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Experimental Study of Thermal Conductivity of Open- Cell Porous Aluminium Manufactured by Infiltration Processing Technique.

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Abstract

The thermal conductivity of open- cell porous aluminium structures has been studied. Open- cell porous aluminium structures were produced by infiltrating liquid aluminium through the pore spaces between loose compacts of sodium chloride beads. The window size, relative density and porosity of the porous aluminium materials were varied by producing samples at different infiltration pressures. The samples were characterized by using scanning electron microscopy, micro- computed tomography and the thermal conductivity of the samples were determined using a C- therm analyzer. Microscopic and tomographic analyses revealed that the structure of the porous materials consisted of near spherical cells, randomly dispersed within aluminium matrix and which are interconnected pore windows and that the window diameter of the porous aluminium structures increases as the infiltration pressure was decreased while the cells replicated the shape and size of sodium chloride beads from which they were manufactured. Thermal analysis showed that the thermal conductivity of the porous samples varies as a power of the relative density of the porous material and that a Scaling function based on percolation theory and the Ashby model best fit the experimental data for the effective thermal conductivity of the porous aluminium structures.

Keywords: Porous Metal, Relative Density, Window Size, Infiltration Processing, Thermal Conductivity

1. Introduction

Improvement of heat transfer in thermal devices such as heat exchangers and electronic equipment has become an important consideration in many industries. As a consequence, many techniques have been proposed such the use of fins, baffles and porous metals. The use of porous aluminium structures in heat transfer applications is receiving considerable attention because of their light weight, large surface area density, high permeability and high thermal conductivity which make them to be promising materials for industrial applications involving fluid flow and heat transfer [1]. According to the connectivity of cells, porous metals can be classified as either closed- or open- celled. Closed cell porous metals possess higher elastic moduli, strength and impact energy absorbing capacity than their open cell counterparts while the morphology of the open- cell sponges make them to be more suitable for functional applications such as filtration, sound absorption and heat exchange [2]. The heat transfer properties of open- cell porous metals are so promising that they are used in multi- functional heat exchangers [3], as compact heat sinks for cooling of micro- electronic devices such as computer chips or power electronics [3] and also to increase the internal energy of a working fluid through heat transfer to the fluid, thereby, increasing the fluids capacity for work [4].

There are a variety of ways for producing open- cell porous aluminium; in which investment casting and perform infiltration are the most widely used routes [1]. Investment casting involves filling the pores of polymer foam like polyurethane foam with a refractory mixture, consisting of mullite, phenolic resin and calcium carbonate [5]. The refractory material is hardened by curing and further heated until the polymer foam vaporizes, leaving the refractory material as a porous mould. Molten metal is poured into the resulting open voids which replicate the

original polymer foam structure. The mould material is removed by pressurized water. This method is expensive but produces porous metal with high quality [5]. Conversely infiltration processing involves liquid penetration of the open pore spaces within the preform of a second, solid material [6]. Infiltration processing technique involves four steps: preparing a leachable preform (usually sodium chloride for the manufacturing of porous aluminium); infiltration of molten metal into the preform; solidification of molten metal; and dissolution of the preform in solvent or water [6]. Remarkable advantages of this method are that porous materials, resulting from this process have microstructures with architecture that is controlled by the microstructure of the preform and the physical and mechanical properties of porous structures are consistent and reproducible because of the uniform distribution of the cell sizes [7]. Porous metal ligaments are dense, leading to fewer internal defects and higher relative density than porous metals made by investment casting [7].

Accurate evaluation of thermal conductivity of porous materials is extremely advantageous because it provides a good understanding about the thermal behaviour of a porous structure. There exist a large number of models for the calculation of the thermal conductivity of porous metals with sometimes inconsistent and inaccurate results [8, 9]. It can be argued that the most reliable source of information is experimental measurement. There are many publications on the experimental determination of the thermal conductivity of cellular materials as reported in [9, 10] but to our knowledge no particular articles on medium porosity open- cell aluminium structures manufactured by infiltration processing method has been reported. A recent study in [8] focused on the experimental evaluation of the thermal conductivity of closed- cell aluminium sponges of equivalent porosity manufactured by a powder metallurgical route. The findings of this work may not give adequate information of the thermal behaviour of open- cell porous aluminium structures manufactured by the liquid infiltration processing method due to structural differences.

In this work, an experimental approach was adopted to determine the thermal conductivity of open- cell porous aluminium sponges. The results were compared and analyzed with some existing theoretical and empirical thermal conductivity models while the constants of some of the empirical models were evaluated for these porous materials in order to improve their predictive accuracies. The objectives of this paper are to measure the thermal conductivity of open- cell aluminium structures manufactured by liquid infiltration processing and to analyze the results by comparing them to predictions from common theoretical and empirical models.

2. Experimental

2.1 Open- cell porous aluminium manufacturing and structural characterization

Porous sodium chloride (NaCl) salt beads, shown in figure 1, having the size range of 2.0- 2.5 mm were used as leachable templates for the production of open- cell porous aluminium samples. The NaCl beads were made using a process described in [10] which consists of the disintegration of a paste containing pre- gelatinized flour, NaCl and water in heated vegetable oil. The beads were poured into a 35 mm diameter flanged stainless steel mould, tapped a few times to improve packing and the arrangement was pre- heated to 600 ^{o}C, inserted into a vacuum chamber which was subjected to suction pressures ranging from 0.12- 1.02 bar (88mmHg- 760 mmHg). Liquid 99.5 % aluminium was, thereafter, cast into the stainless steel- filled NaCl beads mould at 800 ^{o}C and allowed to infiltrate through the beads at the varying applied pressures. Cast samples were machined into suitable sizes for further analyses. The sodium chloride salt beads were dissolved in a water bath maintained at 50 ^{o}C for 48 hours.

The resulting porous aluminium samples were weighed using an electronic balance and the densities of the porous metals were determined from the geometry of the samples and their mass. The relative density of the samples was determined as the ratio of the density of the porous samples to the density of aluminium. The structure of the porous samples and NaCl beads was investigated using the scanning electron microscope (JEOL 6400) and micro computed tomography (Scanco AG, μCT40).

2.2 Thermal conductivity testing

A thermal Conductivity Analyzer (C- therm) was used in testing the thermal conductivity of the open- cell porous aluminium samples. The C-Therm Analyzer is based on the modified transient plane source technique. It uses a one- sided, interfacial, heat reflectance sensor that applies a momentary, constant heat source to a sample. The system comprises a sensor, control electronics and computer software (TCi). In operation, a known current is applied to the sensor's heating element which provides a small amount of heat, resulting in less than 2 ^{o}C rise in temperature at the interface between the sensor and the sample. This temperature rise at the interface induces a change in the voltage drop of the sensor element which is translated to effusivity value of the tested material and the thermal conductivity is calculated from the voltage data by the C-therm's patented iterative method. During the testing of the porous aluminium samples, the base of the specimens was coated with a thermal paste (Wakefield 120-5) in order to minimize contact resistance between the sensor and the samples and a 500 g weight was applied to further ensure good thermal contact. The test was run by executing a computer programme after inputting relevant materials data.

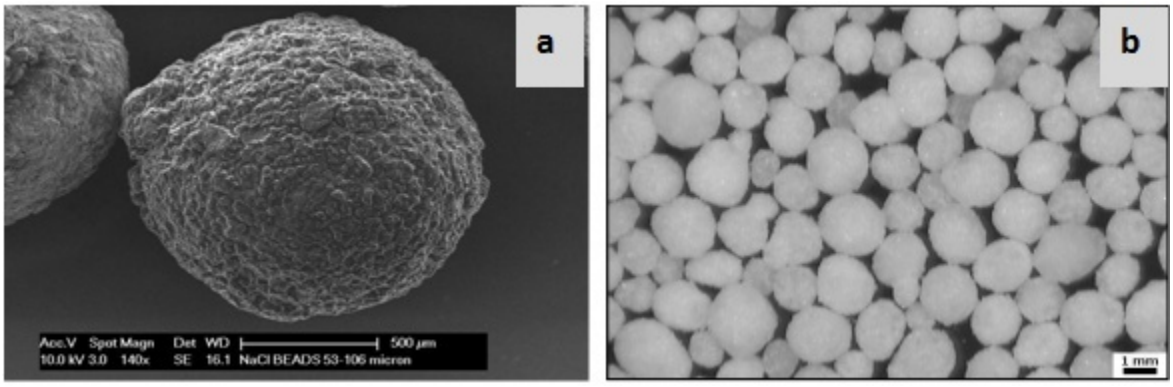

Figure 1: SEM images of sodium chloride salt beads (a) single bead and (b) multiple beads.

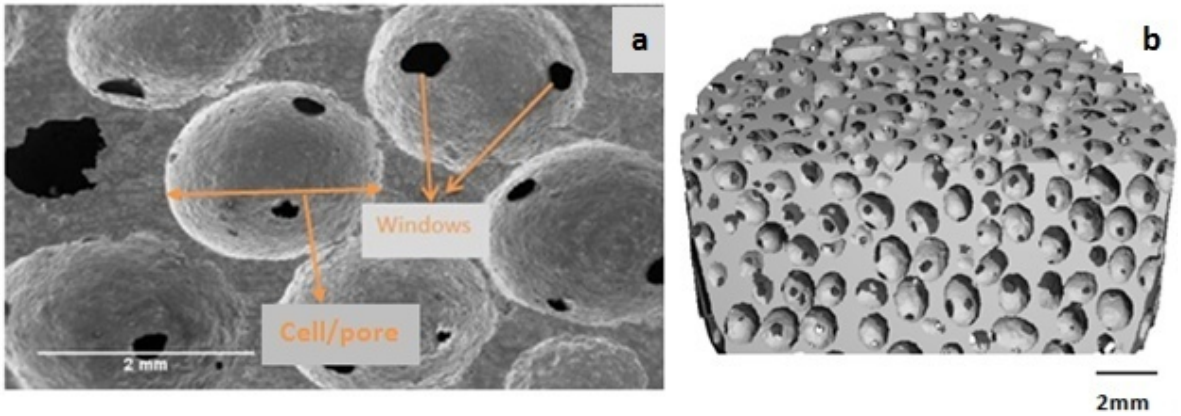

Figure 2: (a) SEM and (b) MicroCT images of open- cell porous aluminium sample.

3. Results of thermal conductivity and discussion

The scanning electron microscope (SEM) image of the porous aluminium manufactured by liquid infiltration processing technique is shown in figure 2 while the morphological characteristics of the porous aluminium samples are shown in Table 1. The SEM image shows the porous aluminium structure consists of randomly dispersed cells which are interconnected by windows. In the nomenclature of the samples, as presented in Table 1, In the nomenclature of the samples as presented in Table 1, 2.0/88 mmHg stands for a porous aluminium sample which was manufactured from sodium chloride salt beads whose size ranges from 2.0-2.5mm under an

infiltration pressure of 88 mmHg. As seen, the relative density of the samples increases as the infiltration pressure is increased while the window size conversely decreases with the applied pressure.

Table 1: Morphological characteristics of experimental open- cell porous aluminium samples

Sample	2.0/88mmHg	2.0/130mmHg	2.0/180mmHg	2.0/400mmHg	2.0/760mmHg
Relative density	0.35	0.36	0.37	0.37	0.38
Window Ø (mm)	0.72	0.66	0.54	0.42	0.40
Cell size Ø (mm)	2.25	2.25	2.24	2.24	2.25

The effect of relative density on the thermal conductivity of the open- cell porous aluminium samples is shown in figure 3. As shown, the thermal conductivity of the porous aluminium structures increases as the relative density of the material is increased. This is expected since at higher relative density, the volume fraction of metal is higher and this increases the effective thermal conductivity of the porous materials. It can be stated from figure 3 that the thermal conductivity, k, of the open- cell porous aluminium structures varies as a power of the relative density, ρ_r, of the porous aluminium according to equation 1:

$$K = 206.89\rho_r^{1.76} \quad (1)$$

The value of the dynamic exponent (1.76) is within the range (1.65- 1.85) prescribed in the scaling function model for the thermal conductivity of porous metals [11] and the correlation coefficient (206.89) is close to the thermal conductivity of pure aluminium.

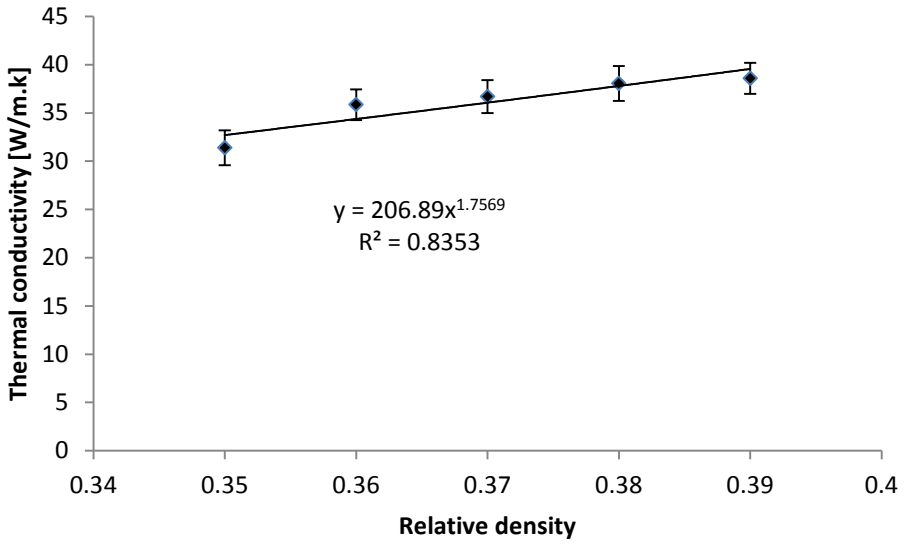

Figure 3: Effect of relative density on the thermal conductivity of open- cell porous aluminium

Figure 4 presents the analysis of experimentally measured thermal conductivity of the porous aluminium samples with thermal conductivity models based on simplified unit cell arrangement. The models include: the Series/Parallel [8]; Parallel/Series [8]; Doherty [12]; Russell [13]; and the Misnar models [8] while figure 5 shows the analysis of measured thermal conductivity with some empirical models which include: Ashby [11]., Scaling function [11]; Bhattacharya [14]. As seen from figure 4, the series/parallel, parallel/series, Doherty, Russells and Misnar models over- estimated the thermal conductivity of the cellular samples. The thermal conductivity models show the

corresponding deviations from the experimental values as follows: Series/parallel model 77.56%; Parallel/series model 94.69%; Doherty model 85.19%; Russell model 95.50%; and Misnar model 75.19%. The above models probably over- estimated the thermal conductivity of the open- cell porous aluminium samples because they assumed simplified, homogeneous and repetitive unit cells such as the cubic cells for the parallel- series, series-parallel and Russell models whereas the experimental samples have structures consisting of randomly dispersed, near- spherical heterogeneous cellular structures which are interconnected by windows as shown in figure 2. The models have been, however, proposed for closed- cell metallic foams. Table 2 presents a summary of some thermal conductivity models.

Table 2: Summary of some thermal conductivity models.

Name	Model	Ref
Series/Parallel	$\lambda_{gs} = \lambda_s (1- V_g^{2/3}) + \frac{\lambda_s V_g^{2/3}}{\lambda_g+(\lambda_s-\lambda_g)V_g^{1/3}}$	[8]
Parallel/Series	$\lambda_{gs} = \lambda_s (1- V_g^{2/3}) + \frac{\lambda_s V_g^{2/3}}{\lambda_g+(\lambda_s-\lambda_g)V_g^{1/3}}$	[8]
Doherty	$\lambda_{gs} = \frac{\lambda_s\lambda_g(2V_g+1)+2\lambda_s^2(1-V_g)}{\lambda_g(1-V_g)+\lambda_s(2+V_g)}$	[12]
Russell	$\lambda_{gs} = \lambda_g(\frac{V_g^{2/3}+(\lambda_s/\lambda_g)(1-V_g^{2/3})}{(1-V_g^{2/3}+V_g)+(\lambda_g/\lambda_s)(V_g^{2/3}-V_g)})$	[13]
Misnar	$\lambda_{gs} = \lambda_s(1+\frac{1-\lambda_s/\lambda_g}{1-V_g^{1/3}(1-\lambda_s/\lambda_g)})$	[8]
Ashby	$\lambda_{gs} = \xi\lambda_s(\rho_f/\rho_s) = \xi\lambda_s(1 - V_g)$	[8]
Scaling	$\lambda_{gs} = \lambda_s(\rho_f/\rho_s)^n = \lambda_s(1 - V_g)^n$	[8]
Bhattacharya	$k_{eff} = M(\varepsilon k_f + (1-\varepsilon)k_s + \frac{(1-M)}{(\varepsilon/k_f+(1-\varepsilon)/k_s)}$	[14]

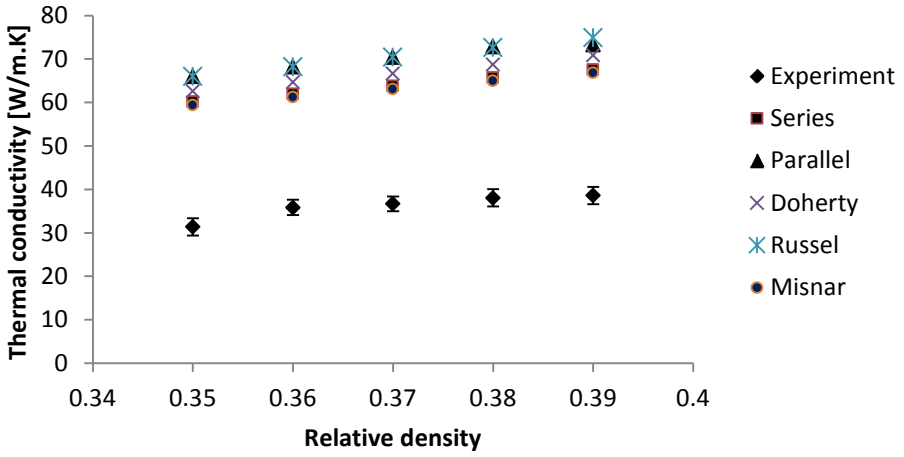

Figure 4: Comparison between measured and thermal conductivity models based on unit cell approaches.

As shown in figure 5, the thermal conductivity models of Ashby, Scaling function, and Bhattacharya which are based on empirical correlations gave thermal conductivity estimates that are close to the measured values. For the Ashby model, the thermal conductivity of the porous samples was calculated using efficiency factor $\xi = 0.5$ which is the mid- range of the efficiency factor, while $n = 1.75$ which is the mid- range of the dynamic exponent was used for the scaling function. $M = 0.35$ was used for the Bhattacharya et al model. The thermal conductivity models were computed using the thermal conductivity of solid aluminium equal to 237 W/m.K [15] and that of air equal to

0.024 W/m.K [16]. It can, however, be deduced from figure 6 that a Scaling function with n = 1.89, the Ashby model with ξ = 0.42, and the Bhattacharya et al model with M = 0.42 fit the experimental data very closely. The parameters: n = 1.89; ξ = 0.42 and M = 0.42 where determined by calibrating these models against the experimental data.

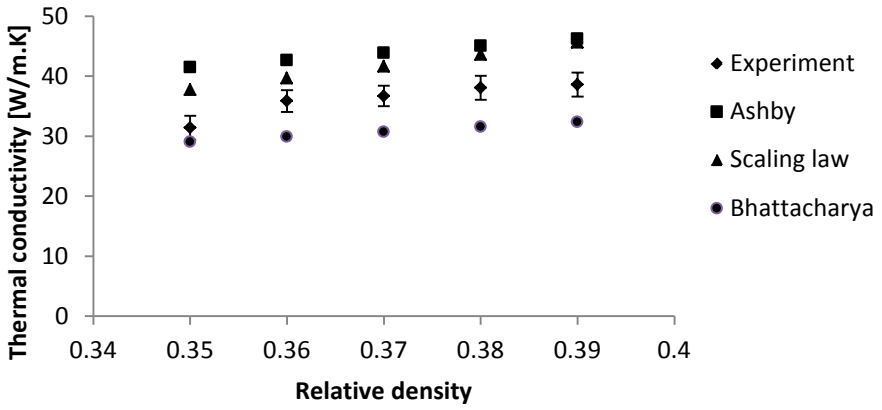

Figure 5: Comparison between measured thermal conductivity and thermal conductivity models based on empirical correlations.

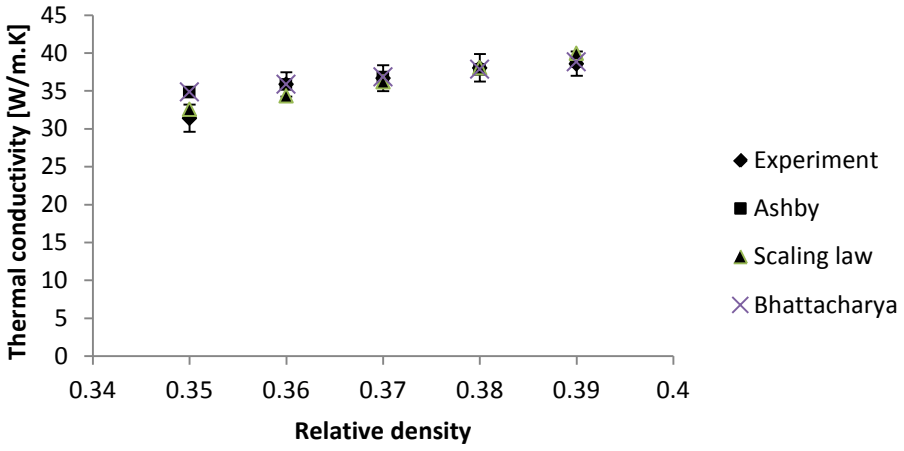

Figure 6: Comparison between measured thermal conductivity and thermal conductivity models with n=1.89, ξ=0.42 and M=0.42 for Ashby model, scaling function and Bhattacharya models respectively.

The Bhattacharya model (with M = 0.35) shows a deviation of 14.70% from the experimental results. However, M was determined for the porous aluminium samples to be equal to 0.42 in order for the Bhattacharya model to predict the thermal conductivity of the open- cell porous aluminium samples more accurately. With M = 0.42, the Bhattacharya model showed 2.55% deviation from the experimental thermal conductivity values. The modified M value was due to the fact that Bhattacharya empirically evaluated M from porous aluminium structures whose porosities ranged between 0.89 and 0.97 whereas the porosity of the experimental samples ranged between 0.62 and 0.65. With a factor of efficiency of ξ = 0.5, the Ashby model shows 21.75% deviation from the experimental data. ξ Was evaluated and found to be equal to 0.42 for the porous open- cell aluminium samples. A linear relationship with ξ = 0.42 fits the experimental data with a deviation of 2.52%. 0.42 falls within the range (0.33- 0.67) prescribed by Ashby. The dynamic exponent (n = 1.75- mid- point of prescribed range) in the scaling function for thermal conductivity shows a deviation of 15.40% while a Scaling function with n = 1.89 was found to fit the experimental data with a deviation of 2.59%. The exponent (1.89) for the experimental data is higher than the

prescribed range (1.65- 1.85). A possible explanation for this out of range behaviour can be attributed to the presence of defects and imperfections such as fractured cell wall, missing cells, cell size variations and solid inclusions such as un- dissolved salt particles that are trapped within the pores that may be present in the porous samples. Since the scaling function did not assume structural imperfections, it is expected that thermal properties predicted by it would be higher than those measured experimentally from manufactured porous materials.

Conclusions

In this paper, the thermal conductivity of open- cell porous aluminium structures manufactured by infiltrating liquid aluminium through the pore spaces between loosely packed sodium chloride beads was measured. The result was compared and calibrated against some common thermal conductivity models. The following conclusions can be drawn from the results of this study:

1. The thermal conductivity of open- cell porous aluminium manufactured by liquid infiltration processing method increases as the relative density of the material is increased and follows a power law expressed as: $k = 206.89\rho_r^{1.76}$.
2. The Ashby model: $k = \xi k_s(\rho/\rho_s)$, with ξ=0.42 can effectively estimate the effective thermal conductivities of open- cell porous aluminium manufactured via infiltration processing method and having relative densities ranging from 0.35-0.40.
3. A power law relationship: $\frac{k}{k_s}=(\frac{\rho}{\rho_s})^n$, with n=1.89 fits the experimental data well for porous aluminium samples produced by liquid infiltration processing and having relative density in the range of 0.35-0.40.
4. The Bhattacharya model: $k_{eff} = M(\varepsilon k_f + (1-\varepsilon)k_s + \frac{(1-M)}{(\varepsilon/k_f+(1-\varepsilon)/k_s)}$, M=0.42 fits the experimental data and can be satisfactorily used to obtain the effective thermal conductivity of the porous aluminium sponges.

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