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Investigations on thermal conductivity of wood dust and glass fibre filled epoxy hybrid composites

Ramesh Chandra Mohapatra[1,*], Antaryami Mishra[2] and Bibhuti Bhushan Choudhury[2]
[1]Government College of Engineering, Keonjhar 758002, India.
[2]Indira Gandhi Institute of Technology, Sarang , India.

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ABSTRACT

Experimental and numerical investigation of the thermal conductivity in particulate filler filled (wood dust) epoxy composites have been studied in the present work. The thermal conductivity of particulate filled polymer composite is calculated experimentally using guarded heat flow meter method in accordance with ASTM-E 1530 standard. This study shows that the incorporation of wood dust results in reduction of conductivity of epoxy resin and there by improves its thermal insulation capability. Further the thermal conductivity of particle filled composites has been calculated numerically using the microstructure images by identifying each pixel with a finite difference equation and accompanying appropriate image processing. It has been observed that numerical results, experimental values and all other models are close to each other at low particulate content. On comparison, it has been found that the errors associated with the numerical values with respect to experimental ones lie in the range of 3.4 to 14.8%, the same results from Rules-of- mixture and Maxwell's correlations lie in the ranges of 3.4 to 29.2% and 4.2 to 46.7% respectively. The incorporation of glass fibre in wood dust filled epoxy resin reduces the thermal conductivity further. With addition of 6.5vol%, 11.3vol%, 26.8vol% and35.9vol%of wood dust and 9.6vol% glass fibre the thermal conductivity of epoxy resin dropped by about 43.6%, 47.5%, 60.3% and 62.8% respectively.

Introduction

Recently, thermoplastic and thermoset polymers are combined with natural fillers to produce the composites, which possess better strength and good resistance to fracture. Due to an excellent property profile, these composites find wide applications in packaging, building and civil engineering fields. Natural fiber as a replacement to synthetic fibre in polymer matrix is the focus of many scientists and engineers. The reason for focus on natural fibre reinforced polymer matrix is because of its low cost eco-friendly, low energy consumption, non abrasive nature, and good insulator of heat and sound. In recent years, major industries such as automotive, construction and packaging industries have shown enormous interest in the development of new bio-composite materials and are currently engaged in searching for new and alternate products to synthetic fibre reinforced composites

Literature review

Effective thermal conductivity is an important characteristic of heat transfer properties of materials. The temperature field in composite materials cannot be determined unless the thermal conductivities of the media are known. Numerous theoretical and experimental approaches have been developed to determine the precise value of this parameter. Maxwell [1] studied the effective thermal conductivity of heterogeneous materials. By solving Laplace's equation, the effective thermal conductivity of a random suspension was determined for sphere within a continuous medium. Procter et al. [2] used Nielsen model as a prediction to investigate the thermal conductivity of several types of polymer composites filled with different fillers and confirm its applicability. Tavman [3] investigated the thermal and mechanical properties of copper powder filled poly-ethylene composites. Agari et al. [4] predicted the effective thermal conductivity of the composite with high loading. Nagai [5] found that Bruggman Model for Al_2O_3/ Epoxy System and modified form of Bruggman Model for AlN/epoxy system are both good prediction theories for thermal conductivity. Griesinget et al. [6] reported that thermal conductivity of low density poly-ethylene (LDPE) increased from 0.35 W/m-K for an isotropic sample to the value of 50M/m-K for a sample with an orientation ratio of 50. Liang et al [7] analyzed the thermal conductivity of a porous material with closed spherical and cylindrical holes. Agrawal et al. [8] measured the thermal conductivity and the thermal diffusivity of oil palm fiber reinforced untreated and differently treated composites with the transient plane source technique at room temperature and atmosphere pressure. Sophina et al.[9] investigated experimentally on thermal properties such as thermal conductivity, thermal diffusivity and specific heat of metal(cooper, zinc, iron and bronze) powder filled HDPE composites in the range of filler content 0-24% by volume. Yu et al.[10] measured the thermal conductivity of polystyrene-aluminium nitride composite and found that the thermal conductivity of the composites was higher for a polystyrene particle size of 2 mm than that of a particle size of 0.5 turn. Mamunya et al. [11] reported the improvement in electrical and the thermal conductivity of polymers filled with metal powder. Tekce et al. [12] noticed the strong influence of the shape factor of fillers on thermal conductivity of the composites. Idicula et al [13] investigated the thermal conductivity, thermal diffusivity and specific heat of polyester/natural fiber composites as function of

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Tele:
E-mail addresses: rameshmohapatra75@gmail.com

filler concentration and for several fibre surface treatments. Weiden feller et al. [14] studied the effect of interconnectivity of the filler particles and its important role in the thermal conductivity of the composites. Patnaik et al. [15] reported the existence of a possible co-relation between thermal conductivity and wear resistance of particulate filled composites. Malkapuram et al. [16] described the novel processing techniques to develop natural fibre reinforced propylene (PP) composites. Osugi et al. [17] examined the thermal conductivity property of natural fibre-reinforced composites. Mounika et al. [18] made thermal conductivity characterization of bomboo fibre reinforced composite by varying volume fraction, temperature and fibre orientation.

Thermal Conductivity Models

Many theoretical and empirical models have been proposed to predict the effective thermal conductivity of two phase mixtures. For a two component composite the simplest alternative would be with the materials arranged in either parallel or series with respect to heat flow, which gives the upper and lower bounds of effective thermal conductivity (Eqns.1 and 2).

Series Model (Rule of Mixture):

$$\frac{1}{K_c} = \frac{1-\phi}{K_m} + \frac{\phi}{K_f} \text{..............................(1)}$$

Where c- composite, m- matrix, f-filler, Φ- volume fraction

Parallel model:

$$K_c = (1-\phi)K_m + \phi K_f \text{ ----------------------- (2)}$$

Where K_c - Thermal conductivity of composite, K_m- Thermal conductivity of matrix, K_f- Thermal conductivity of filler and Φ- is the volume fraction of the filler.

In fact, one can use the series model or parallel model alone or both models according to the practical circumstances. Maxwell [1] using potential theory obtained an exact solution for the conductivity of randomly distributed and non-interacting homogeneous sphere in homogeneous medium as indicated below in Eqn.3.

$$K_c = K_m\left[\frac{K_f + 2K_m + 2\phi(K_f - K_m)}{K_f + 2K_m - \phi(K_f - K_m)}\right] \text{.....................(3)}$$

Experimental Details

Matrix Material (Epoxy)

Epoxy(LY 556) resin and the corresponding hardener (HY 951) are mixed in a ratio of 10:1 by volume supplied by Hindustan Ciba Geigy (India) Ltd.

Filler Material (Pine wood Dust)

Pine wood dust has chosen as the filler material mostly for its very low thermal conductivity (0.068 W/m-^{0}K) and low density (0.52 gm/cc). It is also renewable, eco-friendly, available at low cost, non toxic and basically considered as waste product.

Composite Preparation

The low temperature curing epoxy resin and corresponding hardener were mixed in a ratio of 10:1 by volume as recommended. Pine wood dust (PWD) particles with average size 100µm were reinforced in epoxy resin (density 1.1 gm/cc) to prepare the composites. Further, cross plied E – glass fibers (supplied by saint Gobain Ltd. India) were reinforced separately in PWD filled epoxy resin to prepare a set of glass – epoxy – PWD hybrid composite slabs. E – Glass has an elastic modulus of 72.5GPa, density of 2.59 gm/cc and thermal conductivity of 0.04 W /m –^{0}K at room temperature. The fabrication of these composite slabs was done by conventional hand – lay – up technique. The fillers were mixed thoroughly in the epoxy resin before the glass – fibre mats (9.6vol%) are reinforced into the matrix body. A stainless steel mould having dimensions of 210 × 210 × 40 mm was used for this purpose. Silicon spray was used to facilitate easy removal of the composite from the mould after curing. The cast of each composite was cured under a load of about 50kg for 24 hours before it was removed from the mould. Then this cast was post cured in air for another 24 hours. The specimens were prepared having dimension of 50mm×50mm with thickness of 10 mm.

Determination of thermal conductivity

A guarded heat flow meter has been developed for thermal conductivity measurements. This is achieved by using a thermal conductivity testing system Unitherm Model 2022.(Fig.1)

Specification of the equipment:

Overall dimensions - 258×185×360 mm.
Power supply -220V, 50 /60Hz.
Sample size- 2” diameter
Thermal conductivity – 0.1 – 10W/m - K
Thermal resistance range- 0.002 to0.02 m^2-k/W
Operating temperature range- 20^{0}C to 300^{0}C

The tests are in accordance with ASTM-E-1530 standard. The sample and a heat flux transducer (HFT) are sandwiched between two flat plates controlled at different temperatures to produce a heat flow through the stack. A cylindrical guard surrounds the test stack and is maintained at a uniform mean temperature of the two plates, in order to minimize the lateral leak of heat. At steady state, the difference in temperature between the surfaces contacting the specimen is measured with temperature sensors embedded in the surfaces along with output from the heat flow transducer. These values and the sample thickness are then used to calculate the thermal conductivity.

Operating Principle of Unitherm 2022

Thermal Conductivity is a material property that describes the rate at which heat flows within a body for a given temperature change. The Fourier heat conduction equation for one dimensional heat conduction is

$$Q = KA(T_1 - T_2)/L \text{...................................(4)}$$

Where Q is the rate of heat transfer (W), A is the cross sectional area (m^2), $T_1 - T_2$ is the difference in temperature (^{0}K), L is the thickness of the sample (m). The thermal resistance of a sample can be written as

$$R = (T_1 - T_2)/Q/A \text{......................(5)}$$

Where R is the resistance of the sample between hot and cold surfaces (m^{2}K/W)

From equation (4) and (5) it can be derived that

$$K = L/R \text{....................................(6)}$$

In Unitherm 2022 the heat flux transducer measures the Q value and the temperature difference is obtained between the upper plate and lower plate. Thus the thermal resistance is calculated between the upper and lower surfaces. Giving the input value of thickness and taking the known cross sectional area, thermal conductivity of samples are calculated using Eqn.6. A schematic arrangement of the experiment is given in Fig.2. The prepared specimens have been shown in Fig.3.

Fig.1 The Unitherm 2022

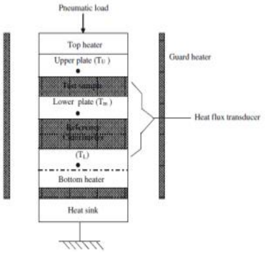

Fig.2 Schematic model showing the testing arrangement

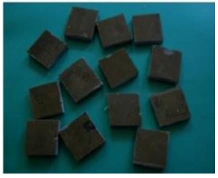

Fig.3 The specimens for thermal conductivity measurement

Numerical Modelling of the problem:

Two – dimensional numerical analysis is carried out for the steady state conductive heat transfer in the composite material (Fig. 4). The temperature field in the composite material is found out by solving Laplace's equation numerically using a finite difference formulation. To solve this problem the boundary conditions are as follows:

a. The horizontal sides perpendicular to the direction of the heat flow are isothermal at the entrance to and the exit from the cell.

b. The vertical sides parallel to the direction of the heat flow are adiabatic.

The heat flow moving into or out of the cell reaches its peak at the centre of the filler particles. For the elementary two – dimensional cell with the dimensions of L_x (along the x axis) and L_y (along the y axis), the thermal conductivity is determined using the following relation:

$$\frac{K_c L_x \Delta T_{cell}}{L_y} = \sum_i k_i x_i \frac{\partial T_i}{\partial y} \text{.......................(7)}$$

With $\sum_i x_i = L_x$ and k_i = (k_m in the continuous phase, k_f in the inclusions). In this heat conduction problem the temperatures at the nodes along the boundaries y = 0 and y = L_y are prescribed and known as T_1 and T_2, but the temperatures at the nodes in the interior region and on the adiabatic boundaries are unknown. Therefore, the problem involves many unknown temperatures. The equations needed for the determination of these temperatures are obtained by writing the appropriate finite difference equation for each of these nodes.

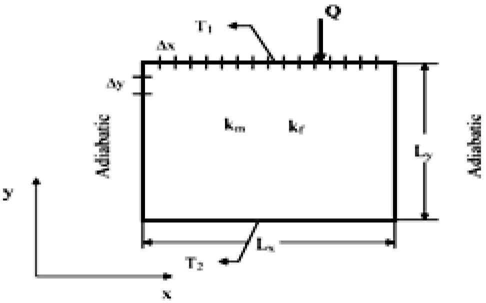

Fig. 4. Two – dimensional model of the composite material

Results and Discussions:

The results obtained from the numerical analysis are compared with the results obtained from the experimental study (Fig.5). On comparison it is found that the thermal conductivities of neat epoxy calculated by all models are same i.e 0.36 W/m-^{0}K. After that as the volume fraction of reinforcement increases the thermal conductivities are reduced but the distribution of thermal conductivities are slightly higher in case of numerical analysis on comparison to experimental study. This is because of the quality of pictures used in image processing carried out on the picture files in numerical study are not so good. It is also interesting to note that the addition of PWD results in reduction in thermal conductivity of epoxy resin and there by improves its thermal insulation capability.

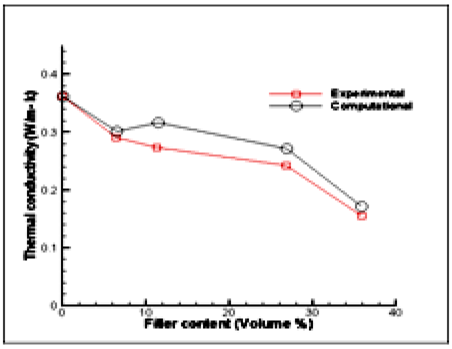

Fig.5. Thermal conductivity of epoxy composites as a function of filler content

In Fig.6 the effective thermal conductivities values obtained from the experimental study for the particulate filled epoxy composites with varied proportions of pine wood dust are compared with Rule of Mixture thermal conductivity model, Maxwell thermal conductivity model and with the numerical results obtained. It is noticed that the results obtained in the numerical analysis are closer to the measured values of effective thermal conductivity for composites of different filler contents. It is further noted that while numerical and Maxwell's model overestimate the value of thermal conductivity the rule of mixture model underestimates the value with respect to the experimental one. The values of the thermal conductivities and percentage of errors associated with each method for individual composites with two components i.e epoxy and PWD are given in Table 1 and Table 2 respectively. Further after addition of glass fibres the thermal conductivities have further reduced as given in Table 3.

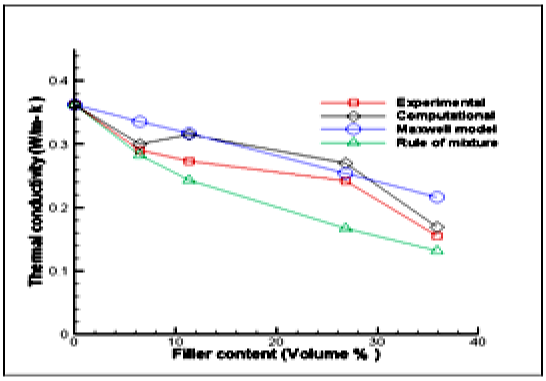

Fig. 6. Comparison of thermal conductivity values obtained from different models

Comparative picture of the thermal conductivity values for particulate filled epoxy composites for different filler content with and without glass fibre reinforcement is shown in Fig.7. It is found that the addition of PWD results in reduction of thermal conductivity of epoxy resin. The incorporation of glass fibre in wood dust filled epoxy resin reduces the thermal conductivity further With addition of 6.5vol% ,11.3vol%, 26.8vol%

and35.9vol%of wood dust and 9.6vol% glass fibre the thermal conductivity of epoxy resin dropped by about 43.6%, 47.5%, 60.3% and 62.8% respectively.

Table 1. Thermal conductivity values of composites obtained from different methods

Sample	Particulate content vol%	Effective thermal conductivities of composites (W/m-k)			
		Rule of mixture	Maxwell's model	Numerical model	Experimental value
1	0(neat epoxy)	0.36	0.36	0.36	0.36
2	6.5	0.28	0.34	0.30	0.29
3	11.3	0.24	0.32	0.31	0.27
4	26.8	0.17	0.25	0.27	0.24
5	35.9	0.13	0.22	0.17	0.15

Table 2. Percentage errors with respect to the measured value

Sample	Particulate content (vol%)	Percentage errors with respect to the measured value (Experimental)		
		Rule of mixture model	Maxwell's model	Numerical model
1	0(neat epoxy)	0	0	0
2	6.5	3.4	17.2	3.4
3	11.3	11.1	18.5	14.8
4	26.8	29.2	4.2	12.5
5	35.9	13.3	46.7	13.3

Table 3. Measured thermal conductivity values of composites of varied composition

Sample	Glass fibre conent V0l%	PWD content Vol%	Measure value of thermal Conductivity(W/m-^{0}K)	% reduction of thermal conductivity with respect to neat epoxy
1	9.6	6.5	0.203	43.6
2	9.6	11.3	0.189	47.5
3	9.6	26.8	0.143	60.3
4	9.6	35.9	0.134	62.8

The corresponding improvement in tensile strength is 115% and 63% respectively. Thus the incorporation of glass fibres serves the dual purpose of providing strength both in tensile and flexural modes and reduces the thermal conductivity of neat epoxy, thereby improving its thermal insulation capability.

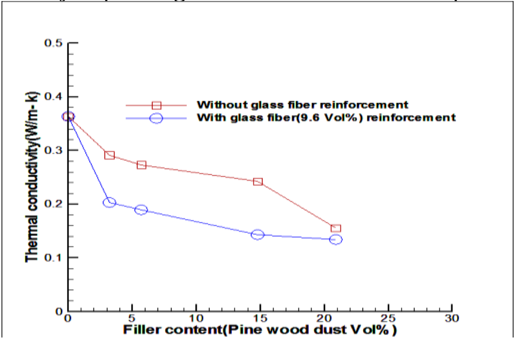

Fig. 7. Thermal conductivity of composites of different filler content with and without glass fibre reinforcement

Conclusions

- The incorporation of pine wood dust results in reduction of thermal conductivity of epoxy resin and there by improves its thermal insulation capability.
- The values of thermal conductivity obtained from numerical analysis are more accurate with respect to the experimental values than the values calculated using ROM and Maxwell's model
- While the incorporation of wood dust results in reduction of thermal conductivity of epoxy resins reinforcement of glass fibre reduces it further.
- The addition of glass fibre serves the dual purpose of providing strength, both in tensile and flexural modes but reduces the thermal conductivity.
- Due to improved insulation capability, the wood dust and glass fibre filled epoxy hybrid composite can be used for applications such as in packaging, buildings, civil engineering fields, automotive, food container, insulation board, Thermo flasks etc.

References

[1] Maxwell J.C. "A Treaties on Electricity and Magnetism," 3rd Ed. New York: Dover, 1954

[2] Procter, P., and Solc, J. "Improved Thermal Conductivity in Microelectronic Encapsulants," IEEE Trans on Hybrids Manuf. Technol. Vol. 14(4), 1991, pp. 708-13.

[3] Tavman, I., "Thermal Anisotropy of Polymers as Function of their Molecular Orientation, Experimental Heat Transfer, Fluid Mechanics and Thermodynamics," Elsevier,1991, pp. 1562-1568.

[4] Agari, Y. Ueda, A, and Nagai, S. "Thermal Conductivity of a Polymer Composite," Jou. Appl. Polym. Sci. Vol. 49, 1993, pp. 1625-1630.

[5] Nagai, Y, and Lai, G.C. "Thermal Conductivity of Epoxy Resin Filled with Particulate Aluminium Nitride Powder," Jou. Ceram. Soc. Jpn. Vol. 105(3), 1997, pp. 197-200.

[6] Griesinger, A., Hurler, W. and Pietralla, M. "A Photo-thermal Method with Step Heating for Measuring the Thermal Diffusivity of Anisotropic Solids," Int. J. of Heat and Mass Transfer.Vol. 40(13), 1997, pp. 3049-3058.

[7] Liang ,X.G, and Qu, W. "Effective Thermal Conductivity of Gas-Solid Composite Materials and the Temperature Difference Effect at High Temperature," Int. J. Heat Mass Transfer. Vol. 42, 1999, pp. 1885-1890.

[8] Agrawal, R., Saxeena, N.S., Sreekala, M.S., and Thomas, S. "Effect of Treatment on the Thermal Conductivity and Thermal Diffusivity of Oil Palm Fibre Reinforced Phenol Formaldehyde Composites," Jou. Polym. Sci. B. Vol. 38, 2000, pp. 916-21.

[9] Sofian, N.M., Rusu, M., Neagu, R. and Neagu, E., "Metal Powder Filled Polyethene Composites," Jou. Thermoplastic Composite Materials. Vol. 14, 2001; pp. 20-33.

[10] Yu, S.Z., Hing, P., and Hu, X., "Thermal Conductivity of Polystyrene-Aluminium Nitride Composite," Composites, Part A- Appl. Sci. Manuf. Vol. 33(2), 2002, pp. 289-292.

[11] Mamunya, Y.P., Davydenko, V.V., Pissis, P. and Lebedev, E.V. "Electrical and Thermal Conductivity of Polymers Filled with Metal Powders,".Jou. European Polymer. Vol. 38, 2002,pp. 1887-1897.

[12] Tekce, H.S., Kumlutas, D., and Tavman, I.H., "Determination of the Thermal Properties of Polyamide-6 (Nylon-6)/Copper Composite by Hot Disk Method," In: Proceedings of the 10th Denizili Material Symposium. 2004, pp. 296-304.

[13] Idicula, Maries., Boudenne ., Abderrahim., Umadevi, L, Ibos, Laurent., Candau, Yves. and , Thomas, Sabu., "Composites Science and Technology," Vol. 66, 2006, pp.2719-2725.

[14] Weidenfeller, B., Ho,˙ fer M., and Schilling, F.R., “Thermal Conductivity , Thermal Diffusivity, and Specific Heat Capacity of Particle filled Polypropylene,” J. Composites Part A: Applied Science and Manufacturing. Vol. 35, 2004; pp. 423-429.

[15] Patnaik, Amar., Abdulla, Md., Satapathy, Alok., Sandhyarani, B, and Bhabani, K.S. “A study on a Possible Correlation Between Thermal Conductivity and Wear Resistance of Particulate Filled Polymer Composites,” J. Materials and Design, In press. 2009.

[16] Malkapuram, Ramakrishna., Kumar, Vivek., and Singh,Negi, Yuvraj, “Recent Development in Natural Fiber Reinforced Polypropylene Composites,” Journal of Reinforced Plastics and Compsites. Vol. 28, 2009; pp. 1169 – 1189.

[17] Osugi, Ryosuke,Takagi, Hitoshi,Liu Ke, and Gennai, Yusuke. “Thermal Conductivity Behavior of Natural Fiber – Reinforced Composites,” Asian Pacific Conference for Materials and Mechanics. 2009.

[18] Mounika, M., Ramaniah, K., Prasad, Ratna A.V., Rao, Mohana, and Reddy, Hema Chandra K. “Thermal Conductivity Characterization of Bomboo Fiber Reinforced Polyster Composite.” J. Mater. Environ. Sci. Vol. 3 (6), 2012; pp. 1109 – 1116.