Heat Transfer Performance of Micro-Porous Copper Foams with Homogeneous and Hybrid Structures Manufactured by Lost Carbonate Sintering

Jan Mary Baloyo and Yuyuan Zhao
School of Engineering, University of Liverpool, Liverpool L69 3GH, UK.

ABSTRACT

The heat transfer coefficients of homogeneous and hybrid micro-porous copper foams, produced by the Lost Carbonate Sintering (LCS) process, were measured under one-dimensional forced convection conditions using water coolant. In general, increasing the water flow rate led to an increase in the heat transfer coefficients. For homogeneous samples, the optimum heat transfer performance was observed for samples with 60% porosity. Different trends in the heat transfer coefficients were found in samples with hybrid structures. Firstly, for horizontal bilayer structures, placing the high porosity layer by the heater gave a higher heat transfer coefficient than the other way round. Secondly, for integrated vertical bilayer structures, having the high porosity layer by the water inlet gave a better heat transfer performance. Lastly, for segmented vertical bilayer samples, having the low porosity layer by the water inlet offered the greatest heat transfer coefficient overall, which is five times higher than its homogeneous counterpart.

INTRODUCTION

Porous metals have attracted a lot of attention both in the academic and industrial communities due to their excellent properties [1-3]. Porous metals have high internal surface area and high permeability for fluids, which make them valuable for thermal management applications. Currently, porous copper is being developed for commercial cooling systems for electronic devices such as computers.

A typical porous metal cooling system is usually made of a fluid coolant flowing through the internal pores or channels of the porous metal medium. The coolant carries the heat away from the porous medium by heat conduction and convection, and therefore, cools the system. The fluid flow of the coolant within the porous medium dictates the efficacy of the porous metal in conducting heat away from the heated device.

A space holder method known as the Lost Carbonate Sintering (LCS) process [4-6] has allowed the production of micro-porous metals with a wide range of porosity (40-85%) and pore sizes. The porous metals produced by the LCS process have a unique internal microstructure making them excellent candidates for thermal management applications. Efficient heat transfer by conduction is achieved through the strong bonding between the small metal particles. Whereas the randomly distributed micro-pores within the LCS foam interconnected through smaller cavity windows, allow high permeability for fluids, hence increasing heat transfer by convection.

This paper investigates and compares the heat transfer performance of homogeneous and hybrid micro-porous copper foams produced by the LCS process under one-dimensional flow conditions at different water flow rates.

EXPERIMENTAL DETAILS

Ten samples in total were fabricated using the LCS process. The copper powder with particle size range of 75μm to 150μm and 99.9% purity was supplied by Ecka Granules UK Ltd. The food grade potassium carbonate powder (pore former) with particle size range of 425μm to 710μm and 98-100% purity was manufactured by E&E Ltd.

Fig. 1 shows the representative microstructure of the as-produced porous copper. Oxidation of copper particles was not observed due to vacuum sintering. Most pores are spherical in the size range of 425-710μm. The small voids between the copper particles act as small windows between pores, allowing the pores to be interconnected. Fluids, such as water, can flow through these voids hence increasing the sample's permeability to fluids.

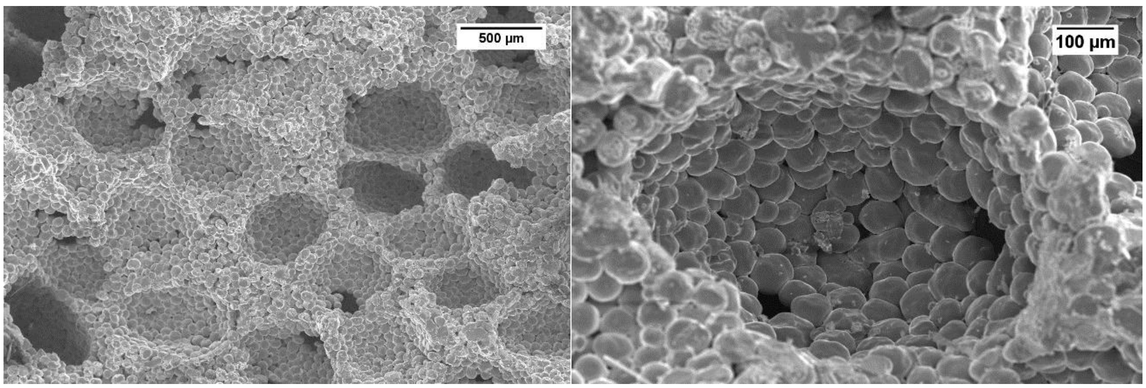

Fig. 1 SEM micrographs of an LCS porous copper showing representative features.

Table I: Porosity and permeability of LCS porous Cu samples.

Sample	1	2	3	4	5	6	7	8 (HB)	9 (VB I)		10 (VB S)	
Nominal Porosity (%)	40	50	60	65	70	75	80	40/80	40-80	80-40	40-80	80-40
Permeability (x10^{-10}m^2)	0.08	0.15	0.19	0.54	0.87	1.97	3.68	1.02	0.13	0.16	0.14	0.10

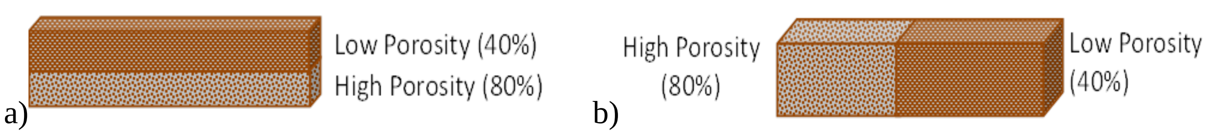

Fig. 2 Schematic diagrams of a) horizontal bilayer (HB) and b) vertical bilayer (VB) LCS porous samples. One layer has 40% porosity and the other layer with 80% porosity.

Table I lists the structural parameters of the ten samples. Nominal porosity is the volume percentage of the K_2CO_3 powder in the Cu/K_2CO_3 powder mixture during sample preparation. The permeability was determined by measuring the water pressure drop in the sample, applying the Darcy-Forcheimer model [7]. Sample 1-7 have a homogeneous structure, i.e. the porosity is the same throughout the sample. Samples 8, 9 and 10 have hybrid structures. They consist of two layers, each having a homogeneous structure and a different porosity, 40% and 80% respectively. Sample 8 has a horizontal bilayer (HB) structure with the two layers arranged top and bottom (Fig. 2a). Samples 9 and 10 are vertical bilayer (VB) samples (Fig. 2b), with the two layers arranged left and right. Sample 9 is an integrated vertical bilayer (VB I) sample, i.e., the two layers were manufactured as one whole sample in one operation. Sample 10 is a segmented vertical bilayer (VB S) sample. The two layers were manufactured separately and then combined. The effect of changing the orientation of the bilayer sample on heat transfer coefficient was also analysed. This was done by flipping the sample so that either the high or low porosity layer is next to the heater for the HB samples and the water inlet for the VB samples.

The heat transfer coefficients of the porous copper samples were measured using a purpose-built apparatus as shown in Fig. 3. The flow channel is 20mm wide and 5mm high. All the samples were 30mm long, 20mm wide and 5mm high, which tightly fit into the channel. The water coolant flowed through a flow meter (Omega FL50001A, ±5% accuracy) into the porous copper sample in the sealed channel. Seven 100W heat cartridges, controlled by a variac, was imbedded in the oxygen-free copper heat block to generate a range of heat fluxes. Attached to the heat block is another oxygen-free copper block with the same cross section as the porous copper sample (30mmx20mm), and was pressed tightly against the porous copper sample to achieve good thermal contact. The temperature of the water inlet, T_{in}, was measured using a thermocouple (PT 100, ±0.1°C accuracy). The temperatures at the top and bottom spots of the lower copper block, T_t and T_b respectively, were measured after a steady state condition was reached using T-type thermocouples (±0.1% accuracy). The temperature of the lower copper block (T_t) varied with heat flux in the range of 17°C to 110°C. The effect of temperature on the heat transfer coefficient is considered not significant. The copper block and the porous copper sample were insulated with low thermal conductivity PTFE (0.20 W/K.m), so the heat flow was reasonably one dimensional. The heat flux J through the lower copper block can be assumed to be equivalent to the heat flux to the sample, and was calculated by:

$$J = k_{Cu} \frac{T_t - T_b}{d} \tag{1}$$

where d is the distance between T_t and T_b (30mm) and k_{Cu} is the thermal conductivity of the oxygen free copper block (390W/m.K). The overall heat transfer coefficient h of the cooling system, which is made of the porous copper sample and water coolant, was determined by:

$$h = \frac{J}{T_b - T_{in}} \tag{2}$$

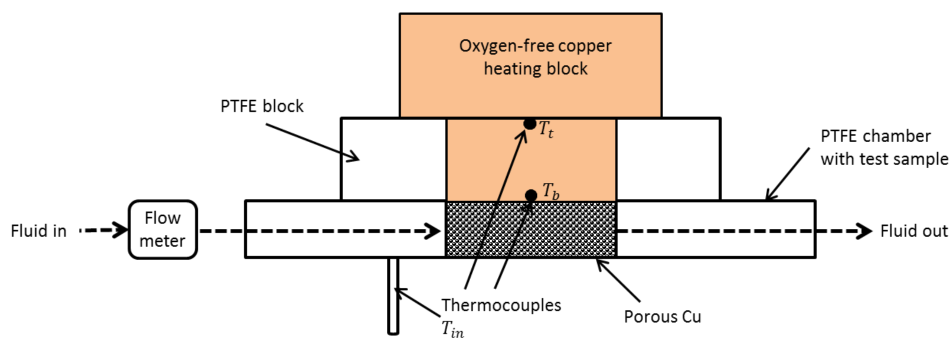

Fig. 3 Schematic of the apparatus used to measure the heat transfer coefficient.

RESULTS AND DISCUSSION

Heat transfer in homogeneous LCS structures

The effect of the sample's porosity on the heat transfer coefficient at different water flow rates was investigated and the results are summarised in Fig. 4. It is evident that the porosity greatly affects the heat transfer performance. At low porosities below 60%, the permeability is very low, limiting the heat transfer by convection. The maximum heat transfer performance was achieved when the porosity reached 60%, in which the heat transfer by conduction and convection is optimised. At high porosities, the amount of copper in the sample decreases which limits heat transfer by conduction.

The presence of the 60% LCS porous sample has dramatically increased the heat transfer by four times compared to an open channel (100% porosity), in agreement with the results obtained by Xiao and Zhao [8]. The findings confirm the suitability and effectivity of utilising LCS porous Cu as heat exchangers for thermal management solutions.

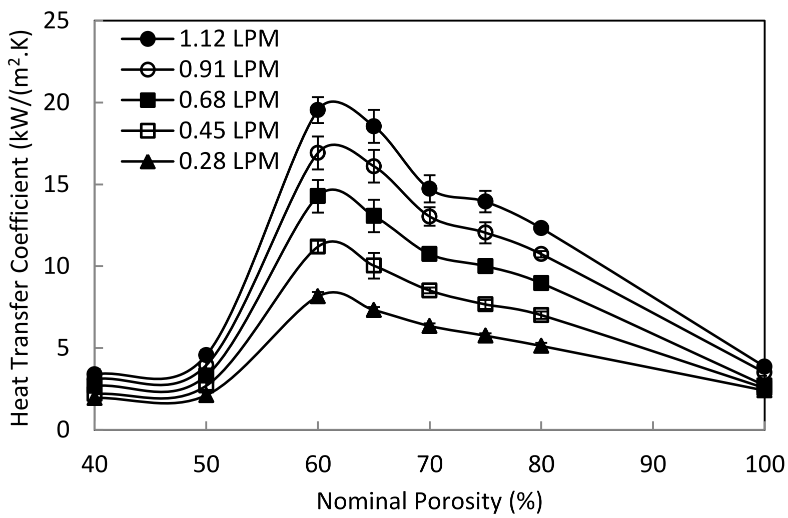

Fig. 4 Variations of heat transfer coefficient with porosity at different water flow rates.

The variation in the heat transfer performance with porosity can be explained as follows. There are two stages involved in the transfer of heat from the heat source to the coolant fluid (water) in the porous copper samples. These are heat conduction in the copper matrix and heat convection between the copper matrix and the coolant. Heat conduction in porous metals is extremely sensitive to porosity [9]. As the density of the porous copper sample is increased by decreasing the porosity, the thermal conductivity of the sample will increase. This leads to an increase in heat transfer by conduction. However, if the sample's porosity becomes too low, water permeability through the sample decreases, hence limiting heat transfer by convection. Therefore, it is very important to look for the optimum parameters that will maximise both conduction and convection heat transfer.

The heat transfer coefficient of the LCS porous Cu samples generally increases with increasing water flow rate. It is acknowledged that at higher water flow rates, a turbulent flow occurs within the porous network. This turbulence will cause mixing and greater fluid access to the smaller channels/voids within the porous copper sample [10]. As a consequence, a greater heat transfer is experienced between the solid copper matrix and the water coolant.

Heat transfer in hybrid LCS structures

Fig. 5 shows the variations in heat transfer coefficient with water flow rate for hybrid LCS porous structures. The heat transfer coefficients of their homogeneous counterparts were also included for comparison. The effect of changing the orientation of the hybrid structures on heat transfer coefficient was also shown.

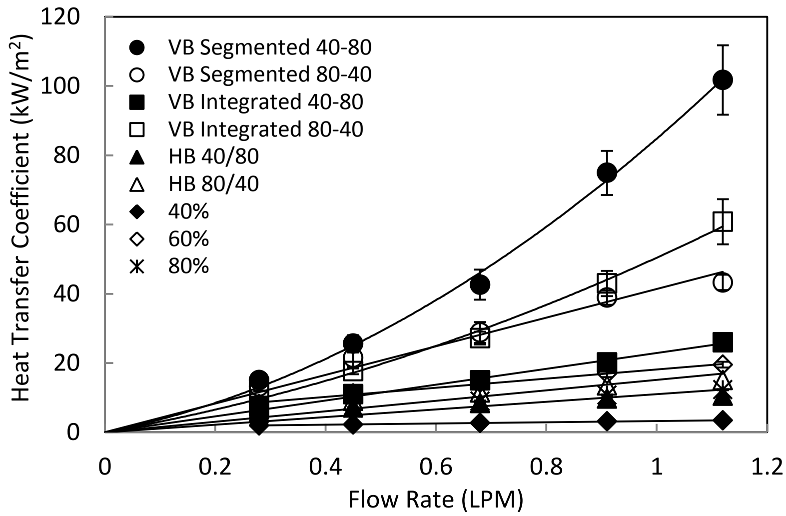

Fig. 5 Variations of heat transfer coefficient with porosity distribution at different water flow rates.

For the horizontal bilayer sample (S8), having the high porosity layer next to the heater (HB 80/40) gave a higher heat transfer coefficient compared to having the low porosity layer next to the heater. This occurs since the majority of the flow passes through the high porosity layer [8]. Apparently, the high porosity layer has a dominant effect on the heat transfer performance since heat removal by convection is increased in the high porosity region. However, the heat transfer coefficients of the horizontal bilayer samples were generally lower than their homogenous counterparts.

For the integrated vertical bilayer samples, a better heat transfer coefficient was achieved by having the high porosity layer (VB I 80-40) by the water inlet. This is likely an outcome of the difference in surface area and permeability of each layer. From the high porosity region, the fluid slows down as it approaches the low porosity region. There is a decrease in the opportunity for the fluid to find alternative routes at the transition from high porosity to low porosity regions. As a consequence, the fluid dwells longer at the high porosity region and turbulence mixing occurs, which increases convective heat transfer.

For the segmented vertical bilayer samples, however, a better heat transfer performance was observed when the low porosity layer was placed by the water inlet (VB S 40-80). As segmented samples are made from two halved samples, hard boundaries between the layers are introduced. There is often a gap between the two layers due to poor coupling so that fluid can dwell longer in the boundary layer. Since the fluid is pre heated in the first layer and dwells at the interface, the second layer needs to have an increased surface area to compensate the reduced temperature gradient [11]. Having the high porosity layer by the water outlet served this function and therefore gave a better heat transfer performance.

In general, segmented vertical bilayer samples gave a much better heat transfer performance than their homogeneous and horizontal bilayer counterparts. The hard boundaries in the segmented vertical bilayer samples act as very large pores where fluid can reside, therefore increasing convective heat transfer at this interface in the vertical direction. The presence of the hard boundaries also increases the opportunity for fluid flow to find alternative routes at the transition region, making the exit of the heated fluid easier compared to that in integrated vertical bilayer samples. This leads to enhanced rate of heat removal by convection from the heat source.

CONCLUSION

The heat transfer performance of porous copper samples produced by the LCS process, with different porosities and structures, was investigated. In general, increasing the water flow rate led to an increase in heat transfer coefficient due to enhanced rate of heat removal from the heater to the water. It was observed that an optimum heat transfer performance was achieved when heat removal by conduction and convection is balanced. For homogeneous samples, the optimum porosity was found to be 60%. For horizontal bilayer samples, having the high porosity layer by the heater gave a better heat transfer performance since water predominantly flows in the high porosity region. For integrated vertical bilayer samples, having the high porosity layer by the water inlet gave a better heat transfer performance. For segmented vertical bilayer samples, however, having the low porosity layer by the water inlet gave the best heat transfer coefficient overall, approximately five times higher than its homogeneous counterpart. The presence of the hard boundary in the segmented samples allowed convective heat transfer vertically, increasing the overall heat transfer performance. This demonstrates that by changing the structure through varying the distribution and orientation of the porosities in the LCS micro-porous samples, the heat transfer performance can be greatly improved.

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