Conductivité thermique effective des mousses cellulaires.

The effective thermal conductivity of open cell foams.

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Résumé

Le développement de lits fixes structurés composés de mousses cellulaires représente une avancée importante pour la maîtrise des transferts de chaleur dans les procédés industriels (échangeur de chaleur, réacteur chimique, etc.). Les principaux avantages de ces mousses résident dans la haute surface de contact entre le fluide et la phase solide ainsi qu'une facilité de mise en œuvre. La connaissance des propriétés de transport de ce milieu poreux est donc devenue indispensable pour assurer son développement à l'échelle industrielle. Dans ce contexte, nous avons développé un modèle géométrique qui permet de 'mimer' au mieux la structure mousse et d'estimer la conductivité thermique effective d'une mousse cellulaire dans un fluide au repos (contribution statique) et/ou en mouvement (contribution dynamique).

Nomenclature (11 points, 2 colonnes)

a Window size, or pore diameter, (m)
ds Strut diameter, (m)
P Peclet number, (-)

Symboles grecs
ϕ Cell size, (m)
ε Cellular porosity, (-)
λ Thermal conductivity, ($W.m^{-1}.K^{-1}$)
Indices et exposants
s Static
eff Effective
d Dispersion

1. Introduction

Packed beds are extensively used in the industrial processes as reactors, separators, dryers, filters and heat exchangers. The reactor packing aims to increase the rate of heat and mass transfer by increasing the gas-solid contact surface and by increasing the turbulence within the fluid phase. One relevant example is the packed bed of pellets. However, due to the low porosity (in the range of 0.3–0.6), these packed beds induce important pressure drops at high flow rates which is detrimental for the global process. The idea of moving from these traditional packed beds to the structured bed (e.g. monolith or wire), has become more and more popular. More recently, the open cell foams have been introduced to overcome some of the above shortcomings of 'conventional' packings. Open cell foams are porous materials with low densities and novel thermal, mechanical, electrical and acoustic properties [1]. In contrast to 'conventional' packings of granular material, the use of open cell foams have become very attractive, since they offer to vary the geometry for the solid-fluid contact, and

especially the bed voidage ($0.70 < \varepsilon < 0.95$). This new medium has as a highly permeable porous structure, which enables a considerable reduction of the pressure drops along the bed even with a high specific surface area.

In industrial processes, it is well known that the effective thermal conductivity and the pressure drop are the most critical aspects for planning and designing processes. If it appears today that the pressure drop for the open cell foams has become largely documented in the recent literature [2], on the contrary, there are relatively few investigations of heat transport phenomena. These works have been summarized in review articles (Kaviany et al. [3], Sullins et al. [4]).

In this context, we have developed an analytical model based on an ideal periodic structure [5] of the open cell foam (perfect regular pentagonal dodecahedron) which allows establishing a simple relation between the volume of the skeleton and the unit cell volume. Next, we have used a simple periodic structure (modified cubic lattice) for performed the conduction analysis and estimated the theoretical effective thermal conductivity as only a function of the porosity. Finally, knowing that the effective conductivity is usually splitted into a static (or stagnant) contribution and a flow contribution (or dispersion conductivity); a empirical relation is used to quantify the dispersion in open cell foam [6]. Finally, the theoretical effective thermal conductivity is compared with the already available models and experimental values from the literature.

2. Open cell foam and ideal periodic structure.

The open cell foams can be manufactured with different geometries and shapes. In this work, we considering the open cell foam obtained by replication of open cell polyurethane foams (Fig. 1) which depicts a high degree of interconnectivity through the entire matrix of the foam. Due to the complexity of the geometric shape of these porous medium, there is no general consensus to define the main structural characteristics. However, generally four morphological parameters denoted, respectively, d_s (strut diameter), a (window diameter), Φ (cell diameter) and ε (foam porosity) are used to describe the foams. Several researchers reported theoretical geometrical models, which describe the relation between Φ, ds, a and ε. Among all these approaches, recently, Truong et al. [5] have proposed a new model based on perfect regular pentagonal dodecahedron geometry in order to estimate the characteristics of the open cell foams (Fig. 1). Based on the numerous similarities between open cell foams and packed dodecahedra, this geometrical model reveals to be quite close to the real structure of a unit cell constituting the open cell foam and enables accounting for triangular or cylindrical struts and matter accumulation (‘Fat’ model) or no (‘Slim’ model) at the strut connections. This model will be used in this work.

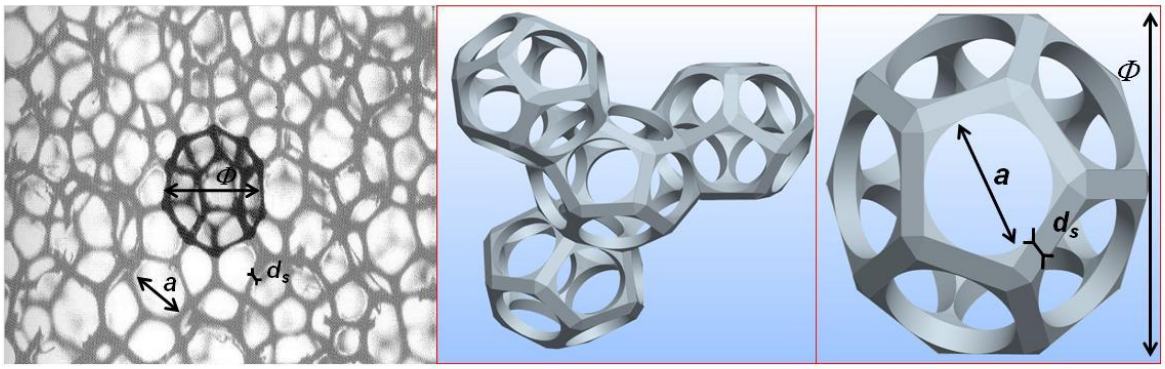

Figure 1 : Open cell foam and perfect regular pentagonal dodecahedron

a : window or pore diameter, d_s : strut diameter, Φ: cell diameter, ε porosity

3. Effective thermal conductivity

The total effective thermal conductivity (λ_{eff}) is usually splitted into a static (or stagnant, λ_{eff}^{s}) contribution and a flow contribution (or dispersion conductivity, λ_{eff}^{d}) (Zehner et al. [7]; Hunt and Tien [8], Calmidi et al. [9]):

$$\lambda_{eff} = \lambda_{eff}^{s} + \lambda_{eff}^{d} \qquad (1)$$

λ_{eff}^{s} is related to the mechanical dispersion due to the geometrical structure of the porous medium. In open literature, we can find different works which proposed empirical, analytical or numerical model including the porous morphology and the fluid and solid conductivities to estimate the static thermal conductivity (λ_{eff}^{s}) of the open cell foam. The main works have been presented by Calmidi and Mahaja [9]), Boomsma and Poulikakos [10] and Edouard [11]. Calmidi and Mahajan [9], and Boomsma and Poulikakos [10] independently developed models based on geometrical estimation for static effective thermal conductivity computation, specifically for metallic open cell foams saturated with a fluid. In these two approaches, the authors show that the porosity and the ratio of the cross-sections of the struts and the intersection strongly influence the results. Both models involved an unknown geometric parameter (r) which represents the ratio of strut diameter to square or circular node and which had to be determined by fitting their models to experimental data. Recently, for the first time, Edouard [11] provided an analysis for estimated the static effective thermal conductivity without any fitting parameters. In this work, the author uses the relationships induced by the regular pentagonal dodecahedron geometry (i.e. relations between the volume of the skeleton and the unit cell volume) in order to establish a direct analogy between the foam and an ideal periodic structure (i.e. the modified cubic lattice, Fig. 2). In this work, the dead volume (i.e. the volume accumulated at the strut connection) is represented by eight variable cubes of size ($2x$) and given directly by analogy with the 'Fat' regular pentagonal dodecahedron model.

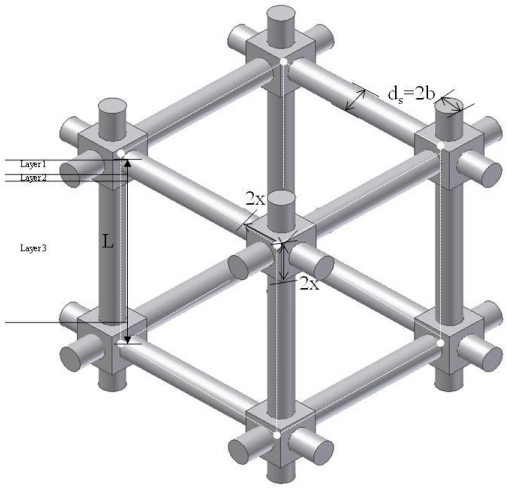

Figure 2 : Modified cubic lattice

Based on this simple representation of the open cell foam and the previous works of Zehner and Schlunder [7], Dul'nev [12] and more recently Calmidi et al [9] and Boomsma et al [10], it is then possible to derive the static effective thermal conductivity (λ_{eff}^{s}) considering only the porosity, the solid volume and the unit cell volume (without fitting parameters). The technique consists then to divide into characteristic parts the unit cell. Then, averaging the thermal conductivity of each part (or layer) on basis of the individual volume fractions and their respective thermal conductivities is given by the following relation:

$$\lambda_n = \frac{V_{n,solid}\lambda_s + \left(V_{n,cell} - V_{n,solid}\right)\lambda_f}{V_{n,cell}} \tag{2}$$

After, the effective thermal conductivity of the cell is calculated by the method of electro-thermal analogy which consists to combining the different layers. In case of the layers are in series, λ_{eff} of the unit cell can be written as:

$$\frac{\sum_{1}^{n} L_n}{\lambda_{eff}^{s}} = \sum_{1}^{n}\left(\frac{L_n}{\lambda_n}\right) \tag{3}$$

Finally, the static effective thermal conductivity (λ_{eff}^{s}) is given by the following equation (see for instance Edouard [11]):

$$\frac{1}{\lambda_{eff}^{s}} = \frac{2d}{\left(d^2\left(4y^2 - 2\pi y\right) + \pi d\right)\lambda_s + \left(d^2\left(2\pi y - 4y^2\right) - \pi d + 1\right)\lambda_f} + \frac{2d\left(y-1\right)}{\left(4y^2d^2\right)\lambda_s + \left(1-4y^2d^2\right)\lambda_f} + \frac{\left(1-2dy\right)}{\left(\pi d^2\right)\lambda_s + \left(1-\pi d^2\right)\lambda_f} \tag{4}$$

$$\text{with} \begin{cases} y = x/b \text{ ('Fat' model) and } y = 1 \text{ ('Slim' model)} \\ d = b/L \end{cases}$$

The dispersion conductivity (λ_{eff}^{d}) can be easy obtained by the empirical correlations proposed by Edouard et al [6], Truong-Huu et al. [13], and Saber et al. [14] for the radial and axial coordinates.

$$\frac{\lambda_{eff}^{d}}{\lambda_g} = \frac{1}{Pe}\,\mathrm{Re}\,\mathrm{Pr} \tag{5}$$

with $\mathrm{Pr} = \frac{\mu Cp_f}{\lambda_f}$, $\mathrm{Re} = \frac{u_f \rho_f \phi}{\mu}$, and $Pe \cong 14$ for radial thermal conductivity and $Pe \cong 1$ for axial one.

4. Results and discussion

Figure 3, λ_{eff}^{s} is plotted for two separate cases. Aluminum (λ_s = 218 W/mK) is used for the solid phase in both cases. In Fig. 3A, air (λ_f = 0.0265 W/mK) is the saturating fluid, and in Fig. 3B, water (λ_f = 0.613 W/mK) is the saturating fluid. These figures compare the results of 'slim' and 'fat' models with the experimental values and the main models issued of the literature.

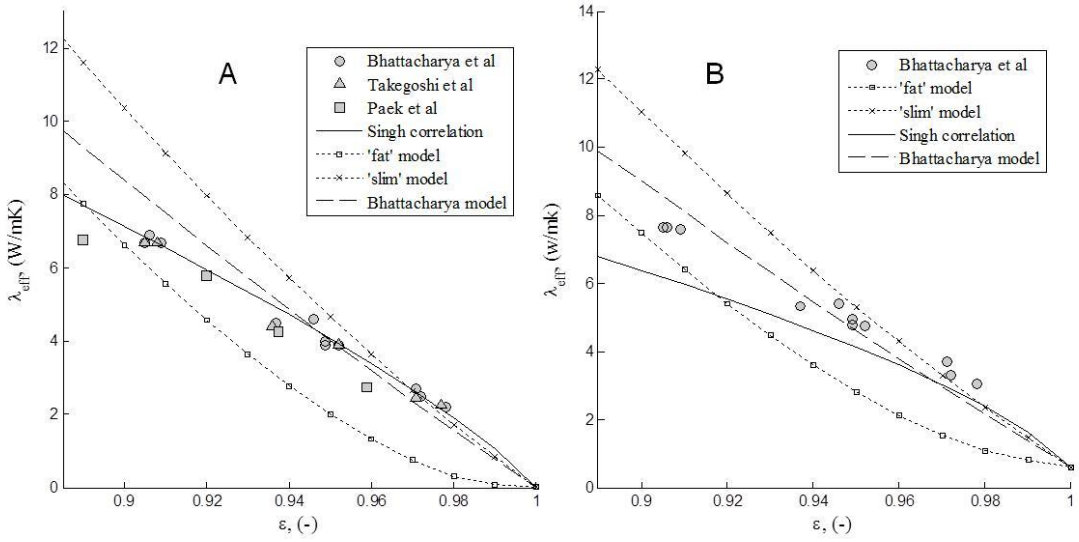

Figure 3 : Comparison of experimental results (symbol) with models (lines) for air (A) and water (B)

We can see that for the porosity range studied, Bhattacharya's [17] model and Singh's correlation [18] (expected for the air) give equivalent results that are coherent with the average of experimental values. However, in case of 'low' porosity ($\varepsilon < 0.94$), Bhattacharya's model has tendency to overestimate the experimental values, whereas for the 'high' porosity ($\varepsilon > 0.94$), this model has tendency to underestimate the experimental values. With the models based on the pentagonal dodecahedron geometry, the majority of the values are within the two value limits of the 'slim' and 'fat' models. Indeed the 'slim' model has tendency to overestimate the experimental data, while the 'fat' model underestimate the experimental

values. This is because for ε given, the strut diameter (b) decreases (due to the excess of solid at the strut connexion of the 'fat' model) and has for consequence an additional thermal resistance. Moreover, the layer 2 itself introduces an additional thermal resistance. In the case of 'high' porosity ($\varepsilon > 0.94$), one can notice that all the values are close to that obtained with the 'slim' model. This is probably explained by the weak ceramic precursor deposed onto the polymeric foam, which permits matter to flow along the nascent struts instead of accumulating at the nodes. Conversely for 'low' porosities, the 'fat' model seems to be more appropriate. We can think that during the important impregnation phase, the added matter is preferentially deposited onto the nodes of cell due to capillary force. This preferential deposit is taken into account in the 'fat' model.

Since that λ_{eff}^{s} is know and λ_{eff}^{d} is given by Eq. 5, it is then easy to obtain the total effective thermal conductivity (i.e. λ_{eff}). Figure 4 compares the radial effective conductivities for metallic (Aluminum, λ_s = 218 W/mK) and ceramic (SiC, λ_s = 5 W/mK) open cell foams versus the fluid flow (superficial velocity). For the simulations, air properties are assumed constant for the whole range of considered pressure (ρ_{gas} = 1.2 kg.m^{-3}, μ_{gas} = 1.838.10^{-5} Pa.s, λ_{gas} = 0.0265 W.m^{-1}.K^{-1}).

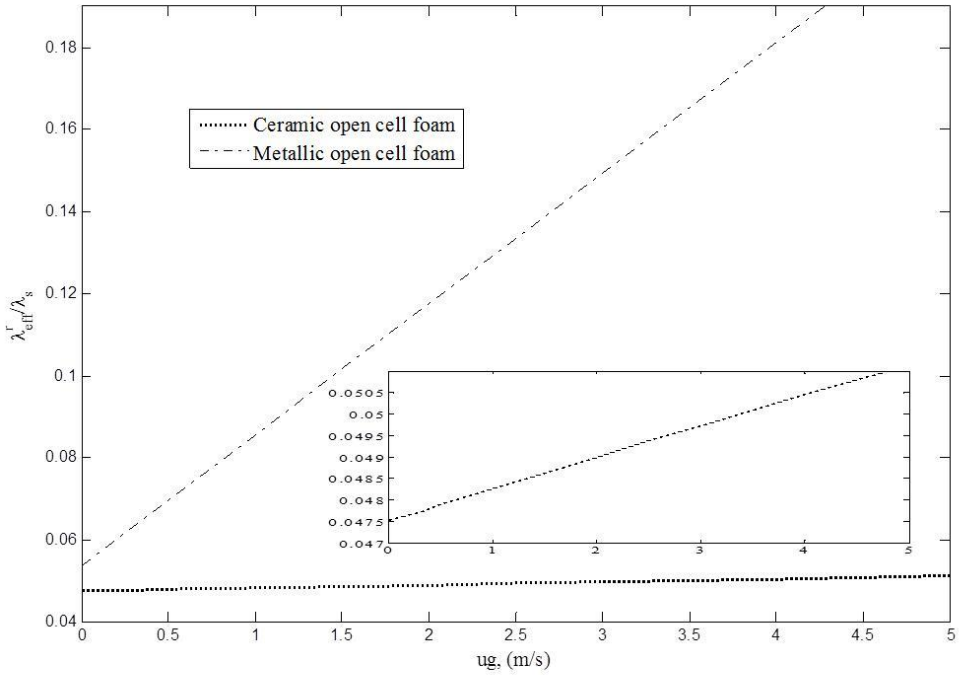

Figure 4 : Plot of the radial dimensionless thermal conductivities for the ceramic and metallic open cell foams versus superficial air velocity.

It is clear that for the ceramic open cell foam, the dispersion becomes prominent at high Reynolds numbers. It is not the case for the metallic open cell foam and in the first approximation the dispersion could be neglected. According the literature, λ_{eff}^{d} is found to be linearly proportional to the flow velocity.

5. Conclusion

In this work, we have investigated the thermal properties of the open cell foams in view of their use in the industrial processes. A simple theoretical model is used in order to estimate without fitting parameters the effective thermal conductivity. The values are hardy function of the foam's porosity and the intrinsic conductivities of the both fluid and solid phases. For ceramic open cell foams, the total effective thermal conductivity depends of the fluid superficial velocity. In other words, it will be necessary to choose judiciously the morphological foam's parameters and fluid flow depending on the considered application.

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