R&D NOTE

The Effective Thermal Conductivity for "Slim" and "Fat" Foams

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Introduction

Solid foams are a class of porous materials with low densities and novel thermal, mechanical, electrical and acoustic properties.[1] Solid foams have been used for a long time in the design of aircraft wing structures in the aerospace industry, core structure for high-strength panels, and also in compact heat exchangers. More recently, solid foams (with or without carbon nanofibers) have been considered as potential candidates for catalytic support.[2–4] In contrast to "conventional" packed beds formed by dense packing of granular material, the use of solid foams has become very interesting, since they offer to vary the geometry for the solid-fluid contact, and especially the bed voidage. Solid foams present a high-specific surface area with low-pressure drop[5,6] which can be advantageous in mass- and heat-transfer processes,[7,8] and in multiphase reaction by intensification of hydrodynamic interactions between fluid and solid phase.[9,10–13] In this context, the knowledge of the value of effective thermal conductivity is often a key characteristic for planning and designing chemical engineering processes.[14] Therefore, there is a need for experimental and theoretical works concerning effective thermal conductivity. In open literature, we can find different works which proposed empirical or analytical model depending on the porous morphology and on the conductivities of the fluid and solid phases to estimate the effective thermal conductivity of solid foams. The main works have been presented by Calmidi and Mahajan,[15] Boomsma and Poulikakos,[16] Battacharya et al.,[17] and Singh et al.[18] Calmidi and Mahajan[15] and Boomsma and Poulikakos[16] independently developed models using geometrical estimate for calculation of effective thermal conductivity specifically for metallic solid foams saturated with a fluid. For high-porosity metal foams Calmidi and Mahajan[15] presented a one-dimensional (1-D) heat conduction model considering the porous medium to be formed of a 2-D array of hexagonal cells. Whereas Boomsma and Poulikakos[16] proposed an analytical effective thermal conductivity model based on the tetrakaidecahedron cells with cubic nodes at the intersection of the struts. The results of these models are in good agreement with experimental measurements made on high-porosity aluminum foams with air or water as the saturating fluid. They show that, despite the high porosity of the foam, the heat conductivity of the solid-phase controls the overall effective thermal conductivity to a large extent, and that an accurate representation of the contribution of the solid is needed to model the effective conductivity. More recently, Battacharya et al.[17] also provided an analysis for estimating the effective thermal conductivity of high-porosity metal foams. They represented also the open cell structure by a model consisting of a 2-D array of hexagonal cells. The presence of lumps of metal at the junction of two struts is taken into account by considering square or circular blobs of metal. The analysis shows 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. It is interesting to note that the value of this fitting parameter changes with the unit cell considerer by the authors. There is, thus, a need for a more representative cell structure of solid foam that would be valid on a wider range of porosities and allows calculating the ratio of strut diameter to size of the intersection (i.e., the node). In this context, first, an analytical model based on an ideal periodic structure of the solid foam (perfect regular pentagonal dodecahedron) is used to establish a simple relation between the volume of the skeleton and the unit cell volume. Next, from this relation and the simplest periodic structure (modified cubic lattice[5]), the conduction analysis is

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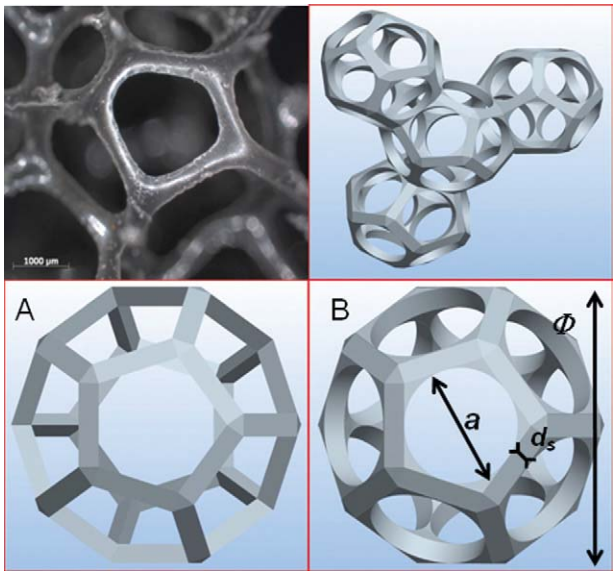

Figure 1. Solid foam and packing of regular pentagonal dodecahedron A= "slim"foam, B= "fat" foam.[19]

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

performed to derive the effective thermal conductivity as only a function of the porosity. Finally, the theoretical results are compared with the already available models and experimental values from the open literature.

Analytical Model

Representation of the solid foams and structural relationship

The main characteristic lengths used to described the solid foam are the cell diameter (Φ), the window diameter (or pore diameter a), and strut diameter (d_s) (see Figure 1). In reality, the structure of the solid foam is very complex one, and it would be difficult to accurately capture its nuances to every bit of detail. However, Truong et al.[19] have proposed a new model based on perfect regular pentagonal dodecahedron geometry to estimate the characteristics of the solid foams and structural relationship. Depending on the porosity of the solid foam, the authors assume either "slim" foam (Figure 1A) or "fat" foam (with matter accumulates at the strut connection during impregnation and synthesis, Figure 1B). Based on the numerous similarities between solid foams and packed dodecahedra, this geometrical model reveals to be quite close to the real structure of a unit cell constituting the solid foam. Moreover, this approaches gives a very versatile representation that enables one to describe the specific surface area, pressure drop, and external solid-fluid mass transfer with a simple relationship that involve the porosity and either the cell diameter. Based on this previous work, we have considered these two marginal cases ("slim" or "fat" foam with triangular struts) for determining two limiting values of effective thermal conductivity. Ratios of solid volume (V_{solid}) to the volume of unit cell ($V_{\text{dodecahedron}}$) for, respectively, "slim" and "fat"foam are given by (e.g., Truong et al.[19])

$$\begin{cases} (1-\varepsilon)=\dfrac{V_{\text{slim,solid}}}{V_{\text{dodecahedron}}}=\dfrac{V_{\text{skeleton,slim}}}{V_{\text{dodecahedron}}}=ks^2\dfrac{\sqrt{15}}{\varphi^4}-ks^3\dfrac{\sqrt{10}}{3\varphi^4} & (A) \\ (1-\varepsilon)=\dfrac{V_{\text{fat,solid}}}{V_{\text{dodecahedron}}}=\dfrac{V_{\text{skeleton,fat}}}{V_{\text{dodecahedron}}}+\dfrac{V_{\text{deadvol.}}}{V_{\text{dodecahedron}}} & (B) \end{cases} \tag{1}$$

$$\text{with}\begin{cases} \dfrac{V_{\text{skeleton}}}{V_{\text{dodecahedron}}}=kf^2\dfrac{\sqrt{15}}{\varphi^4}-kf^3\dfrac{\sqrt{10}}{3\varphi^4} \\ \dfrac{V_{\text{deadvol.}}}{V_{\text{dodecahedron}}}=\dfrac{40\dfrac{\sin^2\left(\frac{\pi}{5}\right)\varphi^2\left(1-\frac{kf}{2}\sqrt{\frac{2}{3}}\right)^3}{32\sqrt{3}(3-\varphi)}\sqrt{\left(\frac{1}{4}-\frac{\sin^2\left(\frac{\pi}{5}\right)\varphi^2}{9-3\varphi}\right)}}{\sqrt{5}\varphi^4} \\ +\left(\dfrac{12kf}{\sqrt{5}\varphi^4}\right)\left(\dfrac{5\varphi}{4\sqrt{3-\varphi}}-\dfrac{\pi}{4}\dfrac{\varphi^2}{(3-\varphi)}\right)\left(1-\dfrac{kf}{2}\sqrt{\dfrac{2}{3}}\right)^2 \end{cases}$$

where $V_{\text{dead vol.}}$ is the volume of matter accumulates at the strut connection, and ks (or kf) the ratio between d_s (strut side), and c (side of the perfect pentagon length).

Effective thermal conductivity

Based on previous works of Zehner and Schlunder,[20] Dul'nev[21] and more recently Calmidi et al.[15–17] and Boomsma et al.[16] it is possible to estimate the effective thermal conductivity (λ_{eff}) of the porous media considering only the porosity, the solid volume and the unit cell volume. The technique consists then to divide into characteristic parts the unit cell. Then, averaging the thermal conductivity of each part (or layer) on the basis of the individual volume fractions and their respective thermal conductivities is given by the following relation

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

After, the effective thermal conductivity of the cell is calculated by the method of electrothermal 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

$$\frac{\sum_1^n L_n}{\lambda_{\text{eff}}}=\sum_1^n\left(\frac{L_n}{\lambda_n}\right) \tag{3}$$

where λ_n is given by the relation (Eq. 2), and L_n is the heights of each layer. In our work, the modified cubic lattice (Figure 2) is divided into three layers in series, namely L_1, L_2 and L_3

$$\begin{cases} L_1=b \\ L_2=x-b \\ L_3=(L-2x) \end{cases} \tag{4}$$

Having the heights defined for these three layers, the total volume for each section is calculated simply by multiplying the unit cell's area by the height of the individual sections to give the following volumes

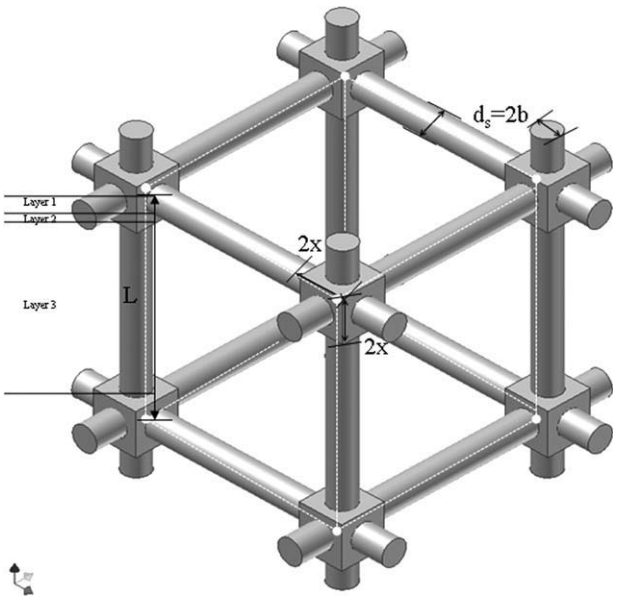

Figure 2. Modified cubic lattice.

$$\begin{cases} V_{1,\text{cell}} = L^2 L_1 = L^2 b \\ V_{2,\text{cell}} = L^2 L_2 = L^2 (x - b) \\ V_{3,\text{cell}} = L^2 L_3 = L^2 (L - 2x) \end{cases} \tag{5}$$

In the modified cubic lattice (Figure 2), the solid volume consists of the contribution of the 12 cylindrical struts and 8 cubes at their meeting point. Moreover, in the unit cell volume (dotted white lines), each strut is shared by four cubic lattices and each cube is shared by eight cubic lattices. Consequently, only a quarter of each strut volume and a eighth of each cube volume have to be considered for calculating the solid volume of each layer

$$\begin{cases} V_{1,\text{solid}} = \pi b^2 (L - 2x) + 4bx^2 \\ V_{2,\text{solid}} = 4(x - b)x^2 \\ V_{3,\text{solid}} = \pi b^2 (L - 2x) \end{cases} \tag{6}$$

Having these relationships, the porosity can be easy calculated by the following equation

$$(1 - \varepsilon) = \frac{2V_{1,\text{solid}} + 2V_{2,\text{solid}} + V_{3,\text{solid}}}{2V_{1,\text{cell}} + 2V_{2,\text{cell}} + V_{3,\text{cell}}}$$

$$= \frac{3\pi b^2 (L - 2x) + 8x^3}{L^3} \quad \text{with} \quad \begin{cases} \text{x} = \text{yb} \\ \text{y} = 1 + \delta; \quad \delta \geq 0 \\ \text{d} = \text{b/L} \end{cases}, \text{we obtain}$$

$$(1 - \varepsilon) = 3\pi d^2 (1 - 2d) + 8d^3 + \delta d^3 \left(8\delta^2 + 24\delta + 24 - 6\pi\right) \tag{7}$$

The next step consists to using the equations of regular pentagonal dodecahedron geometry with the same porosity (i.e., Eq. 1A = Eq. 7, or Eq.1B = Eq. 7) to develop a direct analogy between foam and the modified cubic lattice model and, thus, estimate d and δ (i.e., y).

When no matter accumulates at the strut connection (i.e., $\delta = 0$), we can use directly the "slim" foam model for estimating d as

$$\frac{V_{\text{s lim,solid}}}{V_{\text{dodecahedron}}} = ks^2 \frac{\sqrt{15}}{\varphi^4} - ks^3 \frac{\sqrt{10}}{3\varphi^4} = 3\pi d^2 (1 - 2d) + 8d^3 \tag{8}$$

In contrast, when the matter at the strut connection cannot be neglected, we use the "fat" model for estimating d and δ

$$\frac{V_{\text{fat,solid}}}{V_{\text{dodecahedron}}} \Rightarrow \begin{cases} \frac{V_{\text{skeleton,fat}}}{V_{\text{dodecahedron}}} = 3\pi d^2 (1 - 2d) + 8d^3 \\ \frac{V_{\text{deadvol.}}}{V_{\text{dodecahedron}}} = \delta d^3 \left(8\delta^2 + 24\delta + 24 - 6\pi\right) \end{cases} \tag{9}$$

As soon as the porosity (ε) and, therefore, ks and kf are known, d and δ (i.e., y) are deduced from Eqs. 8 or 9, respectively, for the "slim" or "fat" foam without any fitting parameters. $\frac{b}{x}$ (i.e. $\frac{1}{y}$) is plotted in Figure 3 for different values of ε. Calmidi et al.[15] and Bhattacharya et al.[17] use, respectively, an average value of $\frac{1}{y}$ of about 0.09 and 0.19 following the square or circular intersection. However, as honestly mentioned by the same authors, a close examination (physical measurement by microscope) of the metal foam structure indicates that $\frac{1}{y}$ is not unique, and in fact it varies with the sample's porosity. This variation seems well represented by the "fat" model and the empirical value 0.19 estimated by Bhattacharya et al.[17] is a good approximation only for the high-foam porosities.

From Eq. 2, the thermal conductivity of the layers can be individually written as

$$\begin{cases} \lambda_1 = \dfrac{(\pi b^2 (L-2x) + 4bx^2)\lambda_s + (L^2 b - (\pi b^2 (L-2x) + 4bx^2))\lambda_f}{L^2 b} \\ \lambda_2 = \dfrac{(4(x-b)x^2)\lambda_s + (L^2 (x-b) - (4(x-b)x^2))\lambda_f}{L^2 (x-b)} \\ \lambda_3 = \dfrac{(\pi b^2 (L-2x))\lambda_s + (L^2 (L-2x) - (\pi b^2 (L-2x)))\lambda_f}{L^2 (L-2x)} \end{cases}$$

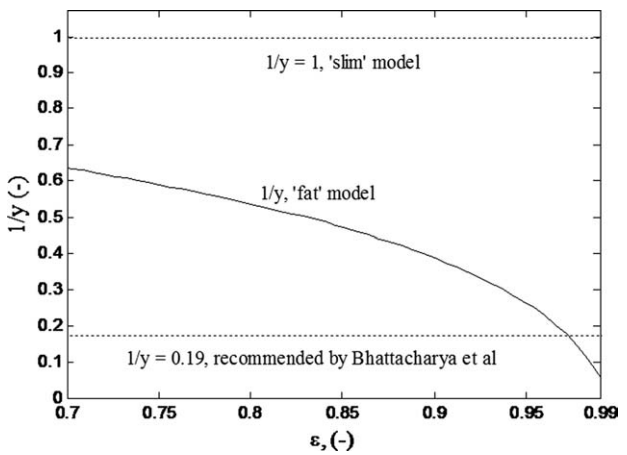

Figure 3. b/x (= 1/y) as a function of ε.

Table 1. Metal Foam Porosities and Effective Thermal Conductivities

References	ε, (-)	λ_{eff}, (W/mK), Al/air	λ_{eff}, (W/mK), Al/water
Bhattacharya et al.[17]	0.971	2.7	3.7
	0.946	4.6	5.4
	0.905	6.7	7.65
	0.949	3.9	4.8
	0.909	6.7	7.6
	0.978	2.2	3.05
	0.949	4	4.95
	0.906	6.9	7.65
	0.972	2.5	3.3
	0.952	3.9	4.75
	0.937	4.5	5.35
Paek et al.[22]	0.959	2.75	-
	0.9375	4.25	-
	0.92	5.8	-
	0.89	6.75	-
Takegoshi et al.[23]	0.905	6.7	-
	0.908	6.7	-
	0.936	4.4	-
	0.952	3.9	-
	0.971	2.45	-
	0.977	2.25	-

with $\begin{cases} x = yb \\ d = b/L \end{cases}$, this system can be rewritten as

$$\begin{cases} \lambda_1 = (d^2(4y^2 - 2\pi y) + \pi d)\lambda_s + (d^2(2\pi y - 4y^2) - \pi d + 1)\lambda_f \\ \lambda_2 = (4y^2 d^2)\lambda_s + (1 - 4y^2 d^2)\lambda_f \\ \lambda_3 = (\pi d^2)\lambda_s + (1 - \pi d^2)\lambda_f \end{cases} \tag{10}$$

From Eq. 3, the effective thermal conductivity through the unit cell λ_{eff}, is then simply the thermal conductivities of the individual layers in series $\lambda_{\text{eff}} = \frac{2L_1+2L_2+L_3}{2L_1/\lambda_1+2L_2/\lambda_2+L_3/\lambda_3}$.

After substituting the equations for the sections lengths ($L_{1,2,3}$), the thermal conductivities for each $\lambda_{1,2,3}$, and the solutions for d and y (Eqs. 8 or 9) for, respectively, "slim" and "fat" foam yields the final equation for the effective thermal conductivity

$$\frac{1}{\lambda_{\text{eff}}} = \frac{2d}{(d^2(4y^2 - 2\pi y) + \pi d)\lambda_s + (d^2(2\pi y - 4y^2) - \pi d + 1)\lambda_f} + \frac{2d(y-1)}{(4y^2 d^2)\lambda_s + (1 - 4y^2 d^2)\lambda_f} + \frac{(1 - 2dy)}{(\pi d^2)\lambda_s + (1 - \pi d^2)\lambda_f} \tag{11}$$

It is clear from Eq. 11 that the size of the cube (i.e., y) at the intersection of the struts plays a significant role in determining λ_{eff}. To assess the validity of this model, in the next section, we consider the experimental data for metal foam (with air or water for fluid phase) issue of the literature and given in Table 1.

Results and Discussion

Since the porosity (ε) and ks (or kf) are known, d, y and, thus, can be calculated without fitting parameters. This λ_{eff} function (Eq. 11) is plotted for two separate cases. Aluminum ($\lambda_s = 218$ W/mK) is used for the solid phase in both cases. In Figure 4A, air ($\lambda_f = 0.0265$ W/mK) is the saturating fluid, and in Figure 4B, water ($\lambda_f = 0.613$ W/mK) is the saturating fluid. These figures compare the results of "slim" and "fat" models with the experimental values (Table 1) and the main models issued of the literature. We can see that for the porosity range studied, Bhattacharya's model and Singh's correlation (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 a tendency to overestimate the experimental values, whereas for the "high" porosity ($\varepsilon > 0.94$), this model has a tendency to underestimate the experimental values. With the models based on the pentagonal dodecahedron geometry for calculated d and y, the majority of the values (i.e., 29 experimental values from a total of 32 data) 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,

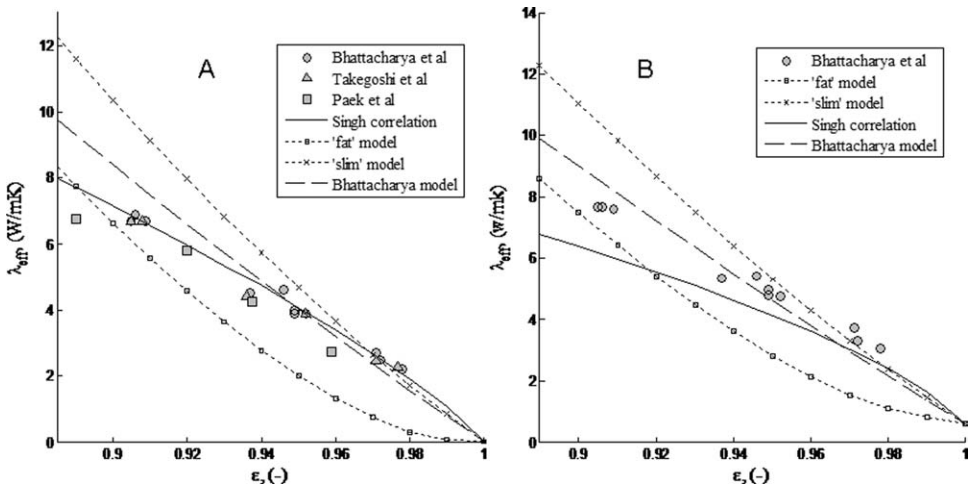

Figure 4. Comparison of experimental results (symbol) with models (lines) for air (A), and water (B).

Table 2. Literature and 'Fat' Models Evaluation by Maximum and Mean Error with the Experimental Data Given by Dietrich et al.[24] (Low Porosity Foams)

Model	*Material* ε = 075-0.8-0.85	*Maximum error* (%)	*Mean error* (%)
Abramenko et al.[25]	Alumina	62	23
	OBSiC	60	38
	Mullit	178	82
Singh et al.[18]	Alumina	44	41
	OBSiC	63	57
	Mullit	22	12
Paek et al.[22]	Alumina	133	56
	OBSiC	46	27
	Mullit	152	61
Boomsma et al.[16]	Alumina	39	36
	OBSiC	66	63
	Mullit	38	28
'Fat' model, this work	Alumina	**23**	**12**
	OBSiC	**16**	**11**
	Mullit	**16**	**10**

the second layer 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. However, further experimental data for aluminum foams with $\varepsilon < 0.9$ would be welcome to get a better understanding of these results and to give better support to or to relax the proposed "fat" model for "low" porosities. Recently, Dietrich et al.[24] have presented a new set of data for ceramic foams (alumina, mullite and OBSiC), with porosities between 0.75 to 0.85. Table 2 gives an overview of the maximum error as well as the mean error of "fat" and existing models[16,18,22–25] in the literature for these samples. The model validation was done by the following error equation: $\text{Error} = \frac{|\lambda_{\text{exp}} - \lambda_{\text{eff}}|}{\lambda_{\text{exp}}}$, where λ_{exp} are the experimentally values given by Dietrich et al.[24] and λ_{eff} the effective thermal conductivities calculated by the models. It is clear that the existing models are not very practicable for modeling the experimental results of ceramic foams with "low" porosities. Conversely the "fat" model gives a relatively good agreement between experimental and theoretical values with the value of the maximum error ranges from 23 to 16%, and the mean error about 11%. The reason for the better representation of the experimental effective thermal conductivity using the "fat" model is closely related to the better determination of volume of matter accumulating ($V_{\text{dead vol.}}$) at the strut connection. Moreover, the variation of this solid volume with the porosity is taken into account in the "fat" model, whereas it is ignored in any other models.

Conclusion

The pentagonal dodecahedron as a model reveals to be quite close to the real structure of a unit cell of solid foam. Assuming matter accumulation or not at the strut connections yields a very versatile representation that enables one to describe the skeleton of the foam with simple relationships that involve the porosity only (without geometric fitting parameters). Depending on the morphological nature of the solid foam and on the porosity range, the choice between the submodels is quite easy. Next, using the analogy with the simplest periodic structure (modified cubic lattice), the effective thermal conductivity is then easily determined as a function of the porosity. The results are very close to the experimental data of the literature. However, further experimental data with "low" porosities would be welcome to give better support to the proposed model, and this will be the subject of a future article. Finally, an important implication of this work is that for one porosity given, it is desirable to manufacture the foams with the minimal of matter accumulating at the struts intersection for higher heat dissipation in the reactor.

Notation

a = window size, or pore diameter, m
c = side of the perfect pentagon length, m
d_s = strut side, m
ks,f = ratio of strut diameter over side of the perfect pentagon for "slim" or "fat" foams[19]

Greek letters

ϕ = cell size, m
ε = porosity of the cellular material
λ = thermal conductivity, $W.m^{-1}.K^{-1}$

Subscripts and superscripts

s = solid phase
f = fluid phase
eff = effective

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