Effective Thermal Conductivity of Composite Materials

Based on Open Cell Foams

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Abstract

Open cell metal foams increasingly find lots of applications in modern energy systems. For example, they improve the efficiency of low-energy modules based on paraffin wax. In this work, the effective thermal conductivity of selected composite materials based on open cell foam solids is calculated by means of computer simulations. The results are compared with appropriate experimental values with a very good agreement. The characteristic constants for three material laws (Bhattacharya, Ashby and Maxwell) are found. The range of validity of these laws is narrowed to enable the well-directed use of them in the future.

Keywords: *open-cell foams; heat transfer; effective thermal conductivity.*

1. Introduction

Open cell metal foams permanently increase their importance by being mounted into modern energy systems. Their huge surface supports the exchange of heat between the metal and the filling substance. The combination of porous metals with air is relevant for the application in the cooling system of devices. Metal foams filled with water can be used for inductive continuous ow water heaters. The very promising application of metal foams is their incorporation into modern heat storage modules based on phase change materials (PCM). During their phase transition, PCM store energy as latent heat. The limiting factor in special cases, like the storage of superfluous room heat on a sunny day, is thereby the low intrinsic thermal conductivity of the appropriate PCM, for example paraffin wax (0.2 $Wm^{-1}K^{-1}$). This makes the loading and the unloading processes inefficient and reduces the popularity of these systems. To overcome this disadvantage, open cell metal foams can be infiltrated with PCM and can be built into the storage modules as composite materials. The high intrinsic thermal conductivity of metal increases the effective conductivity of the composite by orders of magnitude. Aluminum foams filled with paraffin wax, for example, possess the effective thermal conductivity of 3.5 - 11.5 $Wm^{-1}K^{-1}$, depending on the solid fraction.

For the well-directed use of such composites, the reliable knowledge of their effective thermal parameters, e.g. their effective thermal conductivity, is important. The experimental access to these values is not impossible, but also not easy, so that only less sufficient measurements are published, e.g. [1]. Validated simulation methods offer an economical alternative. A detailed description of the state of the art is given in [2], where we presented a method to compute the effective thermal conductivities for open cell metal foams filled with a fluid.

In this paper, we report the values of this homogenized thermal quantity for real open cell foam samples, by means of CT data, for four metals (aluminum, copper, nickel and stainless steel) and for three filling materials (air, water and paraffin wax). For available experiment measurements

([3]) a very good agreement is obtained. For comparison, we also consider polyurethane foams, as the thermal conductivity of polyurethane is considerably smaller than that of metals and closer to the thermal conductivity of the filling materials. The application of polyurethane open cell foams, among other things, is the creation of negative shapes for the production process of metal foams in investment casting [3].

The parameters of the pure solids and fluids used in the simulations are given in Table 1. The considered CT data of several 1cm×1cm×1cm open cell metal foam samples correspond to average porosities of 0.874 (42 samples), 0.942 (36 samples) and 0.891 (72 samples). The resolution of the data is 66.67μm per pixel. Figure 1 shows a sample of each type.

Table 1. Material parameters of pure solids and of pure filling materials.

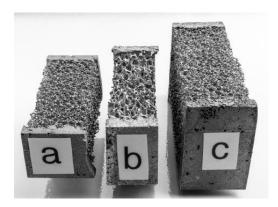|	density [g cm^{-3}]	thermal conductivity [Wm^{-1}K^{-1}]
aluminum	2.80	236.91
stainless steel	7.90	15
copper	8.92	400
nickel	8.91	91
polyurethane	1.15	0.2
air	1.15×10^{-3}	0.025
water	1.0	0.597
paraffin wax	0.77	0.2

Figure 1. Open foam samples used for the simulations [4]. The average porosity is a) 0.874, b) 0.942 and c) 0.891.

2. Methods

We calculate the effective thermal conductivity for composite materials (for example aluminum foams filled with water), using the method, described in [2]. At first, the method simulates the temperature distribution in the domain in the steady-state by means of the finite differences technique by setting the constant boundary conditions for the temperature at the bottom and at the top of the domain. The other boundaries are set to be adiabatically isolated. Then in each cell the familiar local thermal conductivity and the local thermal gradient (which is picked-off from the simulation data) are used to calculate the thermal flow through the cell. Summing up the thermal flow values in each layer one gets the thermal conductivity in it. By averaging the values of all layers being connected in series the effective thermal conductivity of the whole domain is available.

3. Simulation results and their comparison with some experimental measurements

Tables 2, 3 and 4 present the average values for 15 combinations of the materials with their standard deviation.

Table 2. Effective thermal conductivity (in $[\mathrm{Wm^{-1}K^{-1}}]$) for samples with an average porosity of 0.874 (Solid fraction: 12.6%) and their standard deviation. The filling material is given in the first column.

	aluminum	stainless steel	copper	nickel	polyurethane
air	11.33±1.83	0.75±0.11	19.08±3.09	4.37±0.70	0.04±0.001
water	12.10±1.80	1.44±0.11	19.86±3.06	5.12±0.68	0.53±0.005
paraffin wax	11.56±1.82	0.97±0.11	19.32±3.08	4.60±0.69	0.20±0.000

Table 3. Effective thermal conductivity (in $[\mathrm{Wm^{-1}K^{-1}}]$) for samples with an average porosity of 0.942 (Solid fraction: 5.8%) and their standard deviation. The filling material is given in the first column

	aluminum	stainless steel	copper	nickel	polyurethane
air	3.23±0.98	0.24±0.06	5.40±1.65	1.26±0.36	0.03±0.001
water	3.98±0.95	0.89±0.06	6.18±1.62	1.98±0.36	0.57±0.005
paraffin wax	3.46±0.97	0.45±0.06	5.64±1.64	1.49±0.37	0.20±0.000

Table 4. Effective thermal conductivity (in $[\mathrm{Wm^{-1}K^{-1}}]$) for samples with an average porosity of 0.891 (Solid fraction: 10.9%) and their standard deviation. The filling material is given in the first column.

	aluminum	stainless steel	copper	nickel	polyurethane
air	8.53±2.10	0.57±0.13	14.36±3.55	3.30±0.81	0.04±0.002
water	9.35±2.09	1.28±0.13	15.19±3.53	4.09±0.80	0.54±0.006
paraffin wax	8.78±2.10	0.80±0.13	14.62±3.54	3.55±0.80	0.20±0.000

For the validation of our simulation results, we compared our values with those available in [1] (Solid fraction of samples: 12.6% (mean value for 42 sample) for our simulations and 12.7% (one sample) in [1]). The relevant values are summarized in Table 5. In consideration of our standard deviations and the total error of the measurements (6.28%, [1]) we obtain a very good agreement of the experimental values and those calculated by means of our simulations.

4. Discussion: Material laws

In [5] an empirical correlation is given for the computation of the effective thermal conductivity of porous composites (Bhattacharyas law):

$$\lambda_{eff} = f_A(\Phi\lambda_{fluid} + (1-\Phi)\lambda_{solid}) + \frac{1-f_A}{\dfrac{\Phi}{\lambda_{fluid}} + \dfrac{1-\Phi}{\lambda_{solid}}} \tag{1}$$

where Φ is the porosity of the solid structure, λ_{fluid} and λ_{solid} are the thermal conductivities of the fluid and solid phases and f_A the correlation factor, which depends on the individual combination of the materials and on the geometry of the solid structure. We calculate this factor for the considered systems (Solids: aluminum, stainless steel, copper, nickel and polyurethane; fluids: air,

water and paraffin wax). The values are given in Tables 6-10 and in Figures 2-4.

Table 5. Simulative values (with the standard deviation) and experimental values (with the total measuring error) of λ_{eff} in [Wm^{-1}K^{-1}] for samples with the solid fraction of 12.6% (mean value of 42 synthetic structures) and of 12.7% for the one experimental sample, [1].

	aluminum and air	aluminum and water	cooper and air	copper and water
Simulation (mean value of 42samples)	11.33±1.83	12.10±1.80	19.08±3.09	19.86±3.06
Experiment (one sample), [1]	9.78±0.61	10.58±0.66	17.48±1.10	19.08±1.20

Table 6. Bhattacharya correlation factor f_A for aluminum samples filled with air, water and paraffin wax.

	aluminum and air	aluminum and water	aluminum and wax
por. 0.874	0.38	0.38	0.38
por. 0.942	0.23	0.24	0.24
por. 0.891	0.33	0.34	0.33

Table 7. Bhattacharya correlation factor f_A for stainless steel samples filled with air, water and paraffin wax.

	Stainless steel and air	Stainless steel and water	Stainless steel and wax
por. 0.874	0.38	0.44	0.40
por. 0.942	0.24	0.32	0.28
por. 0.891	0.33	0.41	0.36

Table 8. Bhattacharya correlation factor f_A for copper samples filled with air, water and paraffin wax.

	copper and air	copper and water	copper and wax
por. 0.874	0.38	0.38	0.38
por. 0.942	0.23	0.24	0.23
por. 0.891	0.33	0.33	0.33

Table 9. Bhattacharya correlation factor f_A for nickel samples filled with air, water and paraffin wax.

	nickel and air	nickel and water	nickel and wax
por. 0.874	0.38	0.39	0.38
por. 0.942	0.23	0.26	0.24
por. 0.891	0.33	0.35	0.34

Table 10. Bhattacharya correlation factor f_A for polyurethane samples filled with air, water and paraffin wax.

	polyurethane and air	polyurethane and water	polyurethane and wax
por. 0.874	0.50	0.81	any
por. 0.942	0.40	0.78	any
por. 0.891	0.48	0.81	any

Tables 6, 8 and 9 show that for aluminum, copper and nickel, the correlation factor f_A depends on the porosity of the open cell foam and is almost independent of the filling (air, water or paraffin wax). From Table 7 can be taken that for the stainless steel open cell foams, f_A depends not only

on the porosity but also on the kind of the filling, and is the highest for water. This twofold dependence seems to stem from the relatively small intrinsic thermal conductivity of stainless steel ([15 Wm^{-1}K^{-1}]). The f_A values for polyurethane foams confirm this assumption: The thermal conductivity of polyurethane is much smaller (0.20 Wm^{-1}K^{-1}) than that of metals, and the fluctuation with the kind of the filling is actually the strongest (Table 10). For $\lambda_{solid} = \lambda_{fluid}$ for polyurethane foam filled with paraffin wax, f_A is arbitrary ('any') for this material combination.

The values of f_A for aluminum, copper and nickel are close to each other: ($0.38 - 0.39$ for samples with the porosity 0.874, $0.23 - 0.26$ for the porosity 0.942 and $0.33 - 0.35$ for the porosity 0.891). Stainless steel shows, on the whole, slightly higher correlation factors for the structures with the fillings water or paraffin wax. The values for polyurethane foams are higher than those of the metals ($0.40 - 0.81$).
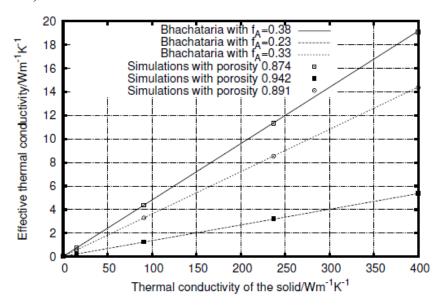

Figure 2. Effective thermal conductivity of open pore foams, filled with air and the law of Bhattacharya.
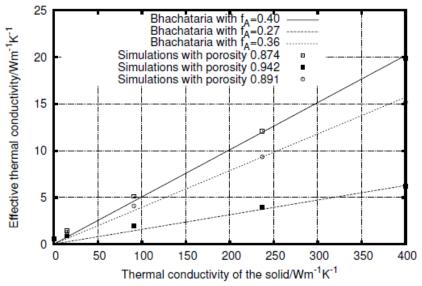

Figure 3. Effective thermal conductivity of open pore foams, filled with water and the law of Bhattacharya.
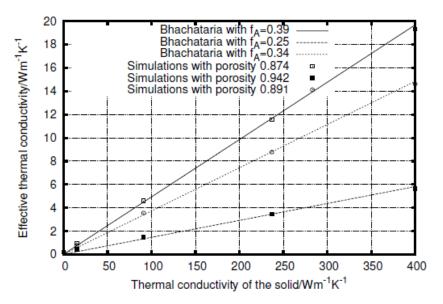
Figure 4. Effective thermal conductivity of open pore foams, filled with paraffin wax and the law of Bhattacharya.

The law of Bhattacharya is a good prediction for the effective thermal conductivity of open cell foams filled with air (Figure 2) or paraffin wax (Figure 4). It gives a quite good estimation for foams made of high-conductivity solids ($\lambda_{solid} \geq 200$ Wm^{-1}K^{-1}) filled with water (Figure 3).

Another model describing the dependence of the effective thermal conductivity λ_{eff} on the geometry of the solid structures for porous composite materials is suggested in [6] (Ashby law):

$$\lambda_{eff} = \lambda_{solid} \cdot \left(\frac{\rho}{\rho_{solid}} \right)^q \qquad (2)$$

where ρ_{solid} is the density of solid, ρ_{solid} is the density of the filling and $\rho = \Phi \rho_{fluid} + (1-\Phi)\rho_{solid}$ is the density of the infiltrated foam. We calculate the power value q for our composite samples. The results are presented in Tables 11-15 and in Figure 5-9.

Table 11. Ashby power value q for aluminum samples air, water and paraffin wax.

	aluminum and air	aluminum and water	aluminum and wax
por. 0.874	1.47	3.61	3.01
por. 0.942	1.52	4.39	3.68
por. 0.891	1.50	3.80	3.17

Table 12. Ashby power value q for stainless steel samples filled with filled with air, water and paraffin wax.

	stainless steel and air	stainless steel and water	stainless steel and wax
por. 0.874	1.45	1.63	1.76
por. 0.942	1.46	1.63	1.85
por. 0.891	1.47	1.63	1.79

Table 13. Ashby power value *q* for copper samples with air, water and paraffin wax.

	copper and air	copper and water	copper and wax
por. 0.874	1.47	2.01	1.89
por. 0.942	1.51	2.31	2.16
por. 0.891	1.50	2.09	1.97

Table 14 Ashby power value *q* for nickel samples filled with air, water and paraffin wax.

	nickel and air	nickel and water	nickel and wax
por. 0.874	1.47	1.92	1.86
por. 0.942	1.51	2.12	2.09
por. 0.891	1.50	1.98	1.93

Table 15. Ashby power value *q* for polyurethane samples filled with air, water and paraffin wax.

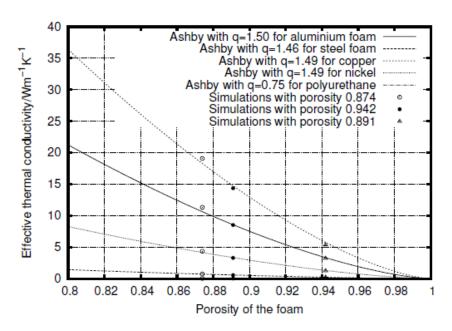|	polyurethane and air	polyurethane and water	polyurethane and wax
por. 0.874	0.81	-8.12	0
por. 0.942	0.67	-7.94	0
por. 0.891	0.78	-8.08	0

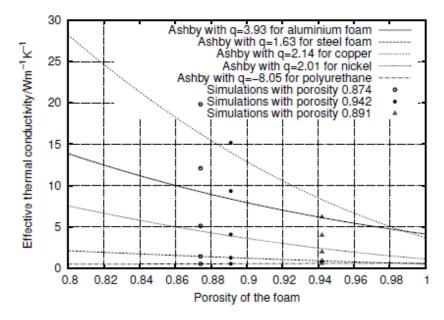Figure 5. Ashby law for the effective thermal conductivity of open pore foams, filled with air.

Figure 6. Ashby law for the effective thermal conductivity of open pore foams, filled with water.
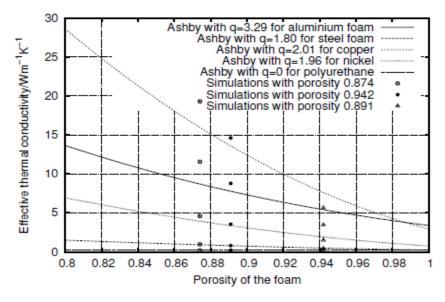

Figure 7. Ashby law for the effective thermal conductivity of open pore foams, filled with paraffin wax.
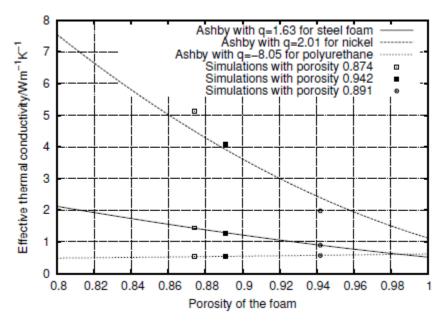
Figure 8. Ashby law for the effective thermal conductivity of open pore foams, filled with water, for solids with the lower thermal conductivity.
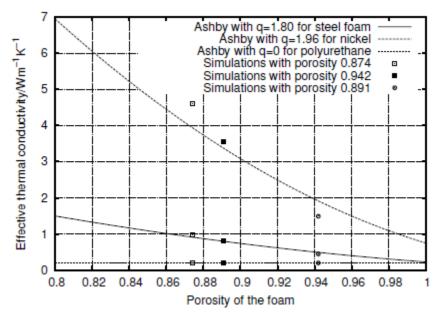

Figure 9. Ashby law for the effective thermal conductivity of open pore foams, filled with paraffin wax, for solids with the lower thermal conductivity.

The values q for aluminum, copper and nickel foams vary both, with the porosity as well as with the kind of the filling (air, water and paraffin wax), and the fluctuations with respect to the kind of the filling are stronger. Especially the value $q = 1.52$ for the aluminum foam with the porosity 0.942 filled with air is much smaller than the value $q = 4.39$ for the aluminum foam of the same porosity 0.942 filled with water. The smallest fluctuations with the porosity occur for stainless steel (Table 12), the values for water-filled foams are even equal to each other. The reason seems

to be the lower difference in the own thermal conductivities of the combined materials. The q values for polyurethane foams confirm this assumption. Anyway, the values for polyurethane foams filled with water are negative, as the thermal conductivity of the solid (polyurethane) is smaller (0.20 Wm^{-1}K^{-1}) than that of water (0.597 Wm^{-1}K^{-1}).

The law of Ashby is a good prediction for the effective thermal conductivity of open cell foams filled with air (Figure 5) and for foams made of lower-conductivity solids (polyurethane, stainless steel) filled with water (Figure 8) or with paraffin wax (Figure 9). It gives a quite good estimation for foams made of medium-conductivity solids (nickel, Figures 8-9).

Another well-known model is that of Maxwell ([7])

$$\lambda_{eff} = \lambda_{solid} \frac{1 - \Phi}{(1 + \Phi)(C - 1)} \tag{3}$$

with a modeling constant C. We determine C for the considered material combinations. The results are given in Tables 16-20 and in Figures 10-11.

Table 16. Maxwell constant C for aluminum samples filled with air, water and paraffin wax.

	aluminum and air	aluminum and water	aluminum and wax
por. 0.874	2.41	2.32	2.38
por. 0.942	3.21	2.79	3.06
por. 0.891	2.61	2.46	2.55

Table 17. Maxwell constant C for stainless steel samples filled with air, water and paraffin wax.

	stainless steel and air	stainless steel and water	stainless steel and wax
por. 0.874	2.35	1.70	2.04
por. 0.942	2.91	1.50	2.01
por. 0.891	2.51	1.68	2.08

Table 18. Maxwell constant C for copper samples filled with air, water and paraffin wax.

	copper and air	copper and water	copper and wax
por. 0.874	2.41	2.36	2.39
por. 0.942	3.22	2.94	3.13
por. 0.891	2.61	2.52	2.58

Table 19. Maxwell constant C for nickel samples filled with air, water and paraffin wax.

	nickel and air	nickel and water	nickel and wax
por. 0.874	2.40	2.20	2.33
por. 0.942	3.17	2.37	2.83
por. 0.891	2.59	2.28	2.48

Table 20. Maxwell constant C for polyurethane samples filled with air, water and paraffin wax.

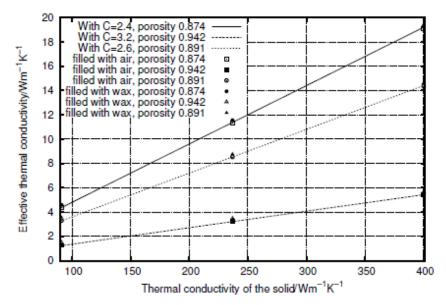|	polyurethane and air	polyurethane and water	polyurethane and wax
por. 0.874	1.32	1.03	1.07
por. 0.942	1.20	1.01	1.03
por. 0.891	1.38	1.02	1.06

Figure 10. Maxwell law for the effective thermal conductivity of open pore foams, filled with air or with paraffin wax.
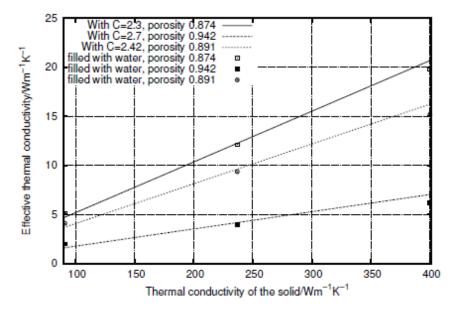

Figure 11. Maxwell law for the effective thermal conductivity of open pore foams, filled with water.

For metals with higher λ_{solid} (aluminum, nickel and copper) the values C rise for the increasing porosity of the foam. The polyurethane foams with all fillings and the steel foams filled with water and paraffin wax show the opposite tendency for C. The value C is the smallest for the porosity 0.942, because the ratio $\frac{\lambda solid}{\lambda eff}$ dominates the expression for these material combinations. For foams with $\lambda_{solid} > 100$ Wm^{-1}K^{-1} filled with air or paraffin wax ($\lambda_{fluid} < 0.2$ Wm^{-1}K^{-1}) the Maxwell constant C can be taken 2:4 for the porosity 0.874, 3.2 for the porosity 0.942 and 2.6 for the porosity 0.891 (Figure 10).

The law of Maxwell is a good prediction for the effective thermal conductivity of open cell foams

made of solids with thermal conductivity $\lambda_{\text{solid}} > 90$ Wm^{-1}K^{-1} filled with air or paraffin wax (Figure 10). It makes acceptable predictions for the same solids filled with water (Figure 11).

The constants f_A, q and C are explicitly calculated, by using the values of the effective thermal conductivity from Tables 2-4.

We summarize our recommendations for the choice of the appropriate material law for considered material combinations in Table 21.

Table 21: The most appropriate method(s) to estimate the effective thermal conductivity of an open cell foam depending on the solid and the filling material. Methods given in brackets are only partly valid.

	polyurethane	stainless steel	nickel	aluminum	copper
air	Bhattacharya Ashby	Bhattacharya Ashby	Bhattacharya Ashby Maxwell	Bhattacharya Ashby Maxwell	Bhattacharya Ashby Maxwell
paraffin wax	Bhattacharya Ashby	Bhattacharya Ashby	Bhattacharya (Ashby) Maxwell	Bhattacharya Maxwell	Bhattacharya Maxwell
water	Ashby	Ashby	(Ashby) (Maxwell)	(Bhattacharya) (Maxwell)	(Bhattacharya) (Maxwell)

5. Conclusions

In the present study we determined the effective thermal conductivities by heat diffusion simulations for fifteen composites, based on CT-data. The values strongly depend on the porosity and on the thermal conductivities of the solids. For metals, the results are in the range of 1.35% and 9.60% of the thermal conductivity of the solid. Polyurethane foams filled with water have effective thermal conductivities between 88.63% and 95.32% of the intrinsic value of water. In addition, we calculated the material constants of the following three material laws. The Bhattacharya constants for aluminum, copper and nickel foams depend only on the porosity of the foam and are not dependent on the choice of the metal. In contrast, foams based on solids of lower thermal conductivity (stainless steel and polyurethane) depend on both. The law of Ashby incorporates the relative density of the composite material instead the porosity of the foam, contrary to the laws of Bhattacharya and Maxwell, which translates to a solid dependent power value. The law of Maxwell makes good predictions for foams with $\lambda_{\text{solid}} > 100$ Wm^{-1}K^{-1}, which are filled with substances with $\lambda_{\text{filling}} < 0.2$ Wm^{-1}K^{-1}. An overview of recommended appropriate material laws depending on the choice of the solid and of the filling is given in Table 21.

6. Acknowledgements

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