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The effective thermal conductivity of open cell replicated aluminium metal sponges

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ABSTRACT

The effective thermal conductivity of aluminium open cell porous materials has been tested using the steady state method. The materials were manufactured using the replication technique producing samples of porosity ranging from 0.57 to 0.77 and pore sizes between 0.7 and 2.4 mm. The effective thermal conductivity was found to decrease with increasing porosity, but there was no notice influence of pore size. The results were found to be in general agreement with similar measurements found in the literature. The differences observed were attributed to the thickness and structure of the material in the matrix. Overall there was better agreement between the experiments than for the correlations and analytical expressions presented in the literature. An empirically derived correlation was obtained for sintered porous materials with porosities ranging from 0.5 to 1.0.

1. Introduction

Metal foams and sponges are versatile materials (see for example [1,2]) that have a number of thermal applications in regenerators, air-conditioning systems, gas turbines, electronic cooling and chemical reactors [3–6]. Their main advantage is their high specific area which enhances the heat transfer and permits miniaturization of the thermal system. Moreover, their geometric construction enhances flow mixing as a result of their tortuous pathways [5,7]. As a result, they have attracted considerable attention in recent times. The thermal conductivity is an important parameter for such applications and can be accessed by approximating the porous material as an equivalent homogenous medium. When heat, driven by a temperature gradient, flows by conduction in this situation, the use of the Fourier law implies knowledge of the effective thermal conductivity (*ETC*).

Heat exchange in porous structures is complex as it takes place in two phases. There is a network of solid ligaments of generally high thermal conductivity and a fluid with lower thermal conductivity [8,9]. The principle process of heat transfer in non-flowing fluid saturated media is conduction through both the solid and fluid phases. However, convection and radiation cannot necessarily be neglected in all cases [7,10].

In such situations, the effective thermal conductivity, *ETC*, is no longer a property of a single material but depends on both the solid and fluid material properties, and also the structure of the porous medium; e.g. its porosity and pore size. A further problem with these materials is that the repeatability of the morphology is not constant, even when the same manufacturing conditions are employed, resulting in an inherent scatter in the material properties unless very large samples are tested [5,11,12].

Porous materials are generally characterised using their porosity and pore size. The porosity (ε, the inverse of the amount of solid material) is well defined and easily measured, it only requires that the mass and volume are known. The effective thermal conductivity has been found to be highly sensitive to the porosity, increasing as the porosity decreases [5–8,13–15]. The effect of pore size on *ETC* is less significant, and generally no noticeable effect of pore size has been reported [5,8,9,15], provided the pore size is below a certain value shown to be 4 mm diameter in closed cell polymer foams which is sufficient to suppress convection [3,16,17]. Although it can be demonstrated that the pore size has little direct influence on *ETC*, the pore size will influence the foam fabrication process, and by establishing limits on what foams may actually be produced (there are usually upper and lower size limits). To this extent, pore size can affect the *ETC* [12,18]. The pore size itself is additionally not well defined as measures including both average pore diameters and Pores Per Inch (*PPI*) are presented in the literature. Conversion between the these measures is also subject to ambiguity [3,17].

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Nomenclature

A	cross sectional area
m	mass
V	volume
d_p	diameter
K	thermal conductivity
L_1	upper aluminium block thickness
L_2	lower aluminium block thickness
L_s	sample thickness
Q_I	upper block heat transfer rate
Q_{II}	lower block heat transfer rate
Q_s	sample heat transfer rate
D_o	insulation outer diameter
D	aluminium block diameter
D_{st}	struts thickness
d_{lu}	node thickness
T	temperature
Q_{Loss}	heat loss to outside
ΔT	temperature difference

Greek symbols

ε	porosity
ρ	density

Abbreviations

ETC & K_{eff}	effective thermal conductivity
PPI	Pores Per Inch
TPS	transient plan source
NaCl	sodium chloride
V.S	very small samples
S	small samples
M	medium samples
L	large samples

Subscript

s	sample
sol	solid
t	total
Al	aluminium
p	pore
o	outer
i	inner
Av	average
eff	effective
in	insulation

There have been a number of attempts to provide theoretical approaches (often based on a simplified unit cell structure) and empirical correlations to predict *ETC* in porous materials. The models require some assumptions to be made; relating to the topology, the arrangement of the solid and fluid phases (whether in series or parallel) and the repeatability of distribution of the unit cells [19,20]. There are many different production techniques available [3,17]. Different production technique and the type of material have an effect in terms of strut shape and size, and distribution of the pores [21], as well as the base material from which the porous metal is made. However, these general approaches have not been successful in predicting the *ETC* of most open celled metal sponges with accuracy. Strategies that go beyond simplified unit cell structures have been explored, for example, by analysing the real foam structure obtained from 3D computed tomography [12] to observe its effects on the *ETC*. This can support the development of more accurate generic correlations [10,12,18], but is limited by the small volumes of foams that can be investigated in this way. A review of the wide range of theoretical and empirical approaches for porous metals found that each model defines a specific morphology and is hence of limited applicability to other types [11,12,18]. This is discussed in more detail later in this work.

Both steady state and transient techniques may be used to measure the thermal conductivity of complex materials [5,6,8–10,15,22,23]. The transient method was first demonstrated by Gustafsson et al. [24] in 1979 for *ETC* measurements of insulating materials. The most common type of transient measurement is the Transient Plane Source technique (TPS) [25,26], where a single element acts as both temperature sensor and heat source . It has been widely used to measure the *ETC* of porous materials [6,12,23]. The TPS element is positioned between two samples with similar characteristics and measures the instantaneous temperature gradient with time [6,25,26]. The main advantages of this approach are that the tests are easy and rapid, and it is possible to measure a wide range of thermal conductivities [6,10]. The analysis can be complex and quantification of uncertainty difficult [10]. Special care of the thermal contact resistance in terms of surface roughness and contact pressure is required [6].

There are a number of steady state methods which can be used to measure the thermal conductivity [10]. The basic principle of a steady state method is to measure the temperature gradient along a sample length under steady state conditions. The rate of heat transfer is obtained by measuring the temperature difference across a known reference material [9,27] or the dissipated heat from the temperature change in a water bath [5]. The main advantages of this method are the simplicity of the evaluation technique, good precision and accuracy and the opportunity to conduct unidirectional measurements [10]. Whilst the main disadvantages are the long times required to achieve steady state conditions, complicated instrumental procedure and the potential difficulties due to thermal contact (which can be especially challenging for a porous matrix [10]).

The primary objective of the experimental work reported here was to measure the effective thermal conductivity of open celled aluminium porous metals with different pore densities and the assessment of models and empirical correlations at a lower range of porosities than previously available. In this study a comparative steady state method was used where heat transfer through the porous media is allowed to become constant, permitting the application of Fourier's law [5,9,27]. Most previous investigations on open celled metal sponges have examined materials with high porosity ($\varepsilon > 0.9$). This study aims to experimentally measure the *ETC* at a lower range of porosities ($0.57 < \varepsilon < 0.77$) using aluminium sponges manufactured using the replication method [28]. The fluid was air. Four different pore sizes (based on the size of the particles used to manufacture the material) were tested, ranging from 0.8 to 2.1 mm in average diameter. The validity of available models and correlations in the literature was tested.

2. Metal samples

Sixty nine aluminium sponge samples were produced by the replication method, using gas pressure to force liquid aluminium to permeate a preform of salt (NaCl) particles, with the salt being washed out once the aluminium has solidified. A detailed