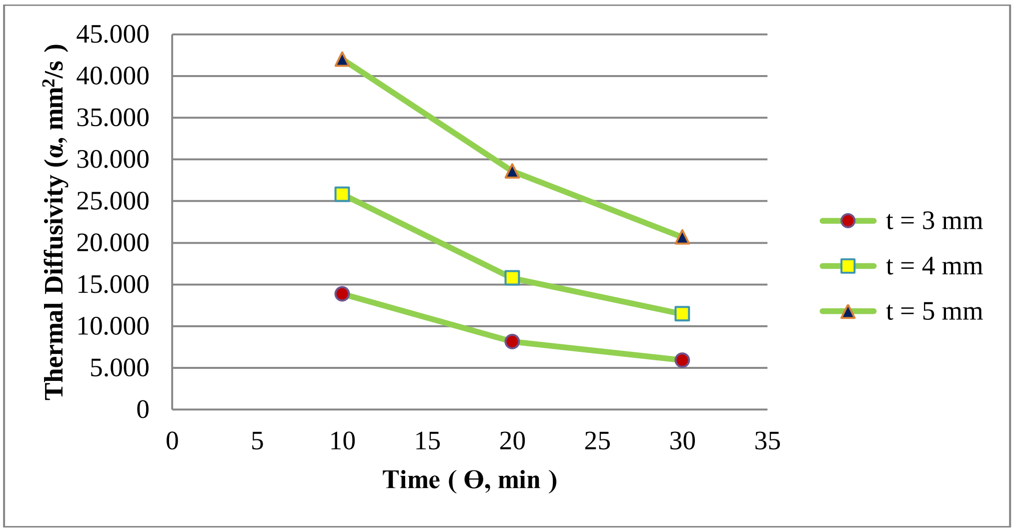


Figure 9. Time Dependent Thermal Diffusivity Variations of The Cu Foams at T_H = 50 ˚C

Analysis results from the Figure 9 show that, α values of the samples decrease depending on the Θ. α values of the 5 mm thickness Cu foam sample are higher than the other samples. α values of the samples change between the 5 mm^2/s ≤ α ≤ 14 mm^2/s for t = 3 mm, 11 mm^2/s ≤ α ≤ 26 mm^2/s for t = 4 mm and 20 mm^2/s ≤ α ≤ 42 mm^2/s for t = 5 mm at T_H = 50 ˚C.

As a result, thermal diffusivity of the porous copper foam samples change between 5 mm^2/s ≤ α ≤ 42 mm^2/s and 0.1 mm^2/s ≤ α ≤ 0.8 mm^2/s for copper foil reference item samples depending on the different parameters of T_H, t and Θ. These results show that speed of heat propagation inside the porous copper foam samples is much higher than the copper foil reference item samples.

Effects of The Cooling Time

In order to define the cooling performance of the Cu foam samples, analysis of effects of the cooling times on thermal profiles of the tested Cu foam samples are presented. Test samples’ contact surfaces, which exposed to T_H = 80 ˚C through heating process for Θ = 10 min, are located on reference plate of white paper as a cooling medium until the contact surface temperature comes to T_R values. Thermal views of the contact surfaces are taken periodically for Θ = 0, 3, 6 and 10 minutes for t = 3 mm Cu foam sample and thermal profiles are shown and compared in Figure 10.

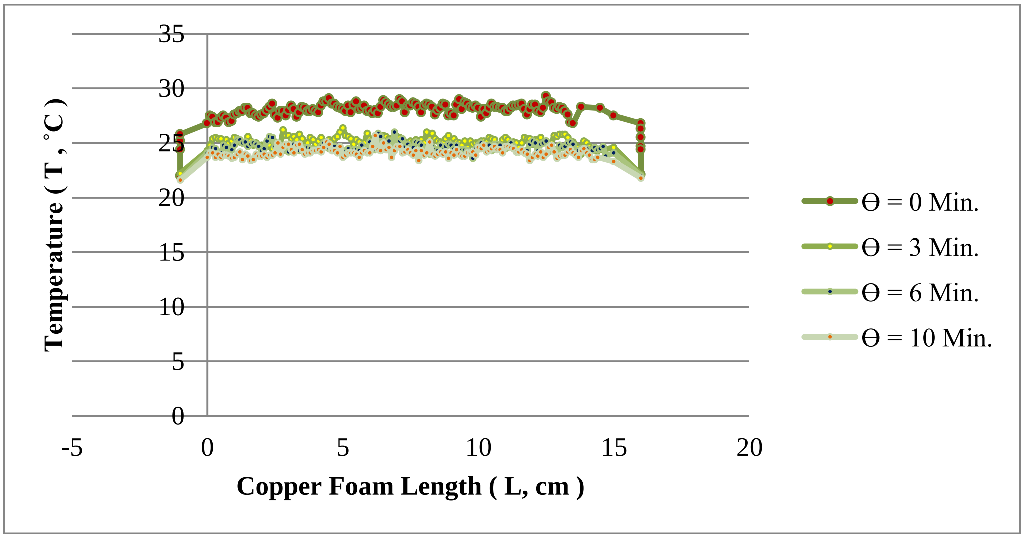


Figure 10. Thermal Profiles of 3 mm Thickness Cu Foam Sample at T_H = 80 ˚C as a Function of Θ.

It is obvious from the Figure 10 that, thermal profiles of the samples show high temperature values at Θ = 0 min. After the 0.min, thermal profiles show near temperature values depending on the increasing Θ. $T_{m,\ contact}$ values for Θ = 0, 3, 6 and 10 min. are 27.8 ˚C, 25.1 ˚C, 24.5 ˚C and 24.1 ˚C for t = 3 mm Cu foam sample.
Figure 11 through Figure 14 shows the thermal images of the contact surface of the sample as a case for Θ = 0, 3, 6 and 10 min.

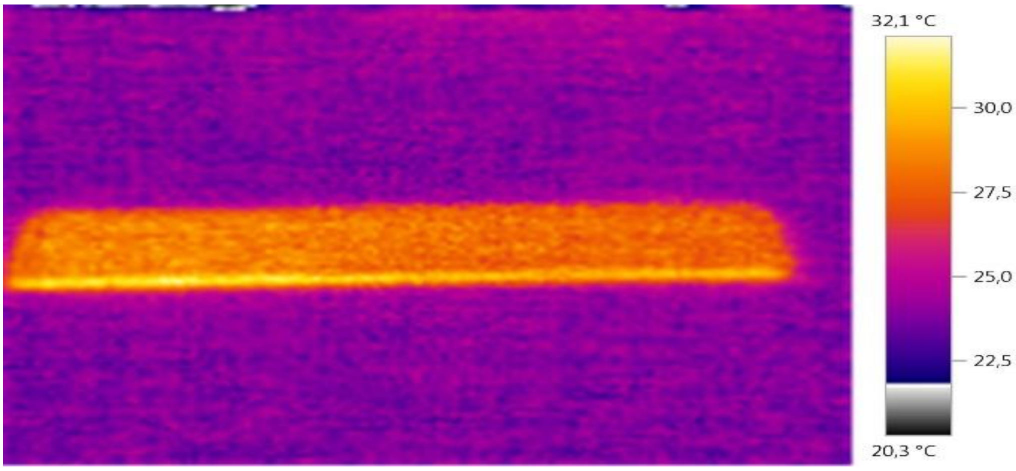


Figure 11. Thermal Image of The Test Sample For Θ = 0 min.

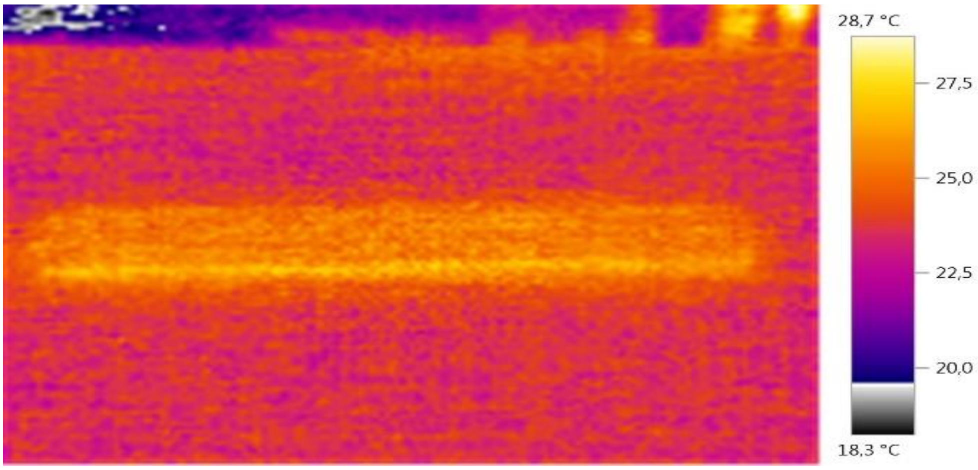


Figure 12. Thermal Image of The Test Sample For Θ = 3 min.

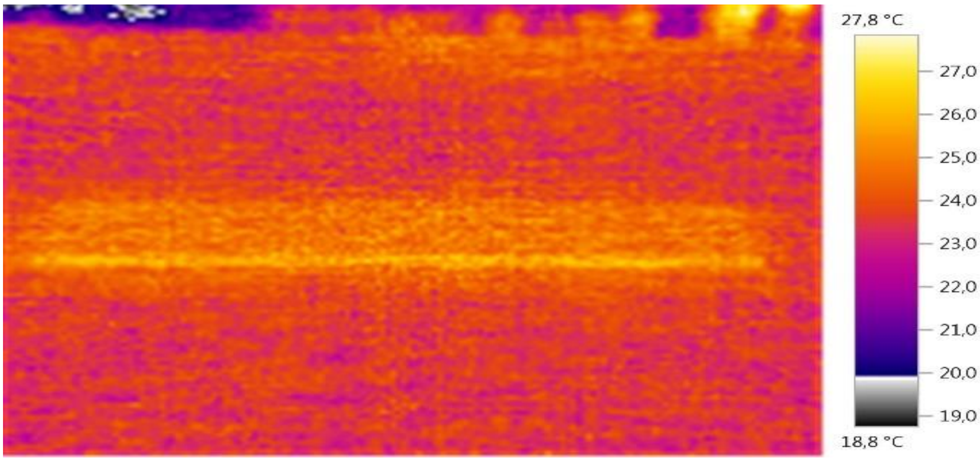


Figure 13. Thermal Image of The Test Sample For Θ = 6 min.

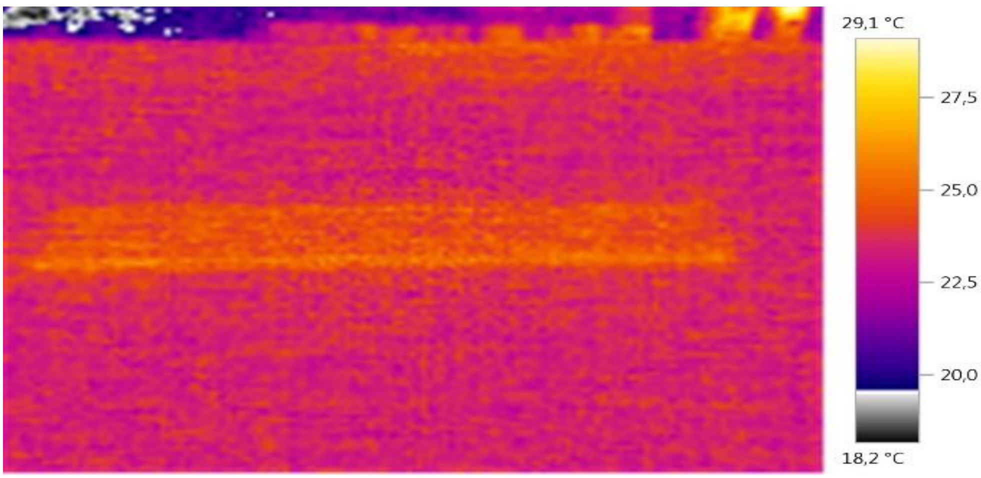


Figure 14. Thermal Image of The Test Sample For Θ = 10 min.

Thermal image views showed the time dependent heat transfer from the all surface of the sample. Analysis results gave information about the heat capacity properties of the sample. From the views and analysis, samples' contact surface temperature came to the surrounding temperature values in a short time.

CONCLUSION

Heat transfer characteristics of porous metal foams are experimentally and theoretically investigated. Copper metal foams are selected for conducted studies. All thermal image analyses of the samples as a function of different parameters are presented in detail. In order to define the thermal characteristics of the copper foam sample, thermal conductivity, heat capacity and thermal diffusivity analyses are given for different cases. Experimental results show the effects of the porous medium on heat transfer.

The results revealed that, micro-structure of the porous medium can have a significant effect on heat transfer. Especially, particular attentions are given to define the thermal characteristics of the material for further heat transfer investigations in many engineering fields.

RECOMMENDATIONS

Some suggestions are summarized and listed for future investigations ;

Optimising the design and production of porous metal foam structures for enhanging the heat transfer in micro channel.

Investigating the effects of the micro / nano porous metal foams on heat transfer.

Defining the relationship between geometrical properties and optimal heat transfer.

Developing the new models to deal with the fluid and thermodynamic challenges for complex porous structures.

Defining the thermal and material characteristics of the porous mediums for different cases and applications.

Developing the innovative porous metal foams for maximazing the heat transfer, especially for solving the cooling problems in many engineering fields.

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