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Thermal Properties of Porous Copper Manufactured by Lost Carbonate Sintering

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Abstract. Active cooling techniques are often required to achieve high rates of heat dissipation in thermal management applications. Open-cell porous metals are good candidates for use as heat exchangers. This paper studies the fluid transport and thermal properties of porous copper samples with different pore structures manufactured using the LCS method. The results showed that the permeability increases with porosity but decreases with pore size. The thermal conductivity increases with relative density according to the power law. The effects of porosity and pore size on the heat transfer performance of the porous copper samples are significant, due to their effects on the permeability and thermal conductivity. For the porous copper samples with double-layer structures, the permeability follows the rule of mixture and the heat transfer coefficient can be predicted by a recently developed segment model.

Introduction

Porous metals have received growing interests in recent years due to their unique physical and structural properties [1]. They have great potential for thermal management applications. Open-cell porous metals can be used to maximize convective heat transfer in heat exchangers.

The thermal properties of a number of open-cell porous metals have been studied in the last few decades. Jeigarnik *et al*. [2] studied the heat transfer of water flow on flat plates and in channels filled with sintered bronze layers. They showed that the convective heat transfer coefficient in sintered bronze porous layers was 5-10 times higher. Jiang *et al*. [3] reported that a channel filled with packed metallic iron particles with average particle diameters of 0.85 mm can enhance the heat transfer performance by up to 15 times. Chiba *et al*. [4] found that the lotus-type porous copper heat sink with a thickness of 1 mm can increase the heat transfer coefficient 7.7 times compared with the conventional groove fins. However, very little research has been conducted on the porous metals manufactured by the space-holder methods, which have porosity typically in the range of 50-85%.

The Lost Carbonate Sintering (LCS) process is a space-holder based fabrication method [5]. The porous copper manufactured by the LCS method has some interesting thermal characteristics [6-8]. The LCS process is also an ideal method to produce hybrid structures, which can enhance the heat transfer performance significantly [8].

This paper studies the convective heat transfer of porous copper manufactured by the LCS process and correlates permeability, thermal conductivity and heat transfer coefficient with porosity and pore size. The thermal properties of single- and double-layer porous copper samples are evaluated and compared with model predictions.

Experimental

Eight porous copper samples with single- or double-layers (see Table 1) were fabricated by the LCS method described in [5] and [8]. The raw materials were commercially pure (99.9%) copper powder (Ecka Granules Metal Powder Ltd., UK) with a particle size range of 50 to 100 μm, and food grade potassium carbonate powder (E.E. Muri & Sons Pty. Ltd., Australia) with different size ranges.

Table 1 Porosity and structural parameters of porous copper samples

Sample No.	S1	S2	S3	S4	S5	S6	S7	S8
Nominal Porosity (%)	60	70	80	70	70	70	60/80	70/70
Pore size (μm)	425-710	425-710	425-710	250-425	710-1000	1000-1500	425-710	425-710/ 1000-1500
Thickness (mm)	5	5	5	5	5	5	2.5+2.5	2.5+2.5
Actual Porosity (%)	61.1	70.7	80.1	71.2	70.8	70.5	71.4	70.8
Permeability ($\times 10^{-10} m^2$)	0.257	1.042	3.62	1.54	0.884	0.768	1.78	0.914
Thermal Conductivity (W/mK)	62.5	32.8	12.4	19.7	33.4	35.1	--	--

The permeability and heat transfer coefficient were measured on a purpose-built apparatus described in [8]. The specimen used for the tests has a dimension of 30mm × 20mm × 5mm, which closely fit into the test channel. The fluid used in the tests was water.

Permeability of the specimen was measured by generating a water flow (0.2 – 1.0 L/min) through the porous copper specimen and measuring the pressure difference of the water flow between the entry and exit of the specimen at room temperature. The permeability was determined from Darcy's law:

$$\frac{\Delta P}{L} = \frac{\mu}{K} v \tag{1}$$

where ΔP is the pressure drop, L is the length of the specimen, μ is the viscosity of water (0.001 Pa·s at 20° C), and v is the Darcian velocity, i.e., the volume flow rate divided by the cross-sectional area of the specimen perpendicular to the water flow direction (1×10^{-4} m^2 in our test).

Heat transfer coefficient measurements were conducted with a heat source generating a constant heat flux (J). The overall heat transfer coefficient of the cooling system (h), composed of the porous copper specimen and the water flow, was determined by:

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

where T_b is the temperature of the heat plate in contact with the porous copper specimen, T_{in} is the inlet temperature of water, and J is the heat flux with a value of 250 MW/m^2.

The thermal conductivity tests were carried out using a method developed by Corsan [9] on a purpose-built apparatus described in [6]. The porous copper specimens were cylindrical with a length of 80 mm and a diameter of 19 mm. A solid copper comparator with the same cross sectional area as the porous copper specimens was clamped onto the specimen in each test.

Under a constant heat flux, the thermal conductivity of the porous copper, k_p, is given by:

$$k_p = k_{Cu} \frac{(\Delta T/\Delta x)_{Cu}}{(\Delta T/\Delta x)_p} \tag{3}$$

where k_{Cu} is the thermal conductivity of the solid copper comparator (390 W/mK), $(\triangle T/\triangle x)_{Cu}$ and $(\triangle T/\triangle x)_p$ are the temperature gradients in the solid copper comparator and the porous copper specimen, respectively, which were measured by a series of thermocouples.

The overall uncertainties of the permeability, thermal conductivity and heat transfer coefficient measurements were estimated to be 3.5%, 2.8% and 2.4%, respectively.

Results and Discussion

Permeability. The variations of pressure drop with the Darcian velocity for porous copper specimens with different porosities or different pore sizes are shown in Figure 1. The pressure drop increases with Darcian velocity, with all the curves fitting well with Eq. (1).

Porosity has a significant effect on the pressure drop. The specimen with the highest porosity shows the lowest pressure drop at any given Darcian velocity. Specimen S8, which has a double-

layer structure, has a much lower pressure gradient compared with specimen S2, which has a single-layer structure and a similar overall porosity as specimen S8 (see Figure 1a). The pressure gradient increases with pore size at any given Darcian velocity for a given porosity of around 71%. The specimen with the finest pore size has a very small gradient. The pressure gradient of specimen S8, which has a double-layer structure, is between those of the constituting specimens with a single layer structure, i.e., specimens S2 and S5 (see Figure 1b).

The variation of permeability with porosity is shown in Figure 2. The permeability increases with porosity. The permeability values of the samples with a similar porosity around 71% (S2, S4-S8) but different pore sizes or layer structures are very different and decreases with pore size. Sample S8, with a double-layer structure of 60%/80%, has the largest permeability.

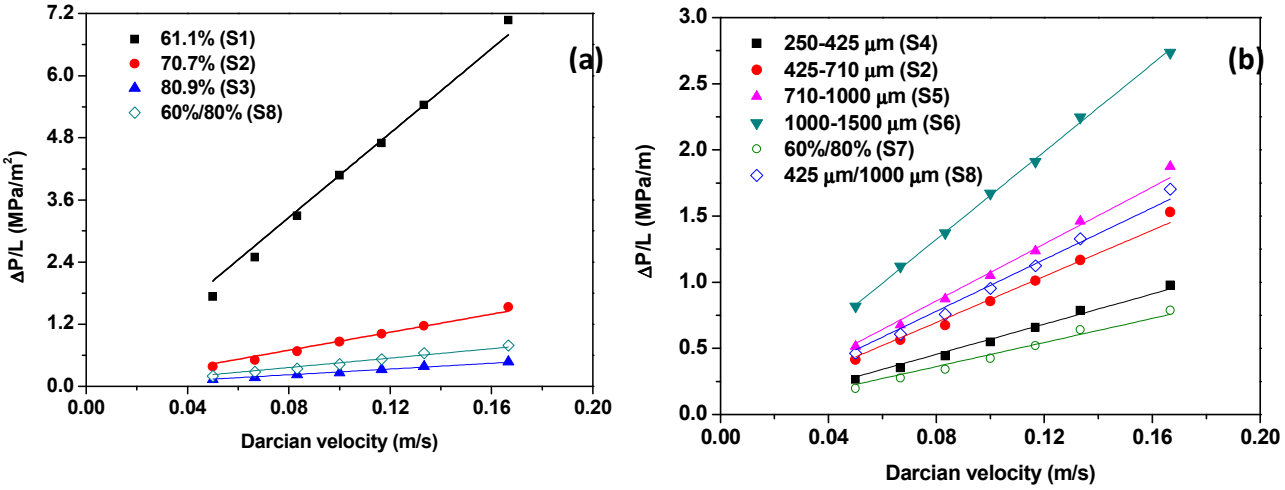

Figure 1 Variations of pressure gradient with Darcian velocity for porous copper specimens: (a) fixed pore size of 425-710 μm and different porosities, and (b) fixed porosity of 71 ± 1% and different pore sizes

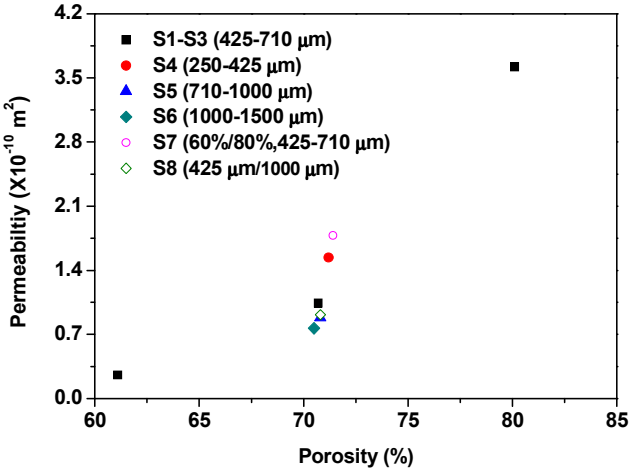

Figure 2 Variation of permeability with porosity for porous copper samples with different pore sizes or layer structures

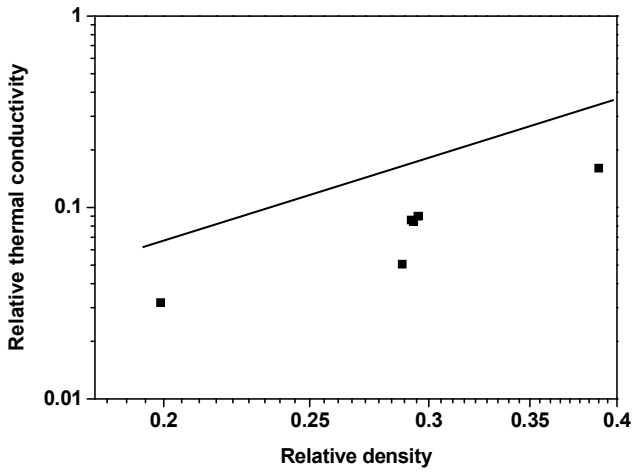

Figure 3 Variation of relative thermal conductivity with relative density

The permeability of LCS porous copper samples with different pore parameters can be explained qualitatively by the connectivity of the pores. Low porosity means less connectivity between neighbouring pores and thus low permeability. As the porosity increases, the chance of one pore being connected to another increases, resulting in a rapid increase in permeability. With a small pore size, the path for fluid flow in the porous samples is less tortuous. The pore size effect on permeability is more obvious at low porosity than at high porosity. The permeability of samples

with double layers is approximately the average of the permeability values of the two constituting layers, as permeability follows the rule of mixture.

Thermal conductivity. Figure 3 shows the variation of relative thermal conductivity with relative density of porous copper samples. There is a power law relationship, which agrees with the results of Thewsey and Zhao [6] and is consistent with the percolation theory [10]. However, the porous copper sample with a fine pore size (250-425 μm, sample S4) deviates from this relationship, indicating that the thermal conductivity is also affected by pore size. The effect of pore size on thermal conductivity stems from the special structure of the LCS porous copper. According to the percolation theory, all copper particles should ideally cluster together to form one dense network, so that the heat could flow smoothly through the network. However, this is not the case for LCS porous copper with randomly packed particles. Dead ends exist in the porous samples, i.e., some particle clusters or cell walls are discontinuous. These dead ends contribute to the mass of the network but do not carry heat flux. When the sizes of the copper particles and potassium carbonate particles are similar to each other, the cell wall may be more discontinuous because copper particles cannot fit into the interstices of the potassium carbonate particle network, leading to decreased probability of copper particles being in contact with each other. Small pores and large copper particles result in increased dead ends, and thus decrease their thermal conductivity. This is another reason that the potassium carbonate particles should be much larger than the copper particles in the LCS method [3].

Heat transfer coefficient. The variations of heat transfer coefficient with Darcian velocity for different porosities or pore sizes are shown in Figure 4. In this study, only one side of the specimen was in contact with the heat resource, so the specimens with double-layer structures were measured in two ways of placement: high permeability layer in contact with the heat resource (normal) or low permeability layer in contact with the heat resource (reverse).

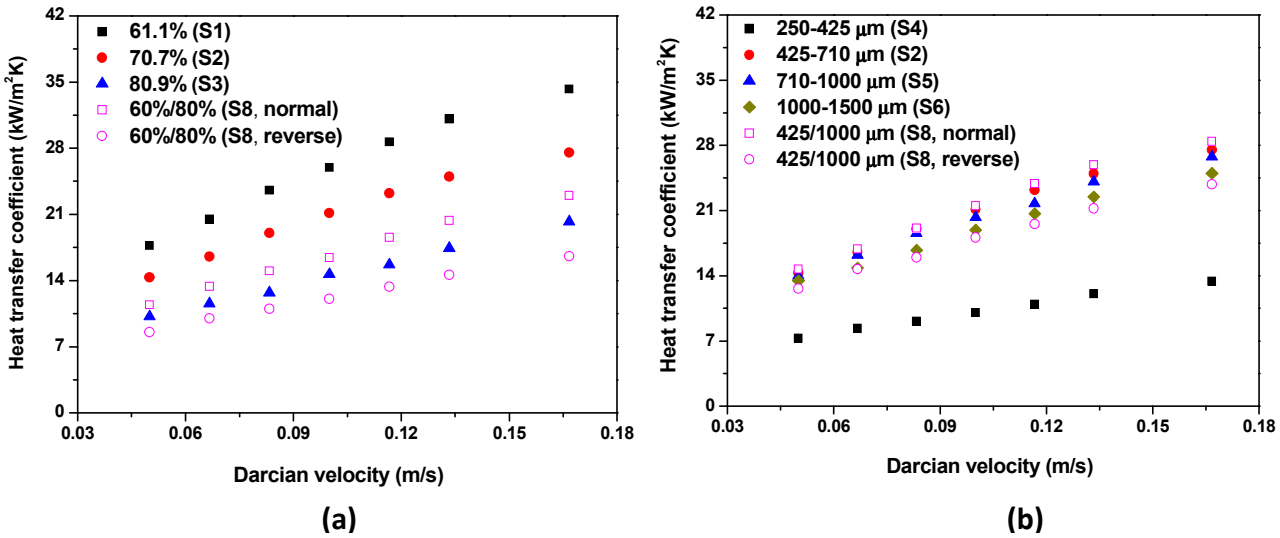

Figure 4 Variations of heat transfer coefficient with Darcian velocity for porous copper samples (a) fixed pore size of 425-710 μm and different porosities, and (b) fixed porosity of 71±1% and different pore sizes

Darcian velocity has a strong effect on heat transfer across all porosities and pore sizes. The heat transfer coefficient increases steadily with Darcian velocity. Increasing the Darcian velocity from 0.05 to 0.17 m/s can increase the heat transfer coefficient nearly twice. The heat transfer coefficient of sample S8, with a double-layer structure of 60%/80%, is higher than that of sample S3 (porosity: 80.1%) but lower than that of sample S2 (porosity: 70.7%). Sample S9 with a double-layer structure of 425 μm/1000 μm and normal placement has better heat transfer performance than the samples

with single layers alone (samples S2 and S6). For double-layer samples, the heat transfer performance is better when the high permeability layer is in contact with the heat source. At all flow rates, the heat transfer coefficients for the samples with normal placement are about 1.5 times of those with the reverse placement.

The surface area, permeability and thermal conductivity of porous copper samples are three key parameters which affect the heat transfer performance. Low porosity samples are less permeable, have lower surface area, but have higher thermal conductivity. Better heat transfer performance at low porosity shows that the influence of thermal conductivity plays a very important role in the heat transfer process of the LCS porous copper.

The effect of pore size on heat transfer coefficient can be explained by the combined effect of permeability and thermal conductivity. For samples with pores larger than 425 μm, their thermal conductivities are similar to each other, but samples with smaller pores are more permeable, leading to better heat transfer performance. The low heat transfer coefficients of samples with the finest pores can be attributed to the low thermal conductivity.

The effect of placement of double-layer samples on heat transfer coefficient is associated with the dominant role of the layer close to the heat plate on transferring heat. The fluid often preferentially chooses the strata with higher permeabilities [11]. As a result, a large amount of the displaced fluid can be left behind in the strata with low permeabilities and makes little contribution to the overall heat transfer. This is the main reason why normal placement is more efficient to remove heat than the reverse placement. A segment model has recently been developed to model the heat transfer performance of porous metals with double-layer structures [8]. Figure 5 shows that the experimental results agree well with the model predictions.

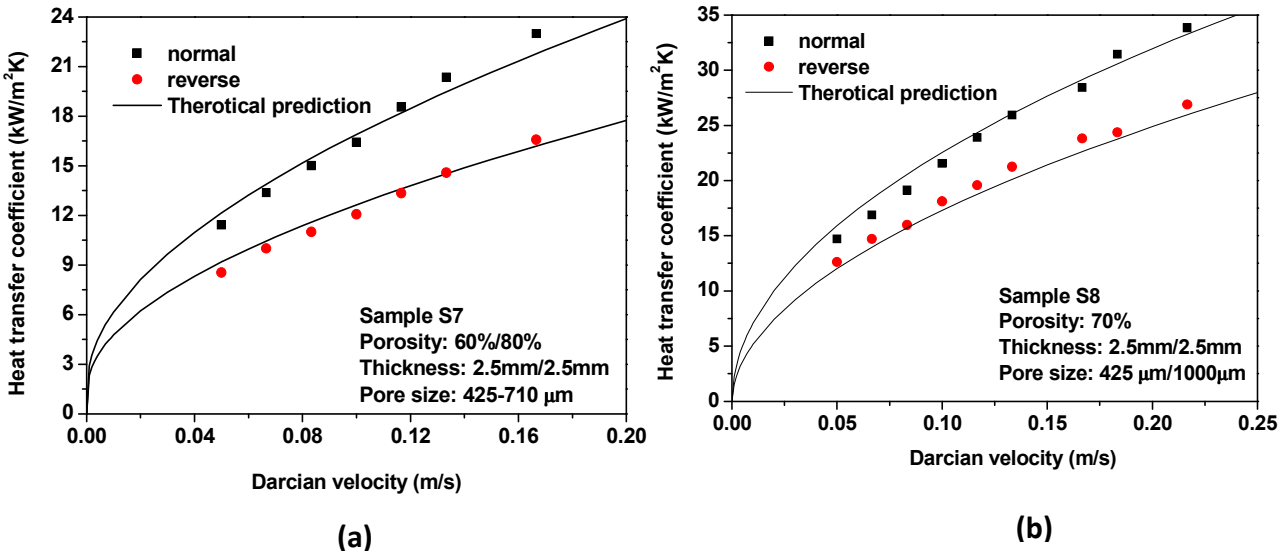

Figure 5 Comparison between the measured values of heat transfer coefficient and the predictions by the segment model for porous copper samples with double layers of different (a) porosity and (b) pore size

Conclusions

The fluid transport and thermal properties of porous copper samples with different pore structures manufactured using LCS method have been investigated. The relationship between the pressure gradient and fluid velocity follows Darcy's law. The permeability increases with porosity but decreases with pore size. The thermal conductivity increases with relative density according to the power law. The porosity and pore size of the porous copper samples have significant effects on the heat transfer performance, because of their effects on the permeability and thermal conductivity.

For the porous copper samples with double-layer structures, the permeability follows the rule of mixture and the heat transfer coefficient can be predicted by the segment model developed in [8].

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