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HEAT CONDUCTION BEHAVIOR OF SHORT FIBER REINFORCED POLYMER COMPOSITES

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ABSTRACT

The present work reports on the enhancement of insulation capability of short fiber reinforced polymer composites. By using law of minimal thermal resistance and equal law of specific equivalent thermal conductivity, a mathematical model is developed to predict the effective thermal conductivity (k_{eff}) of such fiber reinforced composite material. To validate the proposed model, two classes of such composites are fabricated. For first set, short glass fiber and for second set, short banana fiber is taken as reinforcement in epoxy matrix. The k_{eff} of these composite samples are determined experimentally using the Unitherm™ Model 2022. Further, finite element method is implemented to determine the k_{eff} of such composites numerically using finite element package i.e. ANSYS. The numerical and predicted values are found to be in good approximation with the measured ones. It is further observed that, for maximum fiber loading, the k_{eff} of glass fiber reinforced epoxy composites reduces to about 8 % whereas with banana fiber as reinforcement it reduces to 12 %.

Keywords: Banana fibers, Effective thermal conductivity, Epoxy, glass fibers, Polymer matrix composites.

I. INTRODUCTION

Polymers are the most common materials currently being utilized by several industries as they show remarkable properties when it comes to corrosion resistance, durability, low density and fabrication cost. The demand of polymers are increasing invariably and require more tailored properties when it comes to thermal properties and most importantly thermal conductivity. Commonly used polymers are good electrical and thermal insulators but there are various applications where still lower heat conduction is required. It is studied that thermal conductivity of the polymers can be altered by either of the two ways i.e. by molecular orientation or by reinforcement. It has been seen that the heat transfer is more in the direction of orientation as compared to the direction perpendicular to the orientation [1]. But it is not always possible keeping the orientation as per choice. So the more practical method is by adding the thermally conductive/insulative particles or fibers. During last few decades, a lot of work has been reported to improve the thermal conductivity of polymers by the addition of conductive fillers into it which is extremely useful for various heat dissipation applications.

Metals are known for their high thermal conductivity. Copper and nickel [2], aluminium [3], tin [4] and silver particles [5] are used as a filler material to improve the thermal conductivity of polymers. Carbon fibers and graphite platelets possess further high thermal conductivity as compared to metals, had also been used as filler for such purpose [6-7]. In literatures, a lot of thermal conductive composite systems have been investigated by incorporating different type of ceramics filler such as SiC [8], BN [9], AlN [10], Al_2O_3 [11] and ZnO [12] into various type of polymers.

It can be seen that most of the investigations are aimed at enhancing the thermal conductivity of the polymer rather than attempting to improve its insulation capabilities. In applications like building insulation, pipe insulation and in food containers, thermal insulation is needed. Synthetic fibers like glass fiber [13], nylon [14] etc. are considered to be potential filler material for various applications like wear resistant and structural components. Glass fiber reinforced polymer matrix composites are important engineering materials, mainly because of their low density in combination with excellent specific stiffness and strength [15]. This synthetic fiber is found to be potential filler for improving insulation capability of various polymers because of its low thermal conductivity [16]. But these synthetic fiber reinforced polymer composite have some disadvantages like they are corrosive and toxic in nature, cost is high and they are non-recyclable.

It is interesting to note that natural fibers such as jute, banana, sisal, etc. are abundantly available but are not optimally utilized. At present, these fibers are used for the production of yarns, ropes, mats and matting as well as in making fancy articles like wall hanging, table mats, handbags and purses. Fibers such as cotton, banana and pineapple are also used in making cloth in addition to being used in the paper industry. With growing environmental awareness and ecological concern, natural fiber reinforced composites have been receiving increasing attention during the recent decades. The composites have many advantages, including low cost, light weight, non-toxic, biodegradable etc. Various natural fillers like pineapple [17], sisal and bamboo [18], jute [19] etc. as the reinforcements in composites have been reported earlier. Apart from this, natural fibers possess very low thermal conductivity which is much lower than synthetic fiber and can be used as filler for various insulation applications.

Apart from experimental investigations, to evaluate the k_{eff} of composite materials analytically, several models have been proposed in the past. For a two-component composite, the simplest alternatives would be with the materials arranged in either series or parallel with respect to heat flow [4]. Maxwell-Euken model [20] assumes well dispersed small spherical filler within continues matrix. Bruggeman [21] derived an equation of effective thermal conductivity in terms of the solid loading for spherical fillers in a dilute suspension. Little work on the numerical study has also been done to predict the k_{eff} of the polymer matrix composite [4, 22].

In view of this, the present work has been undertaken to study the effect of adding insulative fibers on the thermal conductivity of epoxy resin. A mathematical model is developed to evaluate the k_{eff} using the law of minimal thermal resistance and equal law of the specific equivalent thermal conductivity. The k_{eff} values of all the fabricated composites with different compositions are numerically evaluated using FEM. Short glass fiber and short banana fiber are the two reinforcement used in present investigation individually in epoxy resin to fabricate two sets of composites by hand lay-up technique. The proposed model values and the numerically evaluated values are then validated through experimentation conducted in controlled laboratory conditions. The comparison of the k_{eff} values obtained from incorporation of two different fibers in epoxy matrix is also reported in present work.

II. DEVELOPMENT OF MATHEMATICAL MODEL

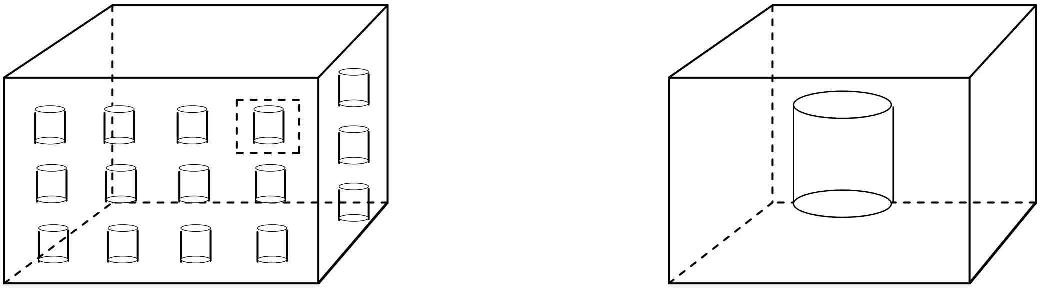
Figure 1 (a) shows the 3-D view of short fiber reinforced polymer composite. A single element is taken out from it for further study the heat transfer behaviours shown in Figure 1 (b), consisting of a small cube with a single fiber is in it. The theoretical analysis of heat transfer in composite material is based on the following assumption:

a. Locally both the matrix and filler are homogeneous and isotropic.

b. Temperature distribution along the direction of heat flow is linear.

c. Thermal contact resistance between the filler and the matrix is negligible

d. The lamina is free from voids.



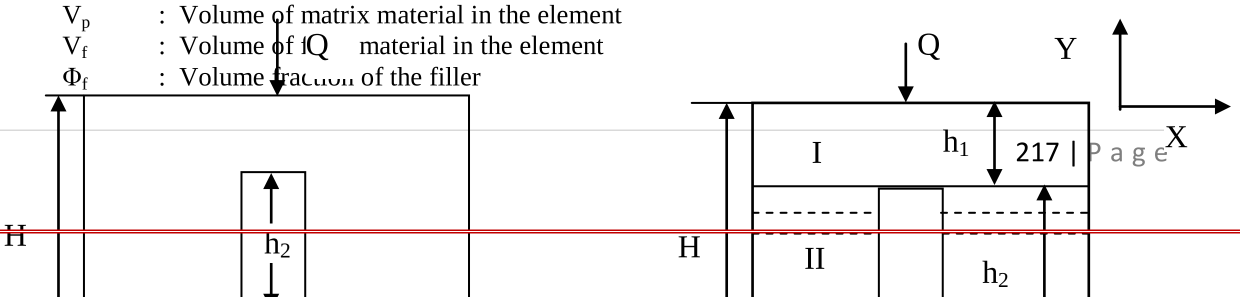
(a) **(b)**

Figure 1 (a) 3-Dimensional view of fiber filled composite (b) 3-Dimensional view of element under

When only heat conduction is considered within the composite system, and the total thermal resistance of the composite is considered equal to specific equivalent thermal resistance of single element of the composite, then according to the law of minimal thermal resistance and equal law of specific equivalent thermal conductivity, the total thermal conductivity of the composite is considered equal to the equivalent thermal conductivity of that single element and while considering that it is not necessary to consider the size of the element [23]. Figure 2 (a) shows the front view of element under study. The composite is a combination of such small cube elements. The direction of heat flow is from top to bottom. A series conduction model through the unit cell of fiber reinforced polymer composite is considered as shown in Figure 2 (b).

Nomenclature

H	: Side length of the cube element
r	: Radius of cylindrical fiber
l	: length of cylindrical fiber
dT	: temperature difference between two side of the element
k_p	: thermal conductivity of polymer matrix
k_f	: thermal conductivity of filler material
k_{eff}	: effective thermal conductivity of the composite material
A_p	: cross sectional area of the matrix material in the element
A_f	: cross sectional area of the filler material in the element
A	: cross sectional area of the composite material for an element
Q_p	: heat flow through the cross sectional area of matrix in the element
Q_f	: heat flow through the cross sectional area of filler in the element
Q	: heat flow through the cross sectional area of an element of composite material
V_p	: Volume of matrix material in the element
V_f	: Volume of filler material in the element
Φ_f	: Volume fraction of the filler



(a) **(b)**

Figure 2 (a) Physical model of heat transfer (b) Series model of heat transfer

The element is divided into three parts; Part *I* and part *III* represent the neat polymer while part II represents the combination of polymer matrix and fiber. k_1, k_2 and k_3 are the mean conductivity coefficient of respective parts. The thickness of part *I* and part *III* are h_1 and h_3 respectively, for simplicity both the above thickness is considered to be equal and $2h_1 = 2h_3 = H - h_2$. Part *II* having a thickness of h_2.To determine the k_{eff} of the whole element, the law of minimum thermal resistance is required to combine the heat resistances of these three parts to get the heat resistance of the complete element and the equal law of specific thermal conductivity is applied to predict the effective thermal conductivity of the complete element. Thermal conductivity of each section can be calculated as:

For part I and III:

Since there is no short fiber in that region, thermal conductivity will be same as that of polymer matrix i.e.

$$k_1 = k_3 = \int_{h_1} k_p \frac{dy}{h_1} = k_p \tag{1}$$

For part II:

Taking a thin piece with thickness *dy*, applying Fourier's law of heat conduction, k_2 is

$$k_2 = \frac{Q_p + Q_f}{\left(\frac{dT}{dy}\right) A} \tag{2}$$

A is cross-sectional area of the composite material for an element,

$$k_2 = \int_{h_2} \frac{(k_p A_p / A + k_f A_f / A) dy}{h_2} = \frac{1}{h_2 A}\left(k_p V_p + k_f V_f\right) \tag{3}$$

Similarly thermal resistance of the three parts are

$$R_1 = R_3 = \frac{h_1}{k_p A} \tag{4}$$

$$R_2 = \frac{h_2}{\frac{1}{h_2 A}\left(k_p V_p + K_f V_f\right) A} = \frac{h_2^2}{k_p V_p + k_f V_f} \tag{5}$$

As the series model is considered for heat transfer in the element, the k_{eff} of composites is given by

$$k_{eff} = \frac{H}{RA} = \frac{H}{(R_1 + R_2 + R_3)A} \tag{6}$$

$$k_{eff} = \frac{H}{\left(\frac{h_1}{k_p A} + \frac{h_2^2}{k_p V_p + k_f V_f} + \frac{h_1}{k_p A}\right)A} \tag{7}$$

Substituting various values into equation (7), the k_{eff} of the composite material is given by

$$k_{eff} = \frac{1}{\frac{1}{k_p}\left(1 - \left(\frac{16\phi_f}{\pi}\right)^{\frac{1}{3}}\right) + \frac{1}{\left(k_p\left(\frac{\pi}{16\phi_f}\right)^{\frac{1}{3}} + \frac{\pi}{16}\left(k_f - k_p\right)\left(\frac{16\phi_f}{\pi}\right)^{\frac{1}{3}}\right)}} \tag{8}$$

The correlation given in equation (8) can be used to estimate the k_{eff} for cylindrical fiber reinforced composite.

III. EXPERIMENTAL DETAILS

Epoxy (LY 556) resin is used as a matrix material for present work. Its common name is Bisphenol-A-Diglycidyl-Ether and it is belonging to the ‘‘epoxide’’ family. Epoxy resin is used with its corresponding hardener triethylenetetramine (TETA, HY 951). Epoxy is chosen primarily because it happens to be the most commonly used polymer. In addition to that it possesses low thermal conductivity (0.363 W/m-K) and low density (1.1 g/cm^3). The epoxy resin and the corresponding hardener used for the present work are supplied by Ciba Geigy Limited, India. For first set of polymer composite a well-known synthetic fiber i.e. short glass fiber is used as filler material. Glass fiber possesses low density (1.5 g/cm^3), higher tensile strength and low thermal conductivity (0.18 W/m-K). For the second set of polymer composites, a natural fiber i.e. banana fiber is used. Scientific name of banana is musaacuminata. Main organic constituents of banana fiber are: cellulose, hemicellulose, pectin, lignin and some extractives. Banana fiber is considered to be remarkable because of its very low density (0.2 g/cm^3), low cost, nontoxicity, biodegradability and eco-friendly nature. It possesses very low thermal conductivity (0.09 W/m-K) which is the prime requirement for present investigation. Glass and banana fibers used in present investigation are procured from Saint Govion, India and M/s ROPE (Rural Opportunity Production Enterprises) International, India respectively. At room temperature, epoxy resin and the corresponding hardener are mixed in a ratio of 10:1 by weight as per recommendation. Short glass fibers are reinforced in epoxy resin to prepare first set of composite specimens. Conventional hand-lay-up technique is used for fabrication purpose. The dough (epoxy filled with glass fibers) is then slowly decanted into the glass moulds, coated beforehand with wax and a uniform thin film of silicone-releasing agent. The composites are cast in these moulds so as to get disc-type specimens (diameter 50 mm, thickness 3 mm). Composites of six different compositions (2.83, 5.65, 7.54, 10.05, 12.56, and 15.7 vol % of glass fiber, respectively) are made. The castings are left to cure at room temperature for about 24 hours after which the samples are released. For preparing second set of composite specimens, banana fiber is used as filler material. Following the same procedure, composites of similar compositions are fabricated. Table 1 show the various sample prepared. The micro-structural features of the various fiber reinforced specimens are examined under Scanning Electron Microscope JEOL JSM-6480 LV. The specimens are mounted on stubs with silver paste. To improve the penetration of light and for better surface micrographs, a thin film of platinum is vacuum-evaporated onto the samples before the micro graphs are taken. Unitherm™ Model 2022, which operates on the double guarded heat flow principle, is used to measure the effective thermal conductivity of all the fabricated samples. The tests are conducted in accordance with ASTM E-1530 standard.

Table1: List of Fiber-reinforced polymer composites fabricated by hand-lay-up technique

Sample	Composition (Glass fiber as filler material)	Composition (Banana fiber as filler material)
1	Epoxy + 2.83 vol% Glass fiber	Epoxy + 2.83 vol% Banana fiber
2	Epoxy + 5.65 vol% Glass fiber	Epoxy + 5.65 vol% Banana fiber
3	Epoxy + 7.54 vol% Glass fiber	Epoxy + 7.54 vol% Banana fiber
4	Epoxy + 10.05 vol% Glass fiber	Epoxy + 10.05 vol% Banana fiber
5	Epoxy + 12.56 vol% Glass fiber	Epoxy + 12.56 vol% Banana fiber
6	Epoxy + 15.7 vol% Glass fiber	Epoxy + 15.7 vol% Banana fiber

IV. RESULTS AND DISCUSSION

4.1 Micro-Structural Characterization

It is known that the behavior of the composite materials is highly dependent on the relation between the reinforced fiber and the matrix body. In order to evaluate this relation, the microstructure of both the fiber i.e. glass fiber and banana fiber together with their distribution and bonding when they are reinforced in epoxy matrix are observed under scanning electron microscope (SEM). The distribution and bonding between the fibers and matrix within the composite body are clearly presented in Figure 4 (a) and Figure 4 (b) for glass fiber reinforced epoxy composite and banana fiber reinforced epoxy composite respectively. This micrograph confirms the near-cylindrical shape of both the fibers. Also a good adhesion between the fibers and matrix can be clearly observed which improves the bonding between them.

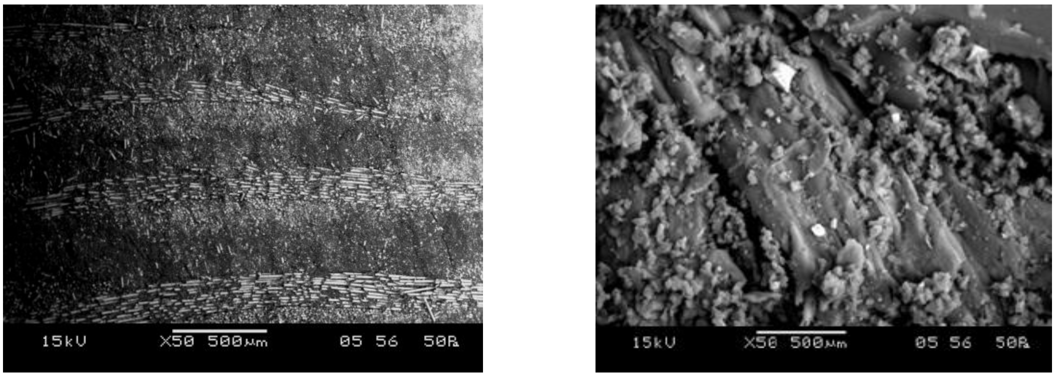


Figure 3 SEM images of (a) glass fiber/epoxy composites; (b) banana fiber/epoxy composites

4.2 Effective thermal conductivity

4.2.1 Numerical analysis and concept of finite element method

The finite element method (FEM) is a powerful tool used in numerical methods to arrive at approximate solutions to mathematical problems so that it can simulate the responses of physical systems to various forms of excitation. FEM reduces the problem to that of a finite number of unknowns by dividing the domain into elements and by expressing the unknown field variable in terms of the assumed approximating functions within each element. Using finite-element package ANSYS, thermal conductivity analysis is carried out through the prepared composite body. In order to make a thermal analysis, three-dimensional physical models with cylinders-in-cube lattice arrays have been used to simulate the microstructure of composite materials for different filler concentrations. Furthermore, the k_{eff} of these epoxy composites reinforced with short fibers up to 15.7 vol % are numerically determined using ANSYS.

4.2.2 Description of the problem

Figure 4 illustrates the heat flow direction and the boundary conditions for the fiber reinforced polymer composite body considered for the analysis of this conduction problem. The temperature at the nodes along the surface ABEF is prescribed as 100°C and the ambient convective heat transfer coefficient is assumed to be 2.5 W/m^2-K at a room temperature of 27°C. The other surfaces parallel to the heat flow direction are all assumed adiabatic. The unknown temperatures at the interior nodes and on the other boundaries are obtained with the help of ANSYS.

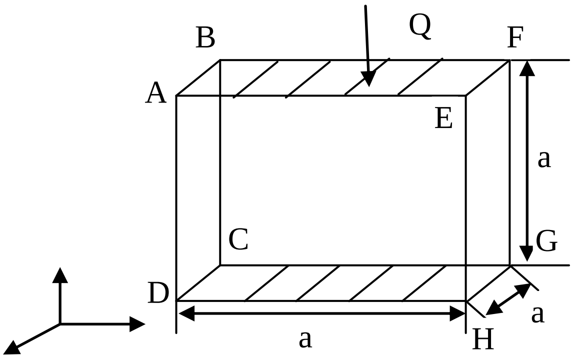
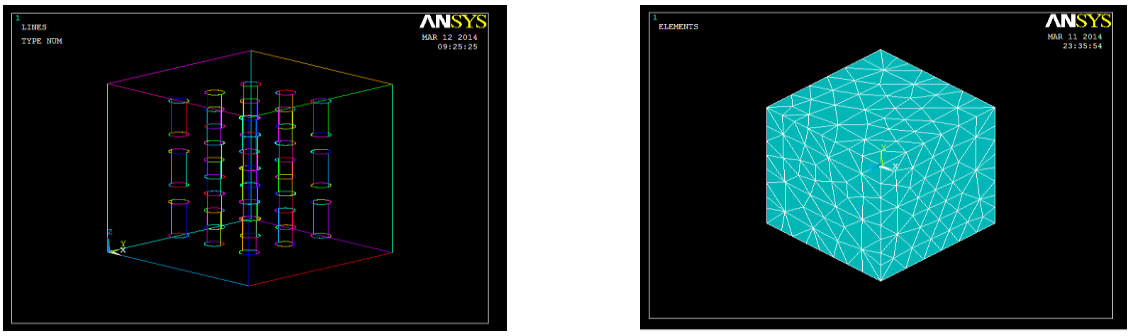


Figure 4 Boundary condition

4.2.3 Effective thermal conductivity of fabricated composites

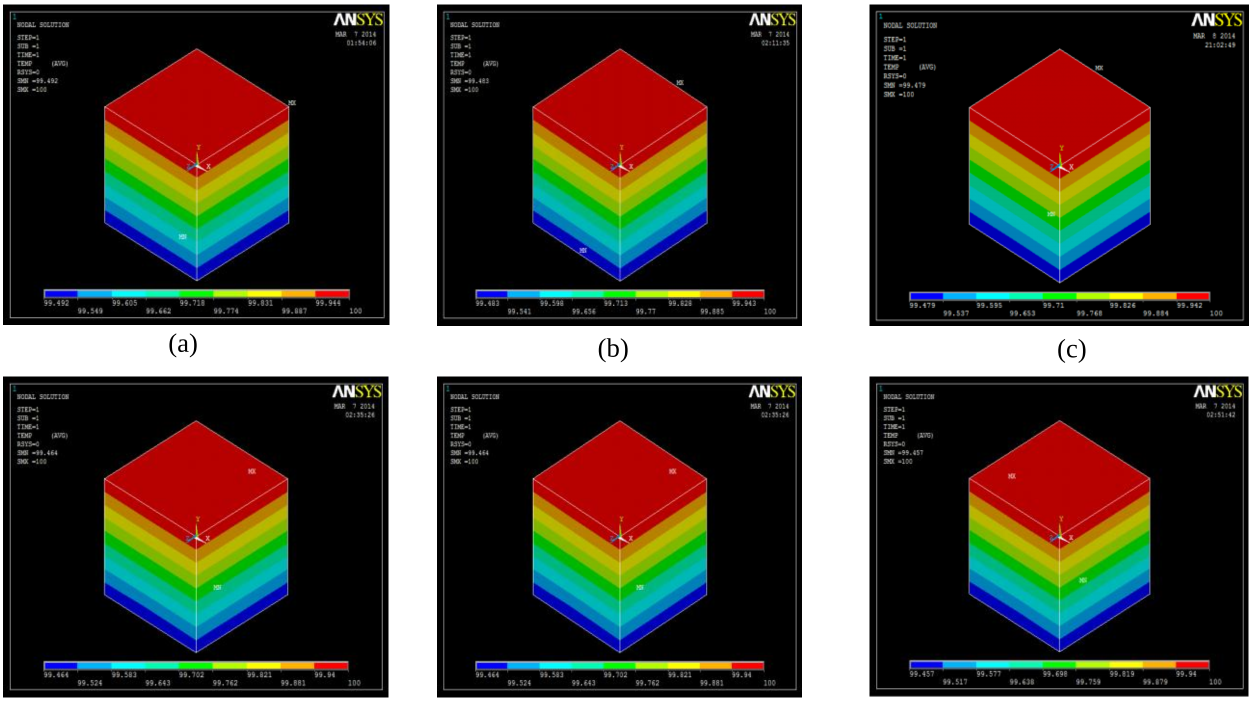
Figure 5 shows the three dimensional view of short fiber in cube model. A typical arrangement of short fiber within the matrix body is shown in Figure 5 (a). Figure 5 (b) shows the meshed view of such fiber in cube model where size of the meshing element purely depends upon the dimension of short fiber.



(a) **(b)**

Figure 5 Three dimensional view (a) fiber arrangement within matrix body, (b) Meshing of such model

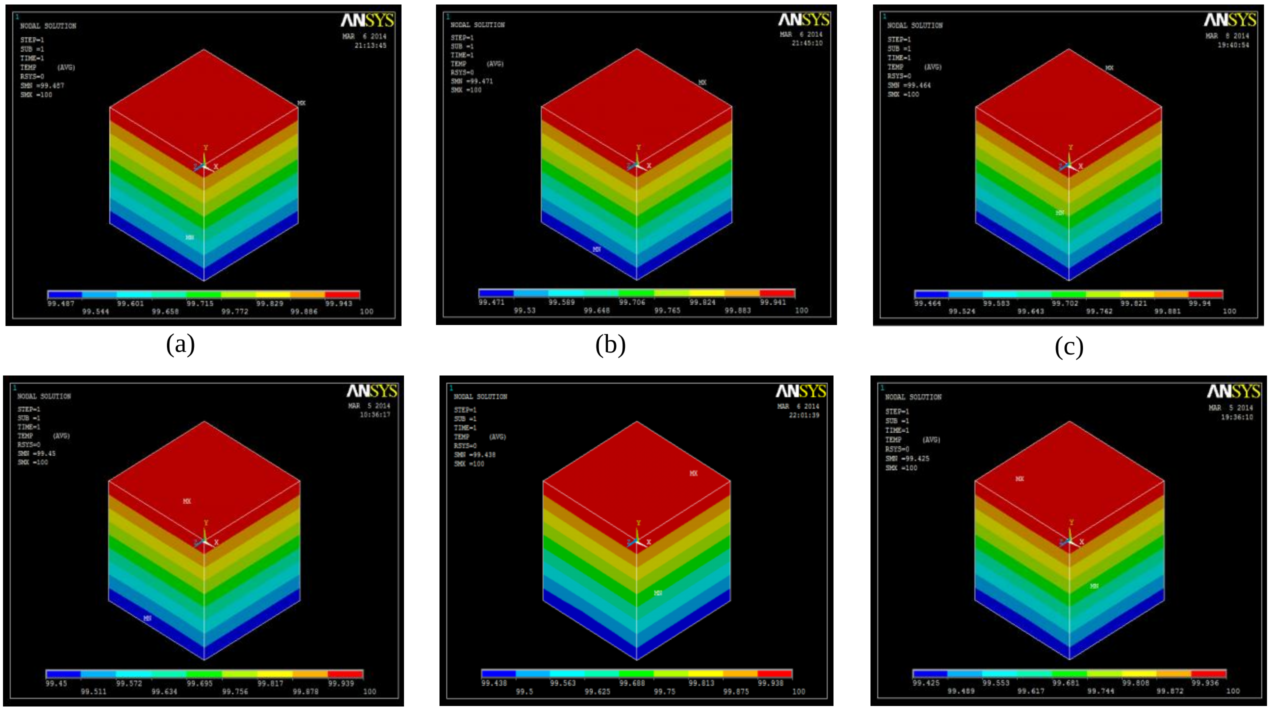
By applying the various boundary conditions, the temperature profiles can be obtained which are shown in Figure 6 and Figure 7. Figure 6 (a)-(f) shows the temperature profiles for glass fiber reinforced epoxy composites for fiber volume fraction of 2.83, 5.65, 7.54, 10.05, 12.56 and 15.7 respectively. The corresponding temperature profiles for banana fiber reinforced epoxy composites are shown in Figure 7 (a)-(f).



(a) (b) (c)

(d) (e) (f)

Figure 6 Temperature profiles of composites with glass fiber loading of (a) 2.83 vol% (b) 5.65 vol% (c) 7.54 vol% (d) 10.05 vol% (e) 12.56 vol% (f) 15.7 vol%



(a) (b) (c)

(d) (e) (f)

Figure 7 Temperature profile of composites with banana fiber loading of (a) 2.83 vol% (b) 5.65 vol% (c) 7.54 vol% (d) 10.05 vol% (e) 12.56 vol% (f) 15.7 vol%

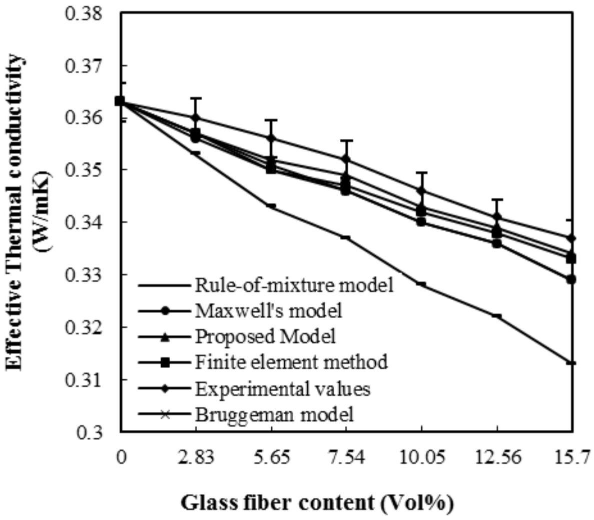


Figure 8 Effective thermal conductivity of short glass fiber/epoxy composites: Rule-of mixure, Maxwell's model, Bruggeman model, Proposed model, FEM and Experimental values

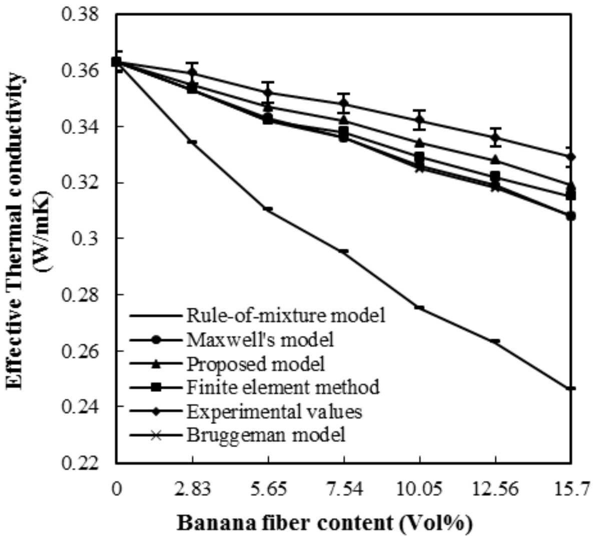


Figure 9 Effective thermal conductivity of short banana fiber/epoxy composites: Rule-of mixure, Maxwell's model, Bruggeman model, Proposed model, FEM and Experimental values

With the help of various temperature profiles, the k_{eff} values for different sets of epoxy-fiber composites are calculated. The comparison of the k_{eff} of glass fiber reinforced epoxy composites obtained from various established model like Rule of Mixture, Maxwell's model and Bruggeman's model together with proposed model, FEM analysis and experimental values are shown in Figure 8. The similar comparison for banana fiber reinforced epoxy composites are shown in Figure 9. From both the figures, it is observed that as the fiber loading in the epoxy resin increases, the values of the k_{eff} decreases which is obvious because both the fibers possesses low value of intrinsic thermal conductivity as compared to epoxy resin. The trend is followed by the analytical models, numerical model and the measured values.

Further it is noticed that the values obtained from Maxwell's model, Bruggeman's model, proposed model and FEM analysis fit well with the experimental data whereas rule of mixture model is far from satisfaction. The percentage error associated with each of the method used in present investigation for glass fiber-epoxy composites and banana fiber-epoxy composites are presented in Table 2 and Table 3 respectively. From the tables it is observed that the errors associated with respect to the experimental values for glass fiber reinforced epoxy composite for proposed model, FEM values, Maxwell's model and Bruggeman's model lie in range of 0.8-2% and for rule-of mixture model it gets widen up to 2-8%. Again for banana fiber reinforced epoxy composites the errors associated with respect to measured values for proposed model and FEM values lie in the range of 1-4%, for Maxwell's model and Bruggeman's model lie in range of 1.6-7% and for rule-of mixture it is in range of 7-34%.

Table 2: Percentage errors associated with respect to measured value for glass fiber/epoxy composites

Sample	Fiber loading (vol%)	Percentage errors with respect to experimental value				
		Rule of mixture	Maxwell's model	Bruggeman's model	Proposed model	Numerical values
1	2.83	1.983	1.123	0.841	0.844	0.840
2	5.65	3.790	1.714	1.424	1.424	1.714
3	7.54	4.451	1.734	1.149	1.734	1.440
4	10.05	5.487	1.764	1.169	1.765	1.169
5	12.56	5.901	1.488	1.186	1.488	0.887
6	15.7	7.667	2.431	1.813	2.431	1.201

Table 3: Percentage errors associated with respect to measured value for banana fiber/epoxy composites

Sample	Fiber loading (vol%)	Percentage errors with respect to experimental value				
		Rule of mixture	Maxwell's model	Bruggeman's model	Proposed model	Numerical values
1	2.83	7.485	1.698	1.699	1.127	1.697
2	5.65	13.548	2.624	2.924	1.441	2.924
3	7.54	17.966	3.571	3.571	1.754	2.958
4	10.05	24.363	4.908	5.231	2.395	3.951
5	12.56	27.756	5.329	5.660	2.439	4.347
6	15.7	33.739	6.818	6.818	3.135	4.444

It is observed that the values obtained from the proposed model and FEM simulation are showing least percentage variation with measured values when both sets of composites are considered for the complete range of fiber loading, whereas Maxwell's and Bruggeman's model show more variation with respect to measured value for banana fiber epoxy composites as compared to glass fiber-epoxy composites. It is seen that rule-of-mixture model underestimates the measured values completely for both sets of composites. It can be observed that for predicting the k_{eff} of composites for a wide range of fiber concentration, proposed model and FEM model are giving the most suitable results.

V. CONCLUSION

Based on the analytical, numerical and experimental work reported on the thermal conductivity of fibers (glass fiber and banana fiber) reinforced epoxy composite, it can be concluded that different sets of epoxy/ glass fiber and epoxy/banana fiber composites can be successfully fabricated by using simple hand lay-up technique for varied volume concentration. The micro-structural features of the various fiber reinforced specimens are examined under Scanning Electron Microscope. A good adhesion between the fibers and matrix are observed results in improving the bonding between both the phases. The values obtained from the proposed mathematical model are in close approximation with the measured values for all the fabricated composites over the entire range of filler content. The results obtained from the proposed mathematical model are also in close approximation with the values obtained by FEM simulation. İt is seen that the FEM analysis is a valuable approach to find out the values of k_{eff} for such composites systems. The study shows that the k_{eff} reduces quite significantly as the fiber loading in the composite increases. A reduction of about 8 % in the value of the k_{eff} is recorded with addition of 15.7 vol % of glass fiber in epoxy resin whereas 12 % decrease is noticed when reinforcement material is banana fiber. Banana fibers also possesses properties like non-corrosive, biodegradable, low cost, recyclable etc. So it can be said that a natural fiber i.e. banana fiber can replace a well-known synthetic fiber i.e. glass fiber for insulation purpose used as reinforcement in composite materials. With light weight and reduced heat conductivity, these fibers reinforced polymer composites finds their potential applications in insulation boards, food containers, thermo flasks, building material etc.

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