Heat transfer performance of LCS porous copper with different structural characteristics

Kaikan Diao[a*], Xianke Lu[b], Zhining Wu[c] and Yuyuan Zhao[d]

School of Engineering

University of Liverpool

Liverpool

L69 3GH

UK

[a]Kaikan.Diao@liverpool.ac.uk, [b]xianke@liverpool.ac.uk, [c]sgzwu5@liverpool.ac.uk,
[d]yyzhao@liverpool.ac.uk

Keywords: Porous metal, LCS porous copper, heat transfer, pressure drop, coefficient of performance

Abstract

Porous metals are highly efficient media for active cooling and thermal management. However, the working fluid requires high pumping power to flow through the porous metals. This paper investigated the effect of structural characteristics (porosity, pore size and Cu particle size) on the heat transfer performance of porous Cu manufactured by Lost Carbonate Sintering (LCS). The heat transfer coefficient and pressure drop of porous Cu samples with porosity from 0.48 to 0.78, pore size from 250-1500 μm and Cu particle size from 75 to 841 μm were measured under the one-dimensional forced convection condition using water. For all the samples with different pore sizes and Cu particle sizes, the optimum heat transfer coefficient was observed at a porosity between 0.6 and 0.7 and the pressure drop decreased with increasing porosity. The effect of pore size on heat transfer coefficient was not pronounced while pressure drop decreased with decreasing pore size. Samples with large Cu particles (841 μm) had higher optimum heat transfer coefficients and lower pressure drops. The coefficient of performance (*CoP*), which can be used to describe the overall heat transfer performance, increased with increasing porosity, decreasing pore size and increasing Cu particle size.

Introduction

Porous metals have excellent properties and have attracted much attention in both academia and industry in the last few decades [1-3]. Open-cell porous metals, in particular, are competitive substitutes for traditional materials, such as microchannels, in thermal management and active cooling. Open-cell porous Cu has been used in cooling systems for some electronic devices due to its good heat transfer performance, i.e., high heat transfer coefficient and reasonable permeability [4-6].

Forced convection cooling is an important active cooling method and has been used in many industrial and personal electronic products. Here, fluid coolant is blown or pumped to flow through heat sinks, such as microchannels and porous metals, to remove the heat [7]. Porous metals can have a higher heat transfer coefficient than their major competitor microchannels. However, porous metals usually cause a higher pressure drop than microchannels so they require a higher pumping power to move the fluid through them. Therefore, both heat transfer coefficient and pressure drop have to be considered in assessing their heat transfer performance.

The Lost Carbonate Sintering (LCS) process can produce open-cell porous metals with a wide range of porosity (40-85%), pore size (75-1500 µm) and metal matrix (such as Cu, Fe, Ti and Ni) [8]. The LCS porous metals can provide a high internal surface area, thermal conductivity and many other interesting thermal properties. They are promising candidate materials for heat transfer applications [9, 10]. A main problem impeding their wider applications is their large flow resistance which leads to a high pumping power required to move the cooling fluid through.

This paper studies the effects of porosity, pore size and Cu particle size on heat transfer coefficient and pressure drop of LCS porous Cu.

Experimental

Twenty three porous Cu samples with different porosities, pore sizes and Cu particle sizes were fabricated by the LCS process, details of which were described in [8]. The raw materials were commercially pure (>99.9%) Cu powders, with three different particle sizes of 75 µm, 425 µm and 841 µm and a food grade K_2CO_3 powder, which was sieved into four particle size ranges: 250-425 µm, 425-710 µm, 710-1000 µm and 1000-1500 µm. Different combinations of K_2CO_3 and Cu powders were mixed at a pre-specified volume ratio according to the target porosity and then compacted into a preform at 200 MPa. For all the samples, the preform was first pre-sintered at 850ºC for half an hour. The samples were then sintered for 1 hour at 950ºC, 1000ºC and 1050ºC for Cu particle sizes of 75 µm, 425 µm and 841 µm, respectively.

Fig. 1 is a schematic diagram of the experimental apparatus for pressure drop and heat transfer coefficient measurements. All the samples had length of 30 mm, width of 20 mm and height of 5 mm and were placed in the flow channel, 20 mm wide and 5 mm high, for the measurements. The coolant of water flowed in success through a flowmeter to measure the flow rate, a J-type thermocouple to measure the inlet water temperature (T_w), a pressure transducer to measure the inlet pressure (P_{in}), the porous Cu sample, and another pressure transducer to measure the outlet pressure (P_{out}). The pressure drop, ΔP, can be obtained from the two pressure transducers by:

$$\Delta P = P_{in} - P_{out} \tag{1}$$

For heat transfer coefficient measurements, the heat flow was produced by the heat cartridges imbedded in a copper heat block. The lower part of the heat block had the same cross-section as the porous Cu sample, i.e., length of 30 mm and width of 20 mm, and was pressed tightly against the sample. The heat transfer coefficient, h, can be obtained by Newton's law:

$$h = \frac{Q}{A(T_b - T_w)} \tag{2}$$

where Q is the heat flow to the coolant, A is the interfacial area between the heat block and the sample, T_b is the temperature of the bottom surface of the heat block and T_w is the temperature of the water before entering the sample.

The heat flow to the coolant can be calculated by the temperature gradient of the lower part of the copper heating block:

$$Q = \lambda A \frac{T_t - T_b}{d} \tag{3}$$

where λ is the thermal conductivity of copper (391 W/mK), T_t and T_b are the temperatures of the top and bottom spots, respectively, of the heating block measured by two T-type thermocouples, and d is the distance between these two spots (60 mm).

Combining Eq. 2 and Eq. 3, the heat transfer coefficient can be determined by:

$$h = \frac{\lambda(T_t - T_b)}{d(T_b - T_w)} \tag{4}$$

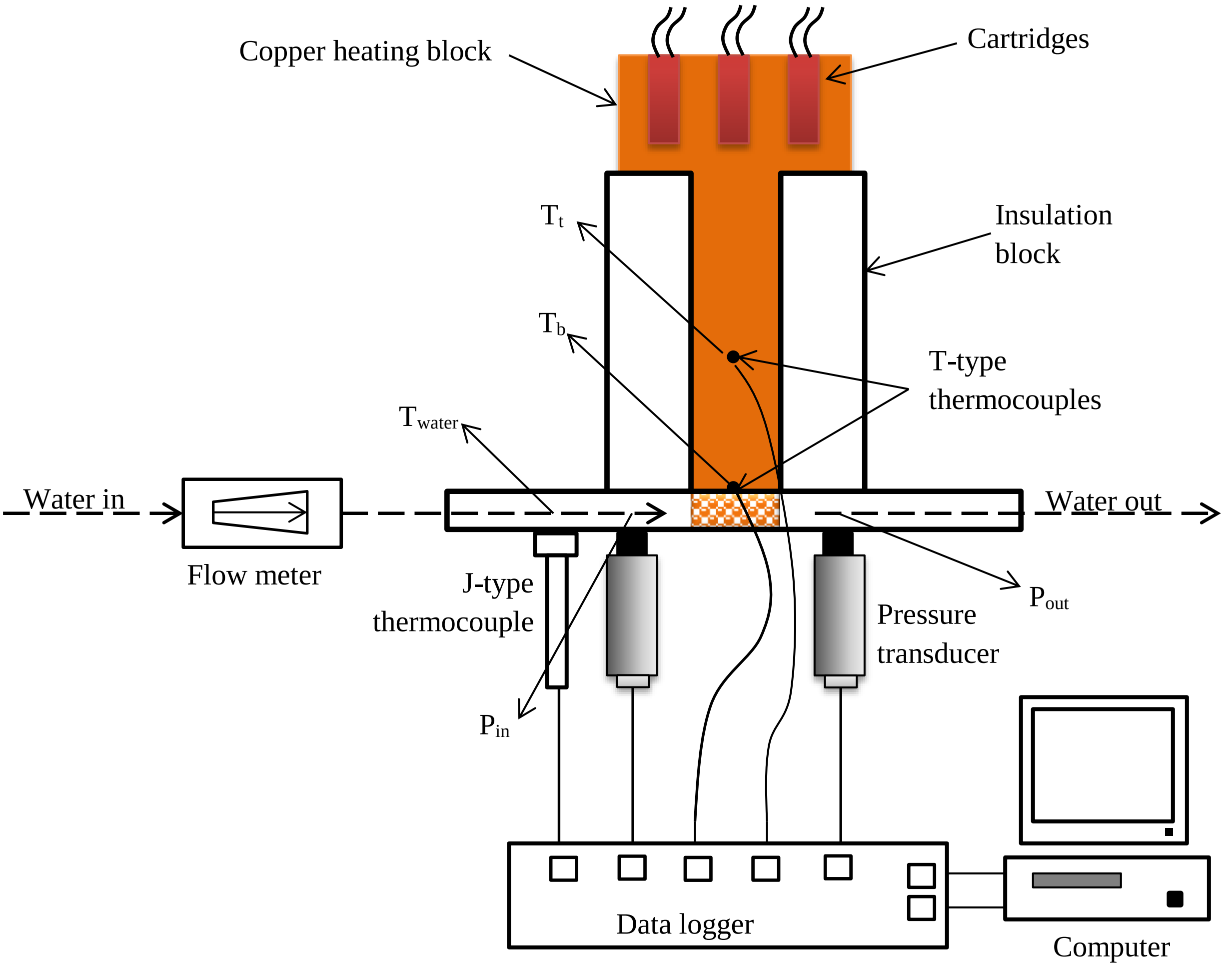

Fig. 1 Schematic diagram of the experimental apparatus for pressure drop and heat transfer coefficient measurements

Results and Discussion

Heat transfer coefficient

The samples with the porosity ranging from 0.48 to 0.78, pore size from 250-1500 µm and Cu particle size from 75 to 841 µm were tested in this study at a flow rate of 2.0 L/min. The effects of these structural characteristics on heat transfer coefficient were investigated and the results are summarised in Fig. 2. For all the samples, the heat transfer coefficients are in the range of 10-25 kW/m^{2}K.

Porosity has a significant effect on the heat transfer coefficient. The heat transfer coefficient first increases with porosity until reaching a peak value (around 24 kW/m^{2}K) at a porosity around 0.6 to 0.7 and then decreases with porosity. The effect of porosity on the heat transfer performance can be analysed by considering both conduction and convection. For a sample with a high porosity, the low volume of copper matrix causes low conduction of heat from the heat plate [9, 11], while there is sufficient convective heat transfer through the coolant. The overall heat transfer coefficient is therefore low due to the low conductive heat transfer. On the contrary, for a sample with a low porosity, the conduction of heat is increased because of the high volume of copper matrix. However, the convective heat transfer is reduced because less open channels for the coolant to flow through and less interfacial area between the solid matrix and the coolant. The optimum porosities, at which there is a good balance between conduction and convection, are 0.6, 0.63 and 0.69 for Cu particle sizes of 841 µm, 425 µm and 75 µm, respectively. At the optimum porosities at 0.6 to 0.7, the heat transfers by conduction and convection are both strong and the highest heat transfer coefficient can be obtained.

The effect of pore size on the heat transfer coefficient is not significant. For a given porosity of 0.68, for example, the heat transfer coefficients for the samples, with the same Cu particle size of 75 µm, and different pore sizes of 250-425 µm, 425-710 µm, 710-1000 µm and 1000-1500 µm, are 22.9, 24.7, 22.0 and 23.6 kW/m^{2}K, respectively. Compared with porosity, the effect of pore size is negligible.

The effect of Cu particle size on the heat transfer coefficient is complex. For samples with the same pore size of 710-1000 µm but different Cu particle sizes, the heat transfer coefficients are in the ranges of 13.1-22.0 kW/m^{2}K, 15.9-25.1 kW/m^{2}K and 22.5-25.4 kW/m^{2}K for Cu particle sizes of 75 µm, 425 µm and 841 µm, respectively. When the porosity is around 0.68, the effect of particle size on heat transfer coefficient is not significant. At a low porosity (<0.65), however, the samples with the large Cu particle size has greater heat transfer coefficients than those with the small Cu particle size (75 µm). An especially interesting trend is that the porosity corresponding to the peak heat transfer coefficient decreases with Cu particle size and the peak heat transfer coefficient increases slightly with Cu particle size.

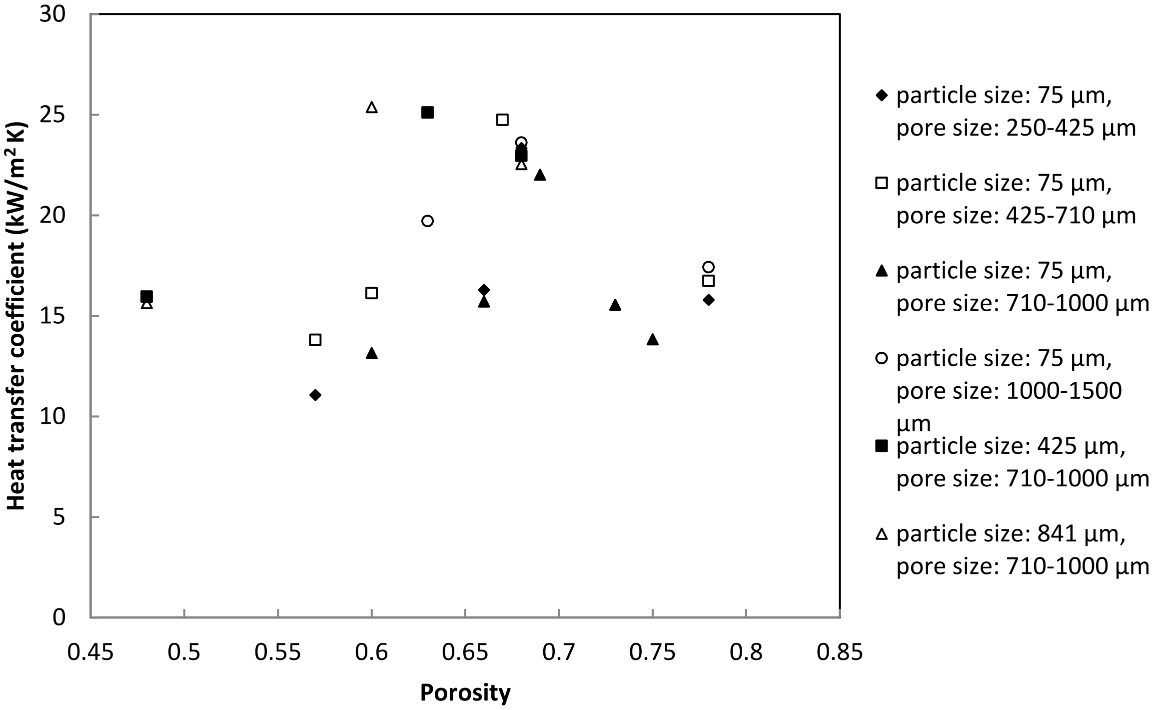

Fig. 2, Variations of heat transfer coefficient as a function of porosity, pore size and Cu particle size at a flow rate of 2.0 L/min

Pressure drop

The samples used in the heat transfer measurements were subjected to the pressure drop measurements at a flow rate of 2.0 L/min. Fig. 3 shows the variations of pressure drop as a function of porosity, pore size and Cu particle size.

The pressure drop decreases with porosity for all the samples with different Cu particle sizes and pore sizes. At a high porosity, there is more space for the fluid flow and the chance of a pore being connected to other pores is also increased. As a consequence, the working fluid can flow through the sample more easily and the pressure drop is decreased. Low porosity means less space for fluid flow, the pores being interlinked by fewer windows and the fluid pathways in the porous metal becoming easily blocked [12, 13], leading to greater pressure drop [14]. The increasing number of interlinked windows for high porosity has been confirmed to result in low tortuosity of fluid pathways in the porous metal [15]. The low tortuosity also leads to low fluid resistance and thus low pressure drop.

The pressure drop increases with pore size for the samples with the same Cu particle size of 75 µm. This is because the tortuosity of the fluid pathways in the porous Cu sample increases with pore size due to the increased chances of pores being connected to each other [15]. Low tortuosity means that the working fluid can flow through the sample more easily. Therefore, the samples with small pore sizes have low pressure drops.

The pressure drop of the porous Cu samples decreases with the Cu particle size, mainly because larger Cu particles have larger interstices between them. The water can flow through the sample not only through the primary pores produced by the K_2CO_3 particles, but also through the interstices between the Cu particles, leading to a decreased pressure drop.

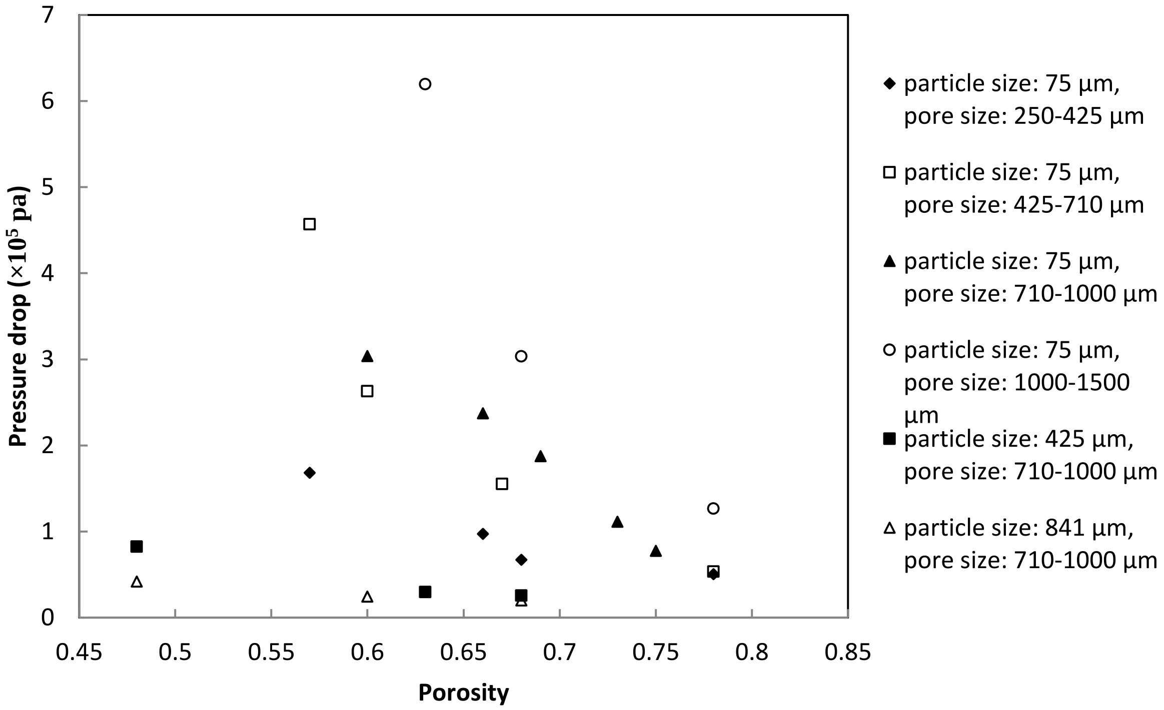

Fig. 3, Variations of pressure drop as a function of porosity, pore size and Cu particle size at a flow rate of 2.0 L/min

Coefficient of performance

Both heat transfer coefficient and pressure drop are very important for thermal applications. However, good heat transfer coefficient is often associated with high pressure drop and vice versa. The overall performance of porous metals for heat exchange applications, such as cooling systems and heat pumps, can be described by the coefficient of performance (*CoP*) [16,17], which is the ratio of the heat flux and the pumping power and can be determined by:

$$CoP = \frac{q}{P_p} = \frac{hA\Delta T}{\Delta PQ} \tag{5}$$

where q is the heat flux transferred by the working fluid through the porous metal and P_p is the pumping power for moving the working fluid. The heat flux and pumping power can be calculated by the numerator and denominator terms on the right hand side of Eq. 5, respectively. Here, h is heat transfer coefficient, A (6 cm^2 in this work) is the interfacial area between the heat block and the porous Cu sample, ΔT is the difference in temperature between the solid surface and the cooling fluid, ΔP is pressure drop and Q is flow rate (2.0 L/min in this work).

The comparison of performance between different samples needs to be conducted under the same temperature difference between the component to be cooled and the coolant. The operating temperature of a commercial electronic part cannot exceed 70°C [18] and the most common coolant is water at room temperature of 25°C. The maximum difference in temperature between the solid surface of electronic part and the cooling water is therefore less than 45°C. For comparison purposes, ΔT is fixed as 45°C in this work. The coefficient of performance of the porous Cu sample in this case, i.e., when the cooling fluid is 45°C cooler than the solid surface, is designated as CoP_{45}.

Fig. 4 shows the variations of CoP_{45} as a function of porosity, pore size and Cu particle size. In most cases, the coefficient of performance increases with porosity. Because pressure drop decreases and heat transfer coefficient increases with porosity up to 0.7 (Figs. 2 and 3), the coefficient of performance increases with porosity. Although heat transfer coefficient becomes lower when the porosity is higher than 0.7 (Fig. 2), the significant decrease in pressure drop can compensate the reduction in heat transfer coefficient. The coefficient of performance still increases with porosity. An exception occurred in the sample with pore size of 250-425 µm and Cu particle size of 75 µm, where CoP_{45} has a peak value at the porosity of 0.68. This is because there is a significant decrease in heat transfer coefficient at high porosity (Fig. 2), which outweighs the decrease in pressure drop.

The coefficient of performance increases with pore size in general, although the effect of pore size on overall heat transfer performance is not as significant as porosity. The samples with a porosity of around 0.68 and the same Cu particle size of 75 µm have *CoP_{45}* values of 63, 95, 129 and 282 for pore sizes of 1000-1500 µm, 710-1000 µm, 425-710 µm and 250-425 µm, respectively. This is because the heat transfer coefficients of these samples are very similar (Fig. 2), but the pressure drop decreases with pore size.

The Cu particle size has a large effect on overall heat transfer performance. The *CoP_{45}* of the porous Cu samples with the same pore size of 710-1000 µm but different Cu particle size of 75 µm, 425 µm and 841 µm are in the ranges of 35-144, 156-729 and 301-908, respectively, in the porosity range studied in this work. Take the samples with the porosity of 0.6 as an example, the *CoP_{45}* values for the Cu particle sizes of 75 µm and 841 µm are 35 and 832, respectively, with a difference nearly 24 times. The rapid improvement in the overall heat transfer performance with Cu particle size is due to the fact that larger Cu particle size results in higher heat transfer coefficient and lower pressure drop as shown in Figs. 2 and 3.

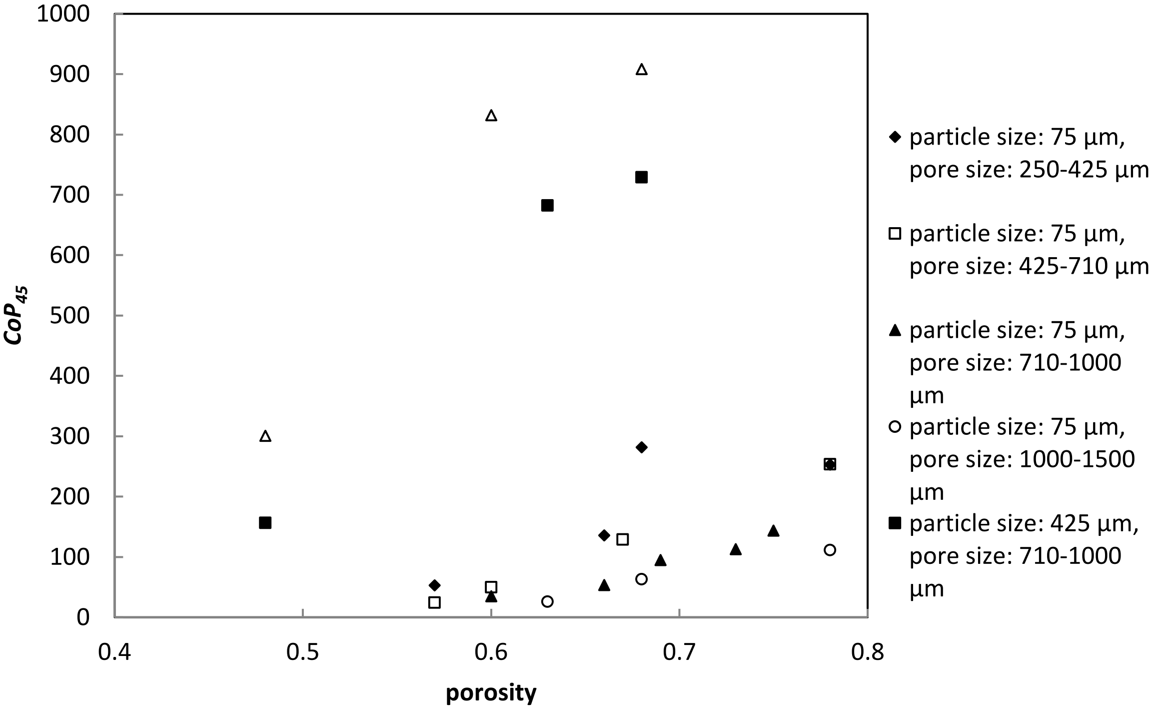

Fig. 4, Variations of coefficient of performance (*CoP_{45}*) as a function of porosity, pore size and Cu particle size at a flow rate of 2.0 L/min

Conclusions

The heat transfer coefficient and pressure drop of porous Cu samples produced by the LCS process with different porosities, pore sizes and Cu particle sizes have been investigated. The heat transfer coefficient is influenced by both conduction and convection. The optimum porosity to give the highest heat transfer coefficient is obtained at 0.6-0.7 because of a balance between conduction and convection. The pressure drop decreases with porosity. The effect of pore size on heat transfer coefficient is not pronounced while pressure drop decreases with decreasing pore size. The overall heat transfer performance can be described by the coefficient of performance (*CoP*). In general, CoP increases with increasing porosity, decreasing pore size and increasing Cu particle size. The effect of Cu particle size is especially large. Larger Cu particle size results in higher heat transfer coefficient and lower pressure drop and therefore CoP.

Acknowledgments

This work has been supported by the Engineering and Physical Sciences Research Council (Grant No. EP/N006550/1).

References

[1] L.J. Gibson, M.F. Ashby, Cellular Solids: Structure and Properties, second ed., Cambridge: Cambridge University Press, 1999.

[2] M. Ashby, Metal Foams: A Design Guide, Boston: Butterworth-Heinemann, 2000.

[3] J. Banhart, Manufacture, Characterisation and Application of Cellular Metals and Metal foams, Prog. Mater. Sci., 46 (2001) 559.

[4] A.J. Fuller, T. Kim, H.P. Hodson, T.J. Lu, Measurement and Interpretation of the Heat Transfer Coefficients of Metal Foams, Proc. IMechE, 219 (2005) 183-191.

[5] G. Hetsroni, M. Gurevich, R. Rozenblit, Sintered Porous medium Heat Sink for Cooling of High-power Mini-devices, Int. J. Heat Fluid Fl., 27 (2006) 259-266.

[6] K. Boomsma, D. Poulikakos, F. Zwick, Metal Foams as Compact High Performance Heat Exchangers, Mech. Mater., 35 (2003) 1161-1176.

[7] M. Wong, I. Owen, C.J. Sutcliffe, A. Puri, Convective Heat Transfer and Pressure Losses across Novel Heat Sinks Fabricated by Selective Laser Melting, Int. J. Heat Mass Tran., 52 (2009) 281-288.

[8] Y.Y. Zhao, T. Fung, L.P. Zhang, Lost Carbonate Sintering Prosciee for Manufacturing Metal Foams, Scr. Mater., 52 (2005) 295.

[9] L.P. Zhang, D. Muulen, K. Lynn, Y.Y. Zhao, Heat transfer performance of porous copper fabricated by the Lost Carbonate Sintering process, Mater. Res. Soc. Symp. Proc., 1188 (2009) 07.

[10] Z. Xiao, Y.Y. Zhao, Heat transfer coefficient of porous copper with homogeneous and hybrid structures in active cooling, J. Mater. Res., 28 (2013) 2545.

[11] Z. Xiao, Y.Y. Zhao, Thermal properties of porous copper manufactured by lost carbonate sintering, Mater. Sci. Forum,783-786 (2014) 1603-1608.

[12] W. Zhou, Y. Tang, M. Pan, X. Wei, H. Chen, J. Xiang, A performance study of methanol steam reforming microreactor with porous copper fiber sintered felt as catalyst support for fuel cells, Int. J. Hydrogen Energ., 34 (2009) 9745-9753.

[13] W. Zhou, Q. Wang, Q. Qiu, Y. Tnag, J. Tu, K.S. Hui, K.N. Hui, Heat and mass transfer characterization of porous copper fiber sintered felt as catalyst support for methanol steam reforming, Fuel, 145 (2015) 136-142.

[14] D.J. Thewsey, Y.Y. Zhao, Thermal conductivity of porous copper manufactured by the lost carbonate sintering process, Phys. Status Solidi A, 205 (2008) 1126-1131.

[15] K. Diao, L.P. Zhang, Y.Y. Zhao, Measurement of tortuosity of porous Cu using a diffusion diaphragm cell, Measurement, 110 (2017) 335-338.

[16] F. Agyenim, The use of enhanced heat transfer phase change materials (PCM) to improve the coefficient of performance (COP) of solar powered LiBr/H_2O absorption cooling systems, Renew. Energ., 87 (2016) 229-239.

[17] Z. Zhuang, G. Li, Y. Zhang, Y. Li, Optimization study on the heat transfer area of the sewage source heat pump system based on year-round coefficient of performance, Procedia Eng., 121 (2015) 1535-1543.

[18] D. Humphrey, L. Condra, N. Pendse, D. Das, C. Wilkinson, M. Pecht, An avionics guide to uprating of electronic parts, IEEE T. Compon. Pack. T., 23 (2000) 595-599.