THERMAL CONDUCTIVITY OF PINE WOOD DUST FILLED EPOXY COMPOSITES

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ABSTRACT

Guarded heat flow meter test method is used to measure the thermal conductivity of pine wood dust filled epoxy composites using an instrument Unitherm^{TM} Model 2022 in accordance with ASTM-E1530. In the numerical study, the finite-element package ANSYS is used to calculate the conductivity of the composites. Three-dimensional spheres-in-cube lattice array models are used to simulate the microstructure of composite materials for various filler concentrations ranging from about 6 to 36 vol%. This study reveals that the incorporation of pine wood dust results in reduction of conductivity of epoxy resin and thereby improves its thermal insulation capability. With addition of 6.5 vol% of filler, the thermal conductivity of epoxy is found to decrease by about 19.8% and with about 36 vol% of filler addition, a 57.3% reduction in thermal conductivity of neat epoxy is achieved. The experimentally measured conductivity values are compared with the numerically calculated ones and also with the already existing theoretical and empirical models. It is found that the values obtained for various composite models using finite element method (FEM) are in reasonable agreement with the experimental values.

KEY WORDS: polymer composite, pine wood dust reinforcement, thermal conductivity, finite-element analysis

INTRODUCTION

Hard particulate fillers consisting of ceramic or metal particles and fiber fillers made of glass are being used these days to dramatically improve the mechanical properties such as wear resistance, even up to three orders of magnitude [1]. Various kinds of polymers and polymer matrix composites reinforced with metal particles have a wide range of industrial applications such as heaters, electrodes [2], composites with thermal durability at high temperature [3] etc. These engineering composites are desired due to their low density, high corrosion resistance, ease of fabrication and low cost [4-6]. Considerable work has been reported on the subject of heat conductivity in polymers by Hansen and Ho [7], Peng et. al [8], Choy and Young [9], Tavman [10] etc. It is well known that thermal transport increases significantly in the direction of orientation and decreases slightly in the direction perpendicular to the orientation. But most of these studies were confined to the thermal behaviour of neat polymers only and not to their composites. Reports are available in the existing literature on experimental as well as numerical and analytical studies on thermal conductivity of some filled polymer composites [11-15]. The fillers most frequently used are aluminum particles, copper particles, brass particles, short carbon fiber, carbon particles, graphite, aluminum nitrides and magnetite particles. Many theoretical and empirical models have also been proposed to predict the effective thermal conductivity of two-phase mixtures [11,16]. For a two-component composite, the simplest alternatives would be with the materials arranged in either parallel or series with respect to heat flow, which gives the upper or lower bounds of effective thermal conductivity. For the parallel conduction model:

$$k_c = (1-Ø)\, k_m + Ø\, k_f \qquad \text{---------} \ (1)$$

where, kc, km, kf are the thermal conductivities of the composite, the matrix and the filler respectively and Ø is the volume fraction of filler.

For series conduction model:

$$\frac{1}{k_c} = \frac{(1-\text{Ø})}{k_m} + \frac{\text{Ø}}{k_f}$$

--------- (2)

For an infinitely dilute composite of spherical particles, the exact expression for the effective thermal conductivity is given as:

$$\frac{k}{k_c} = 1 + 3\left(\frac{k_d - k_c}{k_d + 2k_c}\right)$$

--------------- (3)

where K, Kc and Kd are thermal conductivities of composite, continuous-phase (matrix), and dispersed-phase (filler), respectively, and Ø is the volume fraction of the dispersed-phase. Equation (3) is the well-known Maxwell equation [17] for dilute composites. An exhaustive review of the published literature reveals that most of the investigations are aimed at enhancing the thermal conductivity of the polymer rather than attempting to improve its insulation capabilities. In view of the above, the present work is undertaken to investigate numerically and experimentally the thermal conductivity of epoxy filled with pine wood dust.

EXPERIMENTAL DETAILS

Matrix and Filler Materials

Epoxy LY 556 resin, chemically belonging to the 'epoxide' family is used as the matrix material. Its common name is Bisphenol A Diglycidyl Ether. The low temperature curing epoxy resin (Araldite LY 556) and corresponding hardener (HY951) are mixed in a ratio of 10:1 by weight as recommended. Epoxy is chosen primarily because it happens to be the most commonly used polymer and because of its insulating nature (low value of thermal conductivity, about 0.363 W/m-K). Pine wood dust (PWD) is generated during the cutting of chir pine tree wood. The scientific name of Chir Pine is *Pinus roxburghii.* Main organic constituents of pine wood are: cellulose, glucomannan, xylan, lignin and some extractives. Its dust particles are chosen as the filler material in this work mostly for its very low thermal conductivity (0.068 W/m-K) and low density (0.52 gm/cc).

Composite Fabrication

The low temperature curing epoxy resin (LY 556) and corresponding hardener (HY951) are mixed in a ratio of 10:1 by weight as recommended. Pine wood dust (PWD) particles (collected from HP) with average size 100 μm are reinforced in epoxy resin (density 1.1 gm/cc) to prepare the composites. The dough (epoxy filled with PWD) is then slowly decanted into the glass tubes, coated beforehand with wax and uniform thin film of silicone-releasing agent. The composites are cast by conventional hand-lay-up technique in glass tubes so as to get cylindrical specimens (dia 9 mm, length 120 mm). Composites of four different compositions, as listed in Table 1 are made. Unitherm™ Model 2022 is used to measure thermal conductivity of these composites in accordance with ASTM E-1530.

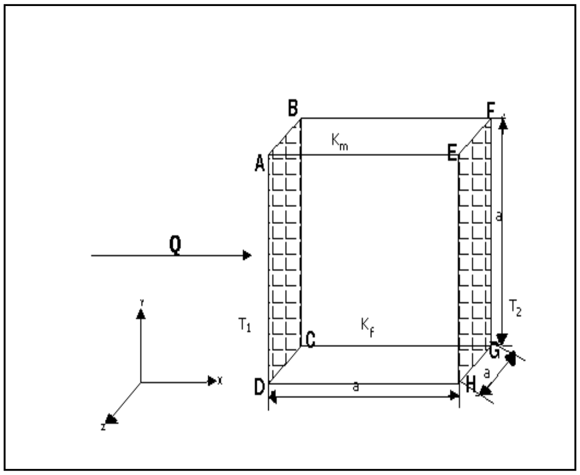
Table 1: list of composites fabricated by hand-lay-up technique

Samples	Composition
1	Epoxy + 6.5 vol% (3.2 wt%) Filler
2	Epoxy + 11.3 vol% (5.7 wt%) Filler
3	Epoxy + 26.8 vol% (14.8 wt%) Filler
4	Epoxy + 35.9 vol % (20.9 wt%) Filler

RESULTS AND DISCUSSION

Numerical Analysis

Using the finite-element program ANSYS, thermal analysis is carried out for the conductive heat transfer through the composite body. In order to make a thermal analysis, three-dimensional physical models with spheres-in-a-cube lattice array have been used to simulate the microstructure of composite materials for four different filler concentrations. Furthermore, the effective thermal conductivities of these epoxy composites filled with pine wood dust up to about 36% by volume is numerically determined using ANSYS.



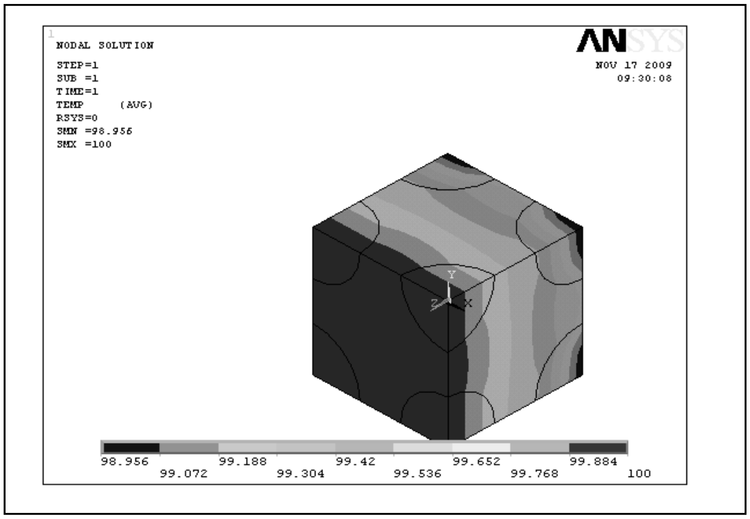


Figure 1 Boundary conditions. **Figure 2**: Temperature profiles for composites (filler 35.9 vol%)

In the numerical analysis of the heat conduction problem, the temperatures at the nodes along the surfaces ABCD is prescribed as T1 (=100^0C) and the convective heat transfer coefficient of ambient is prescribed as 2.5 W/m^2-K at ambient temperature of 27°C. The heat flow direction and the boundary conditions are shown in Figure 1. The other surfaces parallel to the direction of the heat flow are all assumed adiabatic. The temperatures at the nodes in the interior region and on the adiabatic boundaries are unknown. These temperatures are obtained with the help of finite-element program package ANSYS. In the analysis of the ideal case it will be assumed that the composites are macroscopically homogeneous, locally both the matrix and filler are homogeneous and isotropic, the thermal contact resistance between the filler and the matrix is negligible, the composite lamina is free of voids and the filler are arranged in a square periodic array/uniformly distributed in matrix. A typical three-dimensional sphere-in-cube model with the temperature profile obtained from FEM analysis for the composite with pine wood dust concentration of 35.9 vol % are shown in Figure 2.

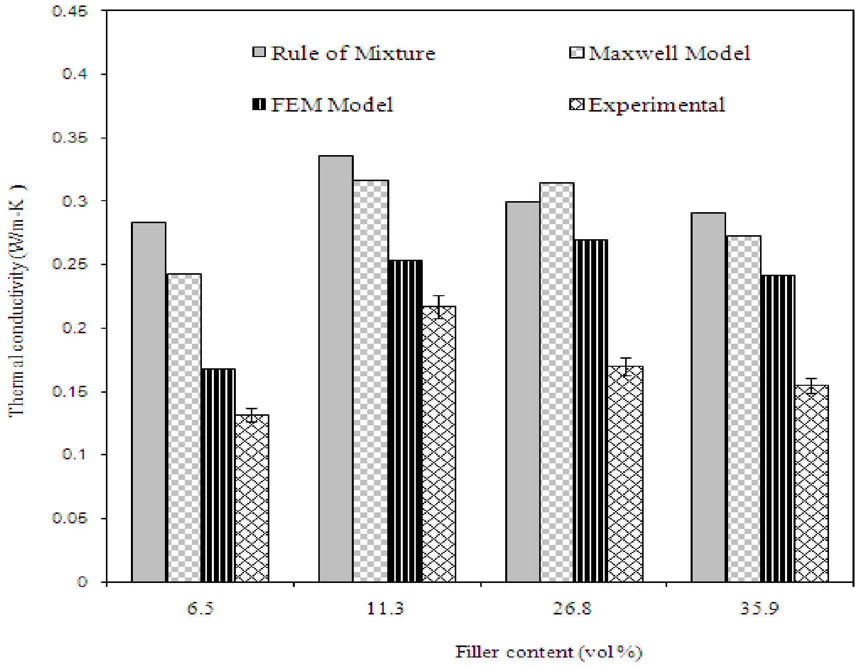


Figure 4: Comparison of thermal conductivity values obtained from different methods

The values of effective thermal conductivities of the particulate filled epoxy composites with varied proportions of pine wood dust obtained using Maxwell's correlation, rules of mixture model and those obtained from FEM analysis are compared in Figure 3. It presents a comparison among the results obtained using these models with regard to the values of effective conductivity obtained experimentally.

Table 3: Percentage errors with respected to the measured value

Models	Vol%	Percentage errors with respected to the measured value		
		Rule of mixture Model (%)	Maxwell's Model (%)	FEM Model (%)
1	6.5	-2.79	13.3929	3.0000
2	11.3	-12.06	13.8801	13.3333
3	26.8	-44.21	4.7244	10.3704
4	35.9	-17.69	28.5714	8.8235

Figure (4) presents comparative picture of the thermal conductivity values obtained from different methods. It is noticed that the results obtained from the finite element analysis using ANSYS are closer to the measured values of effective thermal conductivity for composites of different filler content. On comparison, it is found that while the errors associated with the FEM values with respect to the experimental ones lie in the range of 3 to 13 %, the same for results from rules-of-mixture and Maxwell's correlation lie in the ranges of 2 to 44% and 4 to 28% respectively. The percentage errors associated with each method for individual composites are given as Table 3. It is further noted that while the FEM and Maxwell's model overestimate the value of thermal conductivity the rules-of-mixture model underestimates the value with respect to the experimental ones. It leads to a conclusion that for a particulate filled composite of this kind the FEM model can very well be used for predictive purpose in determining the effective thermal conductivity for a wide range of particle concentration. The difference between the calculated values and the measured value of conductivity for any particular composite sample may be attributed to the fact that some of the assumptions taken for the FEM analysis are not real. The shape of PWD is assumed to be spherical, while in actual practice they are irregular shaped. Although the distribution of pine wood dust in the matrix body is assumed to be in an arranged manner, it is actually dispersed in the resin almost randomly.

CONCLUSIONS

FEM approach can be gainfully employed to determine equivalent thermal conductivity of these composite with different amount of filler content. The value of equivalent thermal conductivity obtained for various composite models using FEM are in reasonable agreement with the experimental values for a wide range of filler contents from about 6 vol% to 36 vol %. The values of thermal conductivity obtained for FEM analysis are more accurate with respect to the experimental values than the values calculated using ROM and Maxwell's correlation. Incorporation of PWD results in reduction of thermal conductivity of epoxy resin and there by improves its thermal insulation capability with addition of 6.5 vol% of PWD, the thermal conductivity drops by about 19.8% and with addition of 35.9% of PWD the thermal conductivity drops by about 57.3% in neat epoxy is achieved. With light weight and improved insulation capability PWD filled epoxy composite can be used for applications such as electronic packages, insulation board, food container, thermo flasks etc.

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