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Determination of effective thermal conductivity from geometrical properties: Application to open cell foams

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ABSTRACT

The thermo-physical behavior of open-celled metal foams depends on their microscopic structure. An ideal periodic isotropic structure of tetrakaidecahedron shape i.e. Kelvin cell is studied. The geometrical parameters of casted metal foams are obtained using iMorph (in-house code). We have proposed an analytical model in order to obtain geometrical parameters correctly as they have substantial influence on thermal and hydraulic phenomena, where strut geometry is of primary importance. Various relationships between different geometrical parameters and porosities are presented. The analytical results are fully compared with the experimental data in the literature and measured morphological data. The relationship of geometrical parameters with physical properties such as effective thermal conductivity is equally important. The range of solid to fluid phase conductivity ratios (λ_s/λ_f) studied is from 10 to 30,000 and for different porosities (80–95%). A modified correlation term, F is introduced in order to take account of thermal conductivities of constituent phases using electrical resistor model. An excellent agreement has been observed between the predicted correlation and experimental data.

1. Introduction

Solid foams are relatively new class of multifunctional materials that present attractive thermal, electrical and acoustic properties. Moreover, open cell foams also enhance mixing and have excellent specific mechanical properties. Open cell foams are widely quoted to present a random topology, high open porosity, low relative density, high thermal conductivity of the cell edges, large accessible surface area per unit volume [1]. Open cell foams are nowadays proposed for their use in numerous industrial applications such as heat exchanger or reactors. Generally, foams are often represented in PPI (pores per inch) and porosity. There are a few authors (Perrot et al. [2], De Jaeger et al. [3], Brun et al. [4]) who have measured all the geometrical parameters of open cell foams. The knowledge of these geometrical parameters is critical as they impact strongly thermo-physical properties. Our focus in this paper is to propose an analytical correlation that covers wide range of porosity, geometrical parameters and their dependence on effective thermal conductivity at local thermal equilibrium (LTE).

1.1. Geometrical considerations of open cell foams

The values and geometrical correlations provided by various authors [5–7] are enlisted in the work of Edouard et al. [8]who have shown that the geometrical parameter values reported in the literature are widely dispersed, that impact strongly thermo-physical properties. It is then, evident that there are discrepancies in the values for different geometrical or thermo-physical correlations. These discrepancies depend on which input parameter either (d_p or d_s or ε) is used to calculate the properties. Calmidi [6] proposed the use of cubic unit cell model to approximate the metal foam structure and proposed a relationship of pore diameter as a function of porosity and pore density. Du Plessis et al. [7] presented a model for evaluating permeability and inertia coefficient for metal foams which was derived by experimental results of foam samples of small pore size (45–100 PPI) and porosity of 0.973–0.978 with water and glycerol as fluid phase. It might be possible that one geometrical model proposed by one author may not be valid for other foams or other physical properties.

The possible reason of discrepancies is that the strut shapes have not been considered correctly when correlating with the idealized foam geometry. The strut cross sections possess circular, equilateral triangle or convex or concave triangle as discussed in the literature by Bhattacharya et al. [9] and Huu et al. [10] depend

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strongly on the porosity of the material. But manufacturing process as well as the type of material also plays an important role in determining the structure of the strut as shown in Table 1.

Thermo-physical and flow properties depend strongly on local morphology of both pore and solid matrix. Local change in the structure could govern the properties (e.g. constriction, strut cross section, surface roughness, etc.). Accurate evaluation of these properties becomes critical for various uses. Yet, solid foam structure and properties are still incompletely characterized (see Hugo and Topin [11]), hence induce lot of discrepancies in thermo-physical properties.

Structural properties (strut length, tortuosity etc.) are also necessary to complete the description as local topology may have a strong influence on properties (e.g. permeability, radiative properties) as presented by Brun [12]. The methodology to determine point and plane tortuosity in cellular structures is fully described in the work of Brun [12]. Brun has calculated tortuosity (ζ) either on skeleton or real foam structure. Moreover, Brun has also presented the importance of directional tortuosity in case of anisotropic foams and showed that tortuosity is sinusoidal with a period of 180° which clearly shows that tortuosity depends on direction of the struts and their orientations.

Kelvin cell is produced by CTIF using foundry route (see Dairon and Gaillard [13]). This process is based on the "infiltration" technique that is similar to conventional foundry techniques, in which a preform, a sort of porous core, is infiltrated with molten metal possesses convex triangular strut shape. In the beginning, balls or aggregates, called "precursors", are placed loose into the mold. As they do not occupy all of the space, these precursors form a network of interconnected pores, i.e. the preform. When precursors are spherical, this network gets a topology similar to that of foams produced by introducing a gas into a liquid. In the second case, open-pore polymer foam is used as lost pattern. The polymer foam is infiltrated by ceramic slurry, then heat-treated to solidify the slurry and burn out the polymer foam. The result is a network of pores having the same shape as the original foam, which can be then infiltrated by metal. Dairon and Gaillard [13] have reported convex triangular strut cross section even at low porosity ($0.825 < \varepsilon < 0.85$) and is presented in Fig. 1.

1.2. Effective thermal conductivity at local thermal equilibrium

The widespread range of applications of metal foams has led to increase in the interest of modeling the heat transfer phenomena in porous media. It is pointed out that the precise calculation of effective thermal conductivity is required for accurate modeling of thermal transport through open-cell metal foam as well as foam heat exchangers.

Many authors [9,14–22] investigated effective thermal conductivity of the porous medium including fluid phase (air/water). In the case of foam and air, in fact, the obtained value of effective thermal conductivity is approximately one-third of the thermal conductivity of the solid phase alone. We have mainly highlighted the works which were performed in local thermal equilibrium condition (LTE) including both the phases in stagnant case.

Manufacturing processes greatly impact the solid phase thermal conductivity of parent material when transformed into foams. As different commercially available foams employ different manufacturing techniques; that lead to significant changes in solid phase thermal conductivity compared to the same parent material one. This is one of the reasons that analytical results sometimes do not hold with the experimental results or with proposed correlations. It is well known that different cooling rates and solidification times can produce substantial variation in the resulting thermal properties of metal (or metal alloys). In the case of ceramic foams, Dietrich et al. [23] have experimentally measured solid phase conductivities of Alumina, Mullite and OBSiC ceramic foams and argued that measured values differ from the pure material values. This decrease in solid phase conductivity in solid phase of ceramic foam could be due to presence of impurities and depends on grain size of parent material.

A group of studies considered a specific geometry and distribution of pores and/or particles, and/or used the analogy between thermal, electrical, and mass transport phenomena. Using the analogy between mass diffusion and heat conduction, Hsu et al. [14] proposed a complex correlation to determine effective thermal conductivity of sponge like porous media using β as a shape factor which is a function of the porosity. Ashby [15] proposed a model that considers conduction in both the solid and gas phases that is suitable for a medium with a small solid to fluid thermal conductivity ratio (e.g., RVC foam-water). The models proposed by Hsu et al. [14] and Ashby [15] provide good estimate for the effective thermal conductivity when $\lambda_f/\lambda_s \approx O(10^{-1})$ (e.g. RVC foam-water), but highly overestimate the effective thermal conductivity for $\lambda_f/\lambda_s < 10^{-2}$.

Various two and three dimensional unit cell geometries can be found in the literature for metal foams. Calmidi and Mahajan [16] have proposed one dimensional conductivity model considering the porous medium to be formed by a two dimensional array of hexagonal cells with square lumps at nodes for high porosity metal foams. They described a parameter, $t/b = 0.09$ (dimensionless) which was obtained through fitting of experimental data. Bhattacharya et al. [9] have extended the model of Calmidi and Mahajan [16] with square and circular lumps at nodes and obtained $t/b = 0.19$. Both the models can predict accurately the thermal conductivity for Al foams but they overestimate the thermal conductivity for other foam structures.

Boomsma and Poulikakos [17] have proposed three dimensional tetrakaidecahedron geometry with cubic nodes at the intersections of ligaments. They proposed a non-dimensional geometrical parameter, $e = 0.16$ using experimental fitting of the data but the model becomes unrealistic when $\varepsilon < 0.9$. Schmierer and Razani [18] presented tetrakaidecahedron geometry with spherical nodes at the intersections of ligaments. They have performed image and geometrical analysis of the microstructure to find node size, $1 < \beta < 2$. Numerical finite element analysis was performed to calculate effective thermal conductivity. Ozmat et al. [19] proposed compact analytical model using dodecahedron geometry that has 12 pentagon-shaped faces with triangular cross-section ligaments. They considered no lumped materials at the intersections of ligaments and found close agreement with experimental data for low thermal conductivity ratios. This model underestimates the conductivity, because it does not include heat conduction in the fluid phase. Krishnan et al. [20] have used body-Centered-Cubic (BCC) structure to propose a numerical model to determine the effective

Table 1
Representation of three kinds of strut shapes which exist and produced by different manufacturers and their applications.

Manufacturer	Strut shape	Applications
ERG		Heat transfer
CTIF casting process		Mechanical & heat transfer
SCPS, ALANTUM, RECEMAT, FOAMTECH		Battery, electrode, electrochemistry