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Heat Storage Coefficient of Highly Porous Metal Foams in Two-Phase Systems by Introducing Interfacial Layer

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Abstract

A theoretical model, to predict the effective Heat Storage Coefficient (Hsc) of highly porous metal foams. The system is reduced to a two-phase system: solid phase, fluid phase and interfacial layer between solid and fluid phases. The resistor model is devloped to find effective heat storage coefficient from the values of Hsc of the constituent phases. In proposed model, we use the concept of averaging the temperature field with in the different phases. To find the value of Hsc in two-phase porous systems, we have to use resistor model, as a porous medium is neither composed of slabs parallel nor perpendicular to the heat flux.

We develop a theoretical expression for Hsc based on resistor model for two-phase systems which is being comprised of contributions from both the phase with interfacial layer. It is supposed to use slabs (solid layer, fluid layer and interfacial layer between solid and fluid layers) inclined at an angle θ with the heat flux lines. Here we are trying to correlate angle of inclination θ in terms of the ratio of heat storage coefficient of the constituent phases and the physical porosity. Using best fitting technique we obtained expressions for θ, is used in our model.

The theoretical calculations of Hsc for porous metal foam systems carried out by the proposed model gives an average deviation of 4.8% from experimental values given in literature. The values predicted by the model are in good agreement with experimental values of Hsc's reported in given literature. A comparison with other models available in the literature has also been made. The theoretical Hsc values are determined from present model shows least deviation from experimental values.

Keywords: Heat storage coefficient (Hsc); series and parallel registors; angle of inclination; interfacial layer; two-phase system; continuous medium; porous metal foams.

Introduction

Theoretical modeling for porous metal foams is very important in determining their ability to storage of heat. The thermal characteristics for these substances of industrial importance are a challenging task for engineers and physicists. The study of thermal parameters of two-phase systems is also valuable for explosive material industry, nuclear reactors and in oil exploration. The thermal characteristics of metal foams an extremely important in determining their ability to store heat.

To solve this problem, we have to need, a set of thermal parameters. These are (a) the thermal conductivity λ, (b) the volumetric specific heat C which is the product of the specific heat c and the density ρ, (c) the thermal diffusivity α (α=λ/C) and (d) the heat storage coefficient (HSC) β. Now it is defined as

$$\beta = \sqrt{\lambda\rho c} = \sqrt{\lambda C} = \frac{\lambda}{\sqrt{\alpha}} \quad \ldots(1)$$

Lichtenecker [1] also presented a very simple and effective working empirical relation for porous mixture. In the literature one finds that the Hsc of composites is an additive property and considering various components as resistors one can take a combination of these to predict effective Hsc. This is a common practice adopted to predict effective thermal conductivity from the thermal conductivity of different phases for porous materials. Accepting the similarity, a geometry dependent resistor model has been proposed for heat storage coefficient of porous metal foams.

The knowledge of the Hsc is necessary in calculating the heat accumulating capacity of a medium when in a transient state. A detailed knowledage of β is given in Verma et.al. {2). In the literature {3-5], one finds very little importance attached knowledge of the Hsc of various materials. The heat storage coefficient characterizes a medium from the viewpoint of its heat storage ability. If we take a section of the medium, then some of the heat entering is retained by it and the rest is transferred to subsequent layers. But when the steady state is reached no heat is retained and all is transferred to the subsequent layers. So here we notice that during the transient state the heat retained by a particular layer is a function of its heat storage coefficient.

In the literature, we have lot of theoretical models for the determination of Hsc of porous materials. Shrotriya et al.[6] considered cubic particles in a cubic unit cell. They proposed a theoretical model for the prediction of Hsc of loose granular substances and compared theoretical values of Hsc obtained from the model with values obtained by experiments performed with plane heat source. Misra et al.[7] defined a resistor model to determine Hsc of two phase systems.

They considered the grains of the medium as spherical in shape and by replacing porosity (ϕ) by porosity correction factor (F_P). In similar manner, Zhang et al.[8] have investigated a model for HSC of soil. For this they used randomly mixed model to stimulate the spatial structure of the multi-phase media and observed, the significant effect of the degree of saturation on heat storage coefficient. Recently, Usha Singh et al.[9] proposed a theoretical model to predict the effective Hsc of fruits.

They considered cubic array has been divided into unit cells and resistor model is applied to determine effective HSC of unit cell. As we know that the Hsc of two phase systems also depends upon various factors such as HSC of constituent phases, porosity, shape factor, size of particles their distribution etc. and, incorporating all these factors in the prediction of Hsc of two phase system is a complex affair. As it is not often possible to conduct experiments on Hsc, a theoretical expression is needed to predict its value.

In the present paper, we are trying to find a suitable expression for predicting the static Hsc for highly porous metal foams in two-phase systems. Here, we take particles of irregular shape have been assumed to be distributed randomly in the continuous medium. The concept of averaging the temperature field within different phases has been used. The resistor model approach has been applied. Equivalent thermal resistors formed out of the phases, in the form of parallel slabs, are considered. These slabs are taken to be inclined at an angle θ to the direction of heat flow.

Using data fitting technique, the expressions for θ has been obtained. Our approach is simpler and provides wider applicability of the proposed relation. It's ability to predict correctly the Hsc of highly porous metal foams in two-phase systems. The theoretical values of Hsc's obtained from this model are compared with values given in the literature and these values show a very good agreement.

Theoretical Formulation

Following closure equations for the temperature field from Hadley [10], can be written as

$$\nabla\langle T\rangle = \phi_s \langle \nabla T_s\rangle + \phi_f \langle \nabla T_f\rangle + \phi_{sf} \langle \nabla T_{sf}\rangle \qquad (2)$$

$$\frac{\beta_e}{\beta_s} \nabla\langle T\rangle = \phi_s \langle \nabla T_s\rangle + \frac{\beta_f}{\beta_s}\phi_f \langle \nabla T_f\rangle + \frac{\beta_{sf}}{\beta_s}\phi_{sf} \langle \nabla T_{sf}\rangle \qquad (3)$$

Where $\langle \nabla T_s\rangle, \langle \nabla T_f\rangle, and\ \langle \nabla T_{sf}\rangle$ are average of the temperature gradients in dispersed (solid), continuous (fluid) and interfacial layer between solid and fluid phases. β_e, β_s , β_f , β_{sf} , ϕ_s , ϕ_f , ϕ_{sf} are the effective Hsc, heat storage coefficient of solid phase, heat storage coefficient of fluid phase, heat storage coefficient of interfacial layer, and the volume fraction of solid phase, volume fraction of fluid phase, volume fraction of interfacial layer, respectively. These two equations (2) and (3) can be solved only when some relation, connecting the parameters ∇T, $\langle \nabla T_s\rangle, \langle \nabla T_f\rangle, \langle \nabla T_{sf}\rangle$ is assumed. So for this reason, if we assume

$\langle \nabla T_s\rangle = \langle \nabla T_f\rangle = \langle \nabla T_{sf}\rangle$,

The average temperature gradients in the two-phases are equal. This condition is met in a collection of phase slabs, parallel to the direction of heat flow

$$\beta_{\parallel} = \phi_s\, \beta_s + \phi_f\, \beta_f + \phi_{sf}\, \beta_{sf} \qquad (4)$$

This expression is equivalent to the heat storage coefficient of resistors arranged in parallel. Similarly, the assumption

$\beta_s \langle T_s \rangle = \beta_f \langle T_f \rangle = \beta_{sf} \langle T_{sf} \rangle$, gives

$$\beta_{\perp} = \frac{\beta_s\, \beta_f\, \beta_{sf}}{\phi_f\, \beta_s\, \beta_{sf} + \phi_s\, \beta_f\, \beta_{sf} + \phi_{sf}\, \beta_s\, \beta_f} \qquad (5)$$

It is an expression valid for the equivalent heat storage coefficient of resistors arranged perpendicular to the heat flow. The above condition is equivalent to $\beta_s \langle T_s \rangle = \beta_f \langle T_f \rangle = \beta_{sf} \langle T_{sf} \rangle$, i.e. the heat flux passing through different phases is the same. This situation is met with the slabs perpendicular to the direction of heat flow. In equation (4) and (5) $\beta_{\parallel}\ and\ \beta_{\perp}$ represent the upper and lower bounds on the effective heat storage coefficient for a mixture.

Thus $\beta_{\parallel}$ = $(\beta_e)_{max}$ and $\beta_{\perp}$ = $(\beta_e)_{min}$. As we know, $\lambda_{sf} = 2\lambda_f$ (i.e. $K_{layer} = 2K_f$) the same value as that given by Leong et al.[11] is used in the calculation of the thermal conductivity. So in the present paper, we use the same phenomena for heat storage coefficient β_{sf} means $\beta_{sf} = 2\beta_f$ (i.e. $\beta_{sf} = \lambda_{sf}/\sqrt{\alpha} = 2\lambda_f/\sqrt{\alpha}$). As we know that the total volume of any system is unity. So we get the volume fraction of solid, fluid and interfacial layer is $\phi_s + \phi_f + \phi_{sf} = 1$. According to this phenomenon we can easily calculate the volume fraction of interfacial layer (ϕ_{sf}), and we get a very small range for interfacial layer. Here, the average values of ϕ_{sf} is just 0.001 only for all samples which we have in Table-1.

It is well known that a porous medium is neither composed of slabs parallel to the heat flux nor perpendicular to it, yet the concept of the slabs is capable of predicting the maximum and minimum limits of the Hsc. Therefore, it is proposed that the slabs of the continuous and dispersed phases with interfacial layer, inclined to the heat flux, may represent the Hsc of the system. Now we assume that the continuous and dispersed phases with the interfacial layer in the form of parallel slabs (equivalent resistors), which make an angle θ with the direction of heat flux. Let us also suppose that has a direction along the slabs. As the slabs are neither parallel nor perpendicular to the heat flux, we resolve the HSC into two components, one parallel to the heat flux (say β_{pl}) and the other perpendicular to it (say β_{pr}).

So, now two components should be such that,

(i) For θ = 0, the component β_{pl} reduces to $\beta_{||} = (\beta_e)_{max}$ and β_{pr} reduces to $\beta_{\perp} = 0$.

(ii) For θ = π/2, we get β_{pl} reduces to $\beta_{||} = 0$ and β_{pr} reduces to $\beta_{\perp} = (\beta_e)_{min}$.

These considerations lead to the conditions that the components should be,

$$\beta_{pl}=(\beta_e)_{max}\cos\theta \qquad (6)$$

and

$$\beta_{pr}=(\beta_e)_{min}\sin\theta \qquad (7)$$

Hence, the effective heat storage coefficient is given by,

$$\beta_e=[(\beta_{pl})^2+(\beta_{pr})^2]^{1/2} \qquad (8)$$

Equations (6) to (8) suggest that an increase in the angle θ will increase β_{pr} and decrease β_{pl} components. The net result will be a decrease in HSC. On the other hand, decrease in θ will have a reverse effect and Hsc will increase. So, from equations (4) to (8), we get

$$\beta_e=[\{\phi_s\,\beta_s + \phi_f\,\beta_f + \phi_{sf}\,\beta_{sf}\}^2\cos^2\theta+\{\frac{\beta_s\,\beta_f\,\beta_{sf}}{\phi_f\,\beta_s\,\beta_{sf}+\phi_s\,\beta_f\,\beta_{sf}+\phi_{sf}\,\beta_s\,\beta_f}\}^2 \sin^2\theta\,]^{1/2} \qquad (9)$$

By knowing the angle of inclination of the slabs 'θ' , the HSC of any system can be obtained. Therefore, rearranging equation (9), we get

$$A\sin^2\theta+B=0 \qquad (10)$$

Where $A=[(\beta_s\beta_f\beta_{sf})^2-\{(\phi_s\,\beta_s + \phi_f\,\beta_f + \phi_{sf}\,\beta_{sf}\,)^2.\}]$ $(\phi_s\,\beta_f\,\beta_{sf} + \phi_f\,\beta_s\beta_{sf} + \phi_{sf}\,\beta_s\beta_f\,)^2\}]$ and

$B=[(\phi_s\,\beta_f\,\beta_{sf} + \phi_f\,\beta_s\beta_{sf} + \phi_{sf}\,\beta_s\beta_f\,)^2.$ $\{(\phi_s\,\beta_s + \phi_f\,\beta_f + \phi_{sf}\,\beta_{sf}\,)^2 - (\beta_e)^2\}]$

The experimental results show that Hsc depends upon various characteristics of the system. The most prominent among them are the non-uniform shape of the particles, the random packing of the phases and the non-uniform floe of heat flux lines in the phases. For the practical utilization of equation (9), we have to calculate the value of angle θ using data given in literature.

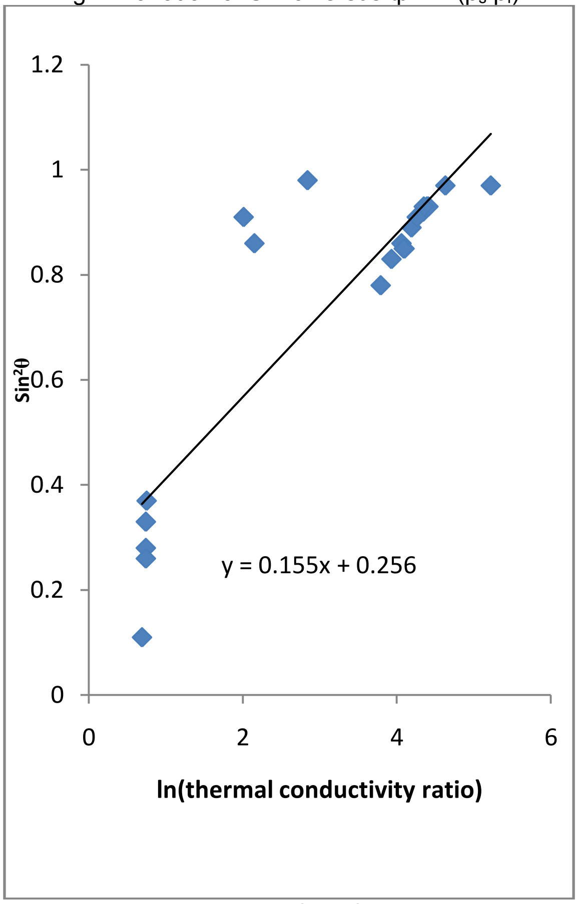
Results and Discussion

We have tested the validity of our empirical model as discussed above on highly porous two-phase systems, for which the characteristics of the constituent phases, including heat storage coefficient of solid phase, fluid phase and interfacial layer between solid and fluid phases, porosity and the experimental results for the Hsc have been cited in the literature [9,12]. First of all, angle θ is calculated from a large number of experimental data reported in the literature, by putting the values of heat storage coefficient of constituent phases and Hsc as in equation (9).

A graph has been plotted between $\sin^2\theta$ and $\phi_s^{1/2}\ln(\beta_s/\beta_f)$. This plot of $\phi_s^{1/2}\ln(\beta_s/\beta_f)$ versus $\sin^2\theta$ is shown in figure 1. It is found that $\sin^2\theta$ decreases roughly linearly with increasing $\phi_s^{1/2}\ln(\beta_s/\beta_f)$.

$$\sin^2\theta=C_1\phi_s^{1/2}\ln(\beta_s/\beta_f)+C_2 \qquad (11)$$

Fig.1. Variation of $\sin^2\theta$ versus $\phi^{1/2}\ln(\beta_s/\beta_f)$.



Equation (11), we obtained from figure 1, by using the best fitting curve technique. The constants C_1 and C_2 are 0.155 and 0.256 respectively for each type of materials, which are shown in Table-1. So now putting equation (11) in equation (9), Hsc for a large number of samples given in the literature has been calculated. On applying above equation in Eq. 9 we have calculated the values of heat storage coefficient for a number of samples in Table-1.

Figure 2 shows a comparison of the experimental results of heat storage coefficient and calculated values from Eq. 9. It is seen from this plot that experimental values and proposed model values show an average deviation of just 4.8%. So this proposed model can be used successfully to predict the heat storage coefficients of similar systems when heat storage coefficients of their constituents phases and the porosity values are known.

In Table-2, the samples under study are porous therefore, a comparison with other models for effective heat storage coefficients for porous materials have also been made. Thus, Hsc using K. J. Singh et al.[12], Usha Singh et al.[9] has been determined. Figure 2 also shows comparison of experimental values of given samples with these models. The average deviation in HSC for given samples is 5.9% and 52%, for K. J. Singh et al.[12], Usha Singh et al.[9] models, respectively. However, the proposed model shows only 4.8% deviation.

Thus, our model provides better results for porous metal foams than the other models. So we get, the results using our model show least deviation from the experimental values.

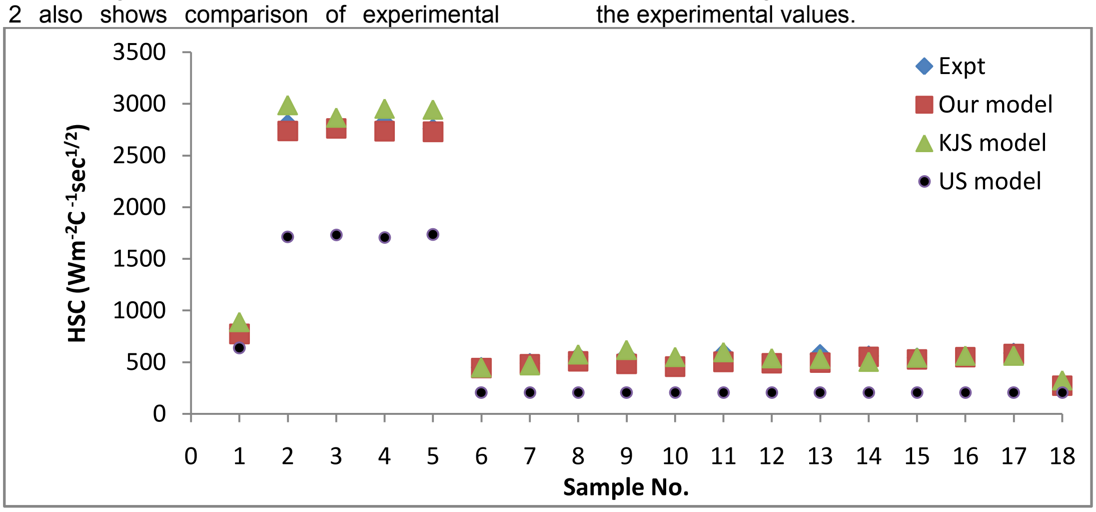


Fig. 2: Comparison of experimental and theoretical values of effective Hsc.

Table-1. Comparison of HSC values for two-phase systems using Eq. 9. The Heat Storage Coefficient β is in $Wm^{-2}C^{-1}sec^{1/2}$.

Sample No.	Sample	ϕ_s	β_s	ϕ_f	β_f	ϕ_{sf}	β_{sf}	β(expt)	β(theo)	%error
1	Glass/IC8	0.431	1335	0.568	462.5	0.001	925	820.2	773.8	5.6
2	Silica/water	0.431	4900.1	0.568	1566.3	0.001	3132.6	2802.6	2738.4	2.2
3	Silica/water	0.439	4900.1	0.56	1566.3	0.001	3132.6	2761.8	2761.2	0
4	Silica/water	0.43	4900.1	0.569	1566.3	0.001	3132.6	2815.2	2735.6	2.8
5	Silica/water	0.428	4900.1	0.571	1566.3	0.001	3132.6	2759.4	2729.9	1
6	Marble/air	0.471	3738	0.528	6.2	0.001	12.4	448.5	442.9	1.2
7	Marble/air	0.443	3738	0.556	6.2	0.001	12.4	490.2	479.7	2.1
8	Marble/air	0.404	3738	0.595	6.2	0.001	12.4	552.9	509.6	7.8
9	Dune sand/air	0.42	3495	0.579	6.2	0.001	12.4	561	482.9	13.9
10	Riverbase sand/air	0.4	3108	0.599	6.2	0.001	12.4	499.5	457.4	8.4
11	Loamy soil/air	0.41	3704	0.589	6.2	0.001	12.4	581.8	503.9	13.3
12	Loamy soil/air	0.43	3704	0.569	6.2	0.001	12.4	507.1	490.1	3.3
13	Dry dune sand/air	0.358	3495	0.641	6.2	0.001	12.4	576.8	496.6	13.8
14	Silica/air	0.424	4897	0.575	6.2	0.001	12.4	559.5	552.8	1.1
15	Silica/air	0.437	4897	0.562	6.2	0.001	12.4	543.7	526.7	3.1
16	Silica/air	0.426	4897	0.573	6.2	0.001	12.4	552.5	549.1	0.6
17	Silica/air	0.408	4897	0.591	6.2	0.001	12.4	588.5	578.3	1.7
18	Dry cement/air	0.56	3041	0.441	6.2	0.001	12.4	285.6	272.1	4.7

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Table-2. Comparison of HSC values for two-phase systems with different models [9,12].

Sample No.	β_s	β(expt)	β(theo)Our model	error	β(theo)KJS model	error	β(theo)US model	error
1	1335	820.2	773.8	5.6	890.7	8.7	637.1	22.3
2	4900.1	2802.6	2738.4	2.2	2987.7	6.6	1713.9	38.8
3	4900.1	2761.8	2761.2	0	2868.3	3.8	1733.4	37.2
4	4900.1	2815.2	2735.6	2.8	2954.1	4.9	1708.1	39.3
5	4900.1	2759.4	2729.9	1	2945	6.7	1734.5	37.1
6	3738	448.5	442.9	1.2	450.3	0.4	207.7	53.6
7	3738	490.2	479.7	2.1	470.6	3.9	207.7	57.6
8	3738	552.9	509.6	7.8	576.8	4.3	207.6	62.4
9	3495	561	482.9	13.9	620.9	10.6	207.6	62.9
10	3108	499.5	457.4	8.4	551.8	10.4	207.8	58.3
11	3704	581.8	503.9	13.3	599.6	3	207.6	64.3
12	3704	507.1	490.1	3.3	539.2	6.3	207.7	59
13	3495	576.8	496.6	13.8	534	7.4	207.6	64
14	4897	559.5	552.8	1.1	505.4	9.6	207.5	62.9
15	4897	543.7	526.7	3.1	545.6	0.3	207.5	61.8
16	4897	552.5	549.1	0.6	564.9	2.2	207.5	62.4
17	4897	588.5	578.3	1.7	565.4	3.9	207.5	64.7
18	3041	285.6	272.1	4.7	325.4	13.9	208.2	27.1
	Average	Error		4.8		5.9		52

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