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Evaluation of effective thermal conductivity of porous foams in presence of arbitrary working fluid

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ABSTRACT

The Effective Thermal Conductivity (ETC) of open-cell porous foams can be either measured using experimental techniques or predicted from the detailed numerical simulation, considering the complex foam structure obtained from three-dimensional (3D) Computed Tomography (CT)-scan images. An alternative approach could be to consider simplified models for a quick and accurate estimation of the ETC. A model for ETC of open-cell porous foams, using an extremely simplified approach, has been proposed recently by Mendes et al. [1] and it provides an expression for the ETC with one adjustable parameter. It relies upon a single numerical prediction of the dimensionless ETC under vacuum condition, based on the detailed foam structure, obtained from 3D CT-scan information. Using experimental techniques, however, the vacuum condition is difficult to achieve. Therefore, it would be more suitable to conduct the measurement of ETC in presence of a commonly available fluid, like air or water, in order to determine the model parameter. From present result it can be concluded that lower thermal conductivity working fluid, like air, is the most suitable for evaluating the model parameter. Nevertheless, higher thermal conductivity working fluid, like water, also yields an accurate estimation of the model parameter if the thermal conductivity of the solid matrix is also sufficiently high.

1. Introduction

Most research efforts on modeling of practical heat and mass transfer applications involving porous media are largely based upon the popular homogenization approach, where the transport processes are analyzed using macroscopic models, thereby effectively neglecting the detailed micro-scale effects of the porous structure [2]. Nevertheless, for obtaining accurate predictions, these macroscopic models require reliable information about effective thermo-physical properties of porous media those essentially reflect micro-scale effects in an implicit manner. In this respect, the effective thermal conductivity (ETC) of porous media is an essential macroscopic parameter.

The most common approach for modeling macroscopic heat conduction through a porous medium is to treat it as a homogeneous medium with an ETC that accounts for the contribution of thermal conductivities of both solid matrix and fluid phase. This assumption is valid whenever the characteristic dimension of the physical problem is much larger than the characteristic dimension of the porous structure, which is typically represented by its pore size.

The ETC of porous media can be either measured with experimental techniques [3–6] or numerically predicted from simulations, considering the detailed morphology of porous media. Owing to the very high porosity of foams, the total heat transfer can take place by both conduction as well as thermal radiation, if the operating temperature as well as the applied temperature difference are relatively high. The structural information, required for numerical simulations, nowadays can be easily obtained from high resolution, three-dimensional (3D) Computed Tomography (CT) scan images for both conduction [1,7,8] and radiation [9–13], although the present investigation is focused only on the conduction heat transfer. Nevertheless, even in presence of combined mode of heat transfer, evaluation of the ETC due to pure heat conduction would find its importance [14,15]. However, such detailed approach could prove to be quite time consuming, since the ETC of a specific structure for a given working fluid is obtained individually on a case to case basis. Therefore, in order to achieve a reasonable compromise between accuracy and measuring (or computational) effort, an alternative approach could be to obtain simplified models for quick and accurate evaluation of the ETC, ideally presenting a wide range of applicability [13].

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Nomenclature

b	structure parameters
d_p	characteristic pore dimension [m]
k	thermal conductivity [W/m K]
L_r	representative size of porous medium domain [m]
Greek symbols	
ϕ	macroscopic porosity
Superscript	
$\sim$	dimensionless variable
Subscript	
eff	effective
f	fluid
HS, lower	lower Hashin–Shtrikman bound for ETC
HS, upper	upper Hashin–Shtrikman bound for ETC
max	maximum generic bound for ETC
min	minimum generic bound for ETC
s	solid

Different types of simplified models can be found in the literature [1,13,16–23] for the prediction of the ETC of porous foams. Most of these models provide analytical expressions or closed form correlations for the ETC, based on either experimental data or theoretical considerations, that grossly simplify either the material morphology or the solution method.

In some of these simplified models [16–18], porosity was considered as the only structural parameter. However, the direct influence of porous media morphology on the magnitude of ETC was neglected by these models, although its influence on the conduction heat transfer is known to be relevant, see e.g., [8].

In order to take into account the morphology of open-cell porous foams, several other authors [19–23] proposed simplified models for the ETC by approximating the geometry of porous media as a cluster of elementary cells with simplified geometry. Complete heat conduction problem in such cases is typically modeled as a network of thermal resistances and in some particular situations, further simplifications are also made with respect to the solution method.

Alternatively, simplified models for the ETC of open-cell porous foams can also be given in terms of correlations, those are obtained uniquely from numerical simulations of conduction heat transfer using the detailed morphology of porous media, where no further simplifications or assumptions are introduced for computations [1,13].

Recently, a model for estimating the ETC of open-cell porous foams using a simplified approach has been proposed by Mendes et al. [1]. This methodology provides an explicit expression for the ETC, with only one adjustable parameter. It relies upon a single numerical prediction of the dimensionless ETC under vacuum condition, based on the detailed geometry of porous media, which is obtained from 3D CT-scan images. Development of a correlation for the ETC of porous media, in the form proposed by Mendes et al. [1], is useful since it applies to any fluid–solid combination and hence the result could be extended even in presence of any hazardous fluid for which experiments may be impossible to conduct. Two main advantages of this approach are the following. First, it requires significantly reduced computational time for calculating the dimensionless ETC under vacuum condition, which scales to the order of the porosity of foams and the result of computation (i.e., $\tilde{k}_{\text{eff,s}} = k_{\text{eff,s}}/k_s$) is independent of the thermal conductivity of solid phase. Second, the dimensionless ETC under vacuum condition implicitly includes the quantitative morphological information of porous media that is relevant for solving any further heat conduction problem.

Using experimental techniques, however, the vacuum condition is very difficult to achieve, if not impossible, although it is quite simple to assume the same during a numerical simulation. Therefore, from the experimental perspective, it is always better to conduct the measurement of ETC in presence of a commonly available fluid, like air or water. It is evident that using the suggested experimental approach, the CT-scan data of foam structures would not be required. The main objective of the present study is to propose a suitable method for the experimental determination of adjustable parameter required in the simplified model of Mendes et al. [1]. As will be shortly apparent, during the present investigation, detailed numerical simulations are performed in order to mimic the real-life experiments. Merits and demerits of this simplified approach for evaluating the ETC of open-cell porous foams using a single point measurement are thoroughly discussed in this paper. Therefore, the outcome of this study is expected to help experimentalists in evaluating the ETC in presence of any working fluid from a single measurement, using a commonly available fluid that would suit the purpose.

2. Theoretical considerations

Let us consider a porous medium, formed by a solid and a fluid phase, with different thermal conductivities k_s and k_f, respectively. The simplified ETC model, in dimensionless form, proposed by Mendes et al. [1] is given as:

$$\tilde{k}_{\text{eff}} = b\tilde{k}_{\min} + (1-b)\tilde{k}_{\max} \tag{1}$$

where all the thermal conductivities are made dimensionless with respected to the thermal conductivity of the solid phase k_s i.e., $\tilde{k} = k/k_s$. Further, $\tilde{k}_{\min}$ and $\tilde{k}_{\max}$ are the generic minimum and maximum dimensionless bounds for $\tilde{k}_{\text{eff}}$ and b is an adjustable parameter to be determined either from a single measurement or from an equivalent detailed numerical prediction of the ETC at a selected reference condition. It may be noted here that $\tilde{k}_{\text{eff}}$, according to Eq. (1), is a linear combination of $\tilde{k}_{\min}$ and $\tilde{k}_{\max}$ with weighting factors b and $1-b$, respectively. However, it will be shortly evident that the generic lower and upper bounds of ETC are, in general, nonlinear functions of the dimensionless fluid conductivity $\tilde{k}_f$, for a particular porous medium. Consequently, Eq. (1) represents a complex nonlinear behavior of $\tilde{k}_{\text{eff}}$ as function of $\tilde{k}_f$.

The previous study of Mendes et al. [1] showed that in general, the Hashin–Shtrikman bounds serve the best for all the investigated open-cell porous foams i.e., when $\tilde{k}_{\min} = \tilde{k}_{\text{HS,lower}}$ and $\tilde{k}_{\max} = \tilde{k}_{\text{HS,upper}}$ are selected. These bounds are given as [24]:

$$\tilde{k}_{\min} = \tilde{k}_{\text{HS,lower}} = \frac{\tilde{k}_f\left[2\tilde{k}_f + 1 - 2\left(\tilde{k}_f - 1\right)(1-\phi)\right]}{2\tilde{k}_f + 1 + \left(\tilde{k}_f - 1\right)(1-\phi)} \tag{2a}$$

$$\tilde{k}_{\max} = \tilde{k}_{\text{HS,upper}} = \frac{2 + \tilde{k}_f - 2\left(1-\tilde{k}_f\right)\phi}{2 + \tilde{k}_f + \left(1-\tilde{k}_f\right)\phi} \tag{2b}$$

where is the macroscopic porosity of the medium. It must be noted here that both lower and upper bounds of the dimensionless ETC can be uniquely determined from known values of $\tilde{k}_f = k_f/k_s$ and ϕ in a straightforward manner from Eq. (2).