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Heat Transfer Model for aerogel filled Polyurethane composite

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Abstract

This work explores heat transfer mechanism in aerogel filled polyurethane composite. The heat transfer in the composite occurs through: conduction by solids, radiation on surface between neighbouring aerogel particles and natural thermal convection of gas in mesoporous aerogel particles. A theoretical model for heat transfer through conduction in aerogel filled polyurethane composites based on law of minimal thermal resistance and equal law of specific equivalent thermal conductivity was developed. The effective thermal conductivity of the composites was estimated using the derived equation and then compared with experimental data from the previous research. The results show that the predictions of effective thermal conductivity are close to measured data. One point to be considered is that, data taken from the past research are from polymer filled with high conductive fillers. Thus, when the derived equation is used to predict thermal conductivity of aerogel-filled polyurethane composite, the estimated value may differ with experimental value and may require a correction factor to count for all discrepancies.

Keywords: Polymer composite; effective thermal conductivity; aerogel; heat transfer; theoretical model

Nomenclature:

H	: Side length of square element	k_{eff}	: Effective thermal conductivity of the composite
r	: Radius of spherical filler (aerogel)	R_{total}	: Total thermal resistance of the element
A	: Cross sectional area of element	V_f, V_p	: Volume of filler material and polymer matrix material in the element
Q	: Heat flow through cross sectional area of an element of composite	K_f, k_p	: Thermal conductivity of filler material and polymer matrix
ΔT	: Temperature difference between two side of the element	Φ_f	: Volume fraction of filler

1. Introduction

Transparent/Translucent insulation (TI) is gaining attention in market due to its ability to provide insulation and harness solar thermal energy at the same time. A new composite material is proposed by adding aerogels in polyurethane. Adding mesoporous aerogels in polyurethane enhances thermal insulation capability of polymers by suppressing heat transfer. It also enhances daylighting capability of the polymer by increasing scattering of visible light. This type of composite can be used as Transparent/translucent insulation material for daylighting and insulating applications in buildings.

Thermal conductivity is an important parameter to determine the insulating capability of any material. For composites, it is required to determine effective thermal conductivity of their heterogeneous mixture, but heat transport process in composites is very complicated in nature. Many researchers have proposed different theoretical models for polymer composites with porous materials. Maxwell was the first to develop effective thermal conductivity expression of two-phase mixture and later on several researchers modified or extended his expressions. Rayleigh developed model for effective thermal conductivity while considering thermal interaction between particles (Cheng and Vachon, 1969; Liang, 2010; Pietrak and Wisniewski, 2015). Russell (1935) presented effective thermal conductivity for porous materials and investigated effects of pore size and shape (Russell, 1935). Lewis-Neilsen developed model for wide range of particle shapes for a two-phase system. But this model is unstable for higher filler loadings (Agrawal and Satapathy, 2013; Pietrak and Wisniewski, 2015). Liang and Li (2007) presented a theoretical model for polymeric composite with hollow microspheres. Later on Liang and Liu, (2009) presented effective conductivity expression for particulate-filled polymer composites. Recently Agrawal and Satapathy, (2013) presented a theoretical model for a two-phase particulate filled composite (Agrawal and Satapathy, 2013). However there have been few studies on theoretical measurement of heat transfer through an aerogel filled polymer composites.

This paper demonstrates heat transfer process in an aerogel filled polyurethane composites. A relevant effective thermal conductivity expression is proposed on the basis of heat transfer model. This expression is in correlation with filler content and thermal conductivities of filler and polymer.

2. Theoretical analysis of heat transfer

Heat transfer in aerogel filled polymer composites is a complicated process due to mesoporous nature of aerogels. In general, heat transport occurs due to thermal conduction by solid, heat radiation on the surface between neighbouring aerogel particles and natural thermal convection in mesoporous aerogel particles.

Previous researches have pointed out that natural convection will not occur when the pore size is smaller than 4mm (Liang, 2010; Skochdopole, 1961). Fuji et al. (2015) mentioned that nano-pore size helps in preventing convective heat flow. According to them, if pore diameter is smaller than mean free path of air molecules, random motion of air molecules is suppressed leading to decreased convective flow in the gas phase. In aerogels, mesopores are of nano size with average pore diameter of approximately 20nm containing air as gas phase. These nano pores are smaller than mean free path of air molecules (approximately 68 nm) preventing convective heat flow. Generally, polymeric composites works under lower temperature conditions where proportion of heat transfer through thermal radiation is very low. Hence thermal radiation is also neglected in modelling heat transfer through composite (Liang, 2010).

2.1 Modelling heat transfer in composites

A detailed heat transfer model to predict accurate effective thermal conductivity requires knowledge shape, size, location and conductivity of each material in the composites. It is difficult to represent this detailed knowledge theoretically for composites filled with particles. To overcome these problems, simplifying assumptions were made: (1) Isotropic composite – Uniform properties in all direction; (2) Aerogel is uniformly distributed in polymer matrix; (3) Linear temperature distribution along the direction of heat flow.

Law of minimal thermal resistance and equal law of specific equivalent thermal conductivity states that when only heat conduction is considered and specific equivalent thermal resistance

of the element of composite is equal to total thermal resistance of composite then equivalent thermal conductivity of element is equal to total thermal conductivity. This law eliminates the need to consider size of the element (Agrawal and Satapathy, 2013; Liang, 2010; Liang and Liu, 2009). Assuming a composite is made up of number of square elements of length 'H' with each element containing only one particle of radius 'r' inside it, as shown in figure 1. To model heat transfer in the composite, an element is selected from the composite and direction of heat flow is shown in figure 1. For the composite element heat quantity (Q) can be expressed as:

$$Q = k_{eff} A \frac{\Delta T}{H} \quad (1)$$

Thus, total thermal resistance of this composite element will be:

$$R_{total} = \frac{H}{k_{eff} \cdot A} \quad (2)$$

For theoretical analysis of heat transfer through a composite element, the element is further divided into five parts - polymer phase and sphere phase. Part 1 is pure polymer with height h_1 , area A_1 , and thermal conductivity k_1 ; Part 2 is pure polymer with height $2r$, area A_2 , and thermal conductivity k_2 ; Part 3 is particle (aerogel) with height $2r$, area A_3 , and thermal conductivity k_3 ; Part 4 is pure polymer with height $2r$, area A_4 , and thermal conductivity k_4 ; Part 5 is pure polymer with height h_3 , area A_5 , and thermal conductivity k_5 . As total height of the element is H , thus $h_1 = H - 2r$. Part 1 and part 5 are pure polymer with equal dimensions, thus $h_1 = h_3$, and $A_1 = A_5$. Similarly part 2 and part 4 are having equal cross sectional area, $A_2 = A_4$.

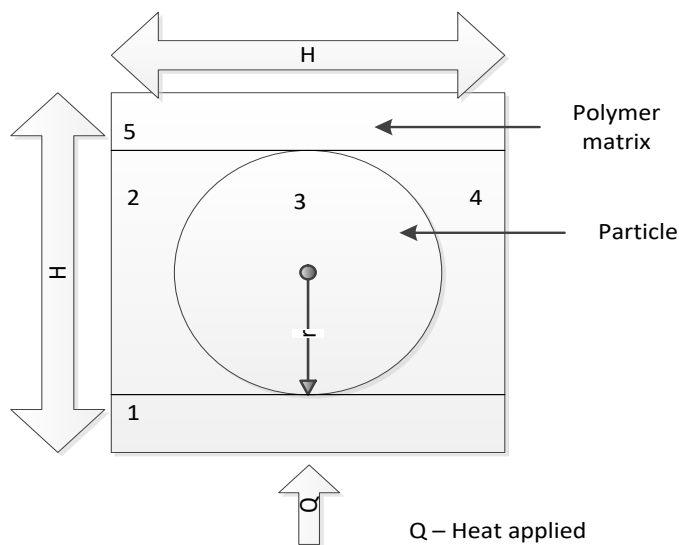


Figure 1 A composite element for heat transfer analysis

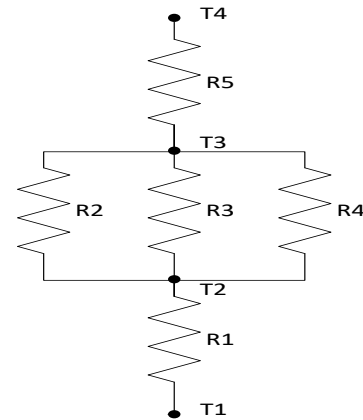


Figure 2 Thermal resistance model of a composite element

Figure 2 shows a series-parallel model for thermal resistance of a composite element. Once total thermal resistance is calculated effective thermal conductivity of the element can be predicted, as follow:

$$R_{total} = R_1 + R_a + R_5 \quad (3)$$

$$R_a = \frac{R_2 R_3 R_4}{R_3 R_4 + R_2 R_4 + R_2 R_3} \quad (4)$$

As temperature is linearly distributed, mean thermal conductivity of each section can be calculated to provide thermal resistance for each part.

Part 1	$k_1 = k_p$	Thermal resistance for this section will be:	$R_1 = \frac{h_1}{K_p A}$
Part 2	$k_2 = \frac{k_p V_2}{2r A}$	Thermal resistance for this section will be:	$R_2 = \frac{4r^2}{K_p V_2}$
Part 3	$k_3 = \frac{k_f V_f}{2r A}$	Thermal resistance for this section will be:	$R_3 = \frac{4r^2}{K_f V_f}$
Part 4	$k_4 = \frac{k_p V_4}{2r A}$	Thermal resistance for this section will be:	$R_4 = \frac{4r^2}{K_p V_4}$
Part 5	$k_5 = k_p$	Thermal resistance for this section will be:	$R_5 = \frac{h_1}{K_p A}$

Thus, the total thermal resistance of the composite element can be expressed in the following equation:

$$R_{total} = \frac{2h_1}{K_p A} + \frac{4r^2}{2K_p V_2 + K_f V_f} \quad (5)$$

The effective thermal conductivity of element can be expressed in the following equations:

$$k_{eff} = \frac{H}{R_{total} A} \quad (6)$$

$$k_{eff} = \frac{H}{\left[\frac{2h_1}{K_p A} + \frac{4r^2}{2K_p V_2 + K_f V_f} \right] A} \quad (7)$$

$$k_{eff} = \frac{1}{\left[\frac{\left(\frac{4\pi}{3\Phi_f} \right)^{\frac{1}{3}} - 2}{k_p \left(\frac{4\pi}{3\Phi_f} \right)^{\frac{1}{3}}} + \frac{\left(\frac{4\pi}{3\Phi_f} \right)^{\frac{1}{3}}}{k_p \left(\frac{4\pi}{3\Phi_f} \right)^{\frac{2}{3}} + \left(\frac{\pi}{3} (k_f - 2k_p) \right)} \right]} \quad (8)$$

3. Results and Discussions

The equation (8) derived in the previous section were validated and compared using experimental data obtained from Liang and Liu, (2009). Two composites (Aluminium powder filled Phenol-aldehyde composites and Graphite powder filled Phenol-aldehyde composites) have been used by the authors. These composites were made with different filler weight fractions; whilst the derived expression in this paper requires volume fraction (Φ_f) of the fillers added in the composites. Thus, weight fractions were expressed in volume fraction using equation 9.

$$\Phi_f = \frac{W_f}{\left[W_f \left(1 - \frac{\rho_f}{\rho_m} \right) \right] + \frac{\rho_f}{\rho_m}} \quad (9)$$

where, W_f is Weight fraction, ρ_f and ρ_m are density of filler and polymer matrix.

$$W_f = \frac{\text{Weight percent}}{100} \quad (10)$$

The effective thermal conductivity for aluminium powder filled phenol-aldehyde is calculated from equation (8) for different volume fractions of filler. These calculated values alongside the experimental data from Liang and Liu (2009) are presented in table 1.

Table 1 Calculated conductivity of Aluminium powder filled phenol-aldehyde composites.

Weight %	Volume fraction (Φ_f)	K-polymer [W/(m K)]	Density polymer [kg/m ³]	K – filler [W/(m K)]	Density filler [kg/m ³]	Keff [W/(mK)]	Kexp [W/(mK)]
10	0.049	0.111	1248	203.5	2670	0.20245	0.195
20	0.1046	0.111	1248	203.5	2670	0.26606	0.289
40	0.2375	0.111	1248	203.5	2670	0.476	0.539
60	0.4121	0.111	1248	203.5	2670	1.4259	1.457

The effective thermal conductivity for graphite powder filled phenol-aldehyde was predicted using equation (8) and the results are shown in table 2. The results were compared with the experimental results taken from Liang and Liu (2009).

Table 2 Calculated conductivity of Graphite powder filled phenol-aldehyde composites

Weight %	Volume fraction (Φ_f)	K-polymer [W/(m K)]	Density polymer [kg/m ³]	K – filler [W/(mK)]	Density filler [kg/m ³]	Keff [W/(mK)]	Kexp [W/(mK)]
10	0.058	0.111	1248	120	2250	0.212865	0.229
20	0.121	0.111	1248	120	2250	0.286317	0.306
40	0.2699	0.111	1248	120	2250	0.5573	0.523
60	0.4541	0.111	1248	120	2250	2.351862	2.228

Figure 3 represents relationship between volume fraction of filler – aluminium powder and effective thermal conductivity of the composite. Keff is calculated thermal conductivity from derived expression and Kexp is measured value obtained from Liang and Liu (2009). It can be observed that thermal conductivity increases with increase in filler volume fraction. The thermal conductivity values from equation (8) are approximately consistent with the experimental values.

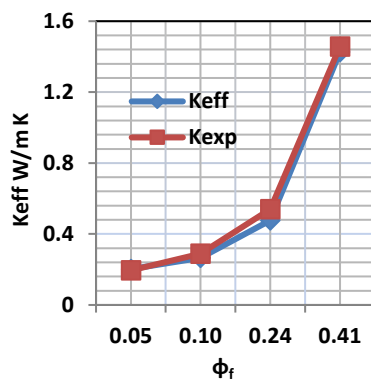


Figure 3 Aluminium powder filled phenol-aldehyde

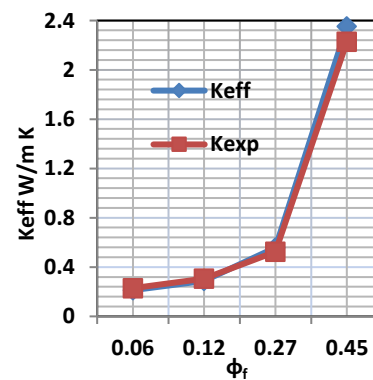


Figure 4 Graphite powder filled phenol-aldehyde

Figure 4 shows the relationship of predicted and experimentally measured thermal conductivity with volume fraction of graphite powder. Both conductivity values are increasing non-linearly with the increase in volume fraction and are approximately identical with one another.

4. Conclusion

A theoretical model of heat transfer for aerogel filled polyurethane composites has been proposed on basis of law of minimum thermal resistance and equal law of the specific equivalent thermal conductivity. The predicted values from model are in good agreement with experimental results of aluminium powder filled phenol-aldehyde composites and graphite powder filled phenol-aldehyde composites. As aerogels are mesoporous in nature, this model might not be able to predict values which are in agreement with experimental results. Thus it may require a correction factor to count for all discrepancy. There might be requirement for modification in the model by considering density of the materials in the derived equation (8) and including gas phase of aerogels if required.

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