DETERMINATION OF THERMAL CONDUCTIVITY OF PINE WOOD DUST FILLED EPOXY COMPOSITES

by

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In the present investigation the thermal conductivity in particulate filler filled (pine wood dust) epoxy composites at different volume fractions (6.5%, 11.3%, 26.8%, and 35.9%) have been determined experimentally by using forced convection apparatus. The composites of pine wood dust particles of 150 μm size have been prepared by using hand-lay-up technique. The experimental results show that the incorporation of pine wood dust results in reduction of thermal conductivity of epoxy resin and there by improves its thermal insulation capability. From the experiments it is also observed that the composite with 35.9% volume fraction of pine wood dust exhibited lowest thermal conductivity i. e. 0.246 W/mK on comparison to 6.5%, 11.3%, and 26.8% volume fractions. Therefore, the composite with 35.9% wood dust may be more suitable for insulation application. Experimental results (22 mm pipe diameter) are also compared with theoretical models such as rule of mixture model, Maxwell model, Russell model, and Baschirow and Selenew model to describe the variation of thermal conductivity vs. the volume fraction of the filler. All these models exhibited results close to each other at low dust filler content. On comparison, it has been found that the errors associated with experimental (26 mm diameter) along with all the previous four models with respect to experimental ones (22 mm diameter) lie in the range of 19.60 to 44.10%, 0.76 to 12.10%, 1.86 to 5.12%, and 8.24 to 19.68%, respectively.

Key words: *forced convection apparatus, epoxy-pine wood dust composite, thermal conductivity, error analysis*

Introduction

Natural fibres are environment friendly materials that are potentially user-friendly. Unlike the typical engineering fibres, *e. g.* glass and carbon fibres, and mineral fillers, these lignocelluloses fibres are able to impart onto the composite certain benefits such as low density, less machine wear during processing, no health hazards, and a high degree of flexibility. The automotive and aerospace industries both demonstrated interest in using more natural fibre reinforced composites. For example, in order to reduce vehicle weight, automotive companies have already shifted from steel to aluminum and now are shifting from aluminum to fibre reinforced composites for some applications. A significant number of automotive components, previously made from glass fibre composites, are now being manufactured using environment

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friendly composites. Natural fiber composites can also be very cost effective material for application in building and construction areas (*e. g.* walls, ceiling, partition, window and door frames), storage devices (*e. g.* bio-gas container, post boxes, *etc.*), furniture (*e. g.* chair, table, tools, *etc.*), electronic devices (outer casting of mobile phones), automobile and railway coach interior parts (inner fenders and bumpers), toys and other miscellaneous applications (helmets, suitcases). The present work has been investigated experimentally the thermal conductivity of epoxy matrix composites filled with wood dust (pine wood dust – PWD). Wood dust (PWD) is an insulating material that retards the conduction and convection of heat. When this wood dust is reinforced with epoxy it formed a composite whose sole effect is to retard the heat transfer rate and hence its insulation capability can be improved. Due to insulation capability these composites can be used for applications such as installing between interior and exterior of the wall and in the floor or ceiling of the roof, insulation boards, aircraft components, automotive components and furniture, industries of all kinds like transportation sectors and even in the field of medical sector, *etc*.

Review of literature

The objective of this work is to determine the thermal properties of epoxy filled with PWD composites which is an important parameter of heat transfer properties of materials. Thermal conductivity is one that helped to determine the temperature fields in composite materials. Numerous theoretical and experimental approaches have been developed to investigate this property. Russell [1] developed a model using the electrical analogy. He derived an equation for the thermal conductivity of the composite using a series parallel network. Maxwell [2] studied the effective thermal conductivity of heterogeneous materials and developed first theoretical model for two phase system. Bashirow and Manukyan [3] developed a model to calculate thermal conductivities of the real media. Suleiman *et al.* [4] investigated the thermal conductivity of wood in both longitudinal transverse directions in the temperature range of 20-100 °C. Their results showed that thermal conductivity is about 1.5 times more in the longitudinal direction than in the transverse direction due to non-homogenous nature of wood. Mangal *et al.* [5] studied the effect of volume fraction of pineapple leaf fibre on thermal properties of the composite using transient plane source technique. Increasing the fibre content in the matrix decreases the thermal conductivity and thermal diffusivity of the pineapple leaf fibre reinforced composite which means that it could not provide the conductive path to the heat energy in the composite material. Paul *et al.* [6] worked on the periodical method to estimate the thermal conductivity, thermal diffusivity of polypropylene/banana fibre composites at room temperature. It was found that the thermal conductivity and thermal diffusivity of composite decreased with fibre loading. Wang *et al.* [7] investigated effective thermal conductivity of carbon fibre composites with higher accuracy and efficiency using a 3-D numerical method. The resultant predictions agree well with the available experimental data. Compared with the existing theoretical models, their model did not depend upon empirical parameters which have to be determined case by case so that it was useful for design and optimization of new materials. Alam *et al*. [8] prepared an experimental set-up to determine and analyze thermal conductivities of insulating materials and compared with the literature values. Lee's and Charlton's apparatus was used to measure this property of insulating materials by steady-state technique. The thermal conductivities obtained by this apparatus were 0.797 W/mK, 0.3023 W/mK, and 0.057 W/mK for borosilicate glass, styrene butadiene rubber and polyolefin foam faced aluminum foil, respectively. The experimental results were found 9-30% deviation for the literature values. Gori *et al* [9] calculated theoretically the steady-state effective thermal conductivity in the main directions for two extreme thermal assumptions, *i. e.* parallel isothermal lines and parallel heat flux lines. They evaluated the effective thermal conductivity of the composite for a variable thickness of the reinforcement, *i. e.* for a variable volume fraction. The anisotropy degree, defined as the ratio between the thermal conductivities along the two main directions, increases with the ratio between the thermal conductivities of the reinforcement material and the matrix. AL-Shabander [10] presented the flexural properties and thermal conductivity of composites made from wood dust filler particles and epoxy resin. Experimental results showed that the flexural strength of the composites decreased with the increase of the filler particle content and the thermal conductivity of the composite decreased with increasing weight percentage of wood dust. Prisco [11] investigated experimentally the thermal conductivity of wood flour (WF) filled high density polyethylene composite (wood plastic composite – WPC). Experimental results showed that the WPC thermal conductivity decreases with the filler content and WF content. Chandana and Hussain [12] determined the thermal conductivity of bamboo fibre reinforced in epoxy resin composites. They prepared the test sample as per ASTM standards using simple hand lay-up technique at different fibre weight fractions (10%, 20%, 30%, 40%, 50%, and 60%). Thermal conductivity, K, of the composite materials was determined experimentally and was validated by the results obtained by rule of mixture, E-S model and also by finite element modeling. Narendra *et al.* [13] fabricated the low cost natural fiber composites with excellent thermal insulation properties from *Borassus* seed short fiber by varying volume fraction using polyester resin. Thermal conductivity of *Borassus* seed short fiber reinforced composite was in the range of 0.176 to 0.196. Thermal insulation of the composite increases as fiber content increased The results obtained have significant potential benefits for thermal design of engineering applications like automotive, electronic devices, building constructions, *etc.*

Keeping previous review in mind, the composites of epoxy with varying content of PWD has been developed in the present work. Further thermal conductivity measurements have been carried out using forced convection apparatus and results were compared with that obtained from various theoretical models. Finally error percentage was estimated for each composite. so developed in house.

Thermal conductivity models

Many theoretical and empirical models have been proposed to predict the effective thermal conductivity of two phase mixtures.

Series model (Rule of mixture)

For a two component composite the simplest alternative would be with the materials arranged in series with respect to heat flow which gives the lower bounds of effective thermal conductivity:

$$\frac{1}{K_c}=\frac{1-\phi}{K_m}+\frac{\phi}{K_f} \tag{1}$$

where c is the composite, m – the matrix, f – the filler, ϕ – the volume fraction of filler, K_c – the thermal conductivity of composite, K_m – the thermal conductivity of matrix, and K_f – the thermal conductivity of filler (PWD). In this paper filler is considered PWD. Hence for all models the thermal conductivity of filler, K_f, is equal to the thermal conductivity of PWD whose value is 0.068 W/mK. Here the matrix is epoxy whose thermal conductivity, K_m, is 0.363 W/mK.

Maxwell model

The Maxwell model uses potential theory to obtain an *exact* solution for the conductivity of randomly distributed and non-interacting homogeneous spheres in a homogeneous continuous medium, as shown:

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

Russel model

Russel derived an equation for the thermal conductivity of the composite, using a series parallel network:

$$K_c = K_m \left[\frac{\phi^{\frac{2}{3}} + \dfrac{K_m}{K_f}(1 - \phi^{\frac{2}{3}})}{\phi^{\frac{2}{3}} - \phi + \dfrac{K_m}{K_f}(1 + \phi - \phi^{\frac{2}{3}})} \right] \tag{3}$$

Baschirow and Selenew model

Baschirow and Selenew developed the following equation for the case when the particles are spherical and two phases are isotropic:

$$K_c = K_m \left\{ 1 - \frac{a^2\pi}{4} + \frac{a\pi p}{2} \left[1 - \frac{p}{a} \ln(1 + \frac{a}{p}) \right] \right\} \tag{4}$$

where

$$p = \frac{K_f}{K_m - K_f}, \quad a = \sqrt[3]{\frac{6\phi}{\pi}} \tag{5}$$

Experimental details

Materials

Epoxy (LY 556) resin and the corresponding hardener (HY 951) were procured from Hindustan Ciba Geigy Ltd., India. The PWD collected from local market has been chosen as the filler material mostly for its very low thermal conductivity (0.068 W/mK) and low density (0.52 g/cm^3). It is also renewable, eco-friendly, available at low cost, non-toxic and basically considered as a waste product.

Composite preparation

To prepare the composite samples for measurement of thermal conductivity using forced convection apparatus a mould was prepared as shown in the fig. 1 The diameter of solid pipe 22/26 mm and inner diameter of outer pipe 37 mm with length 300 mm and thickness 7.5/5.5 mm, respectively. The low temperature curing epoxy (LY 556) resin and the corresponding hardener (HY 951) were mixed in the ratio of 10:1 by weight supplied by Hindustan Ciba Geigy Ltd. The PWD with average size 150 μm was reinforced in epoxy resin density (1.1 g/cm^3) to prepare the composite. The PWD supplied by local vendor was dried before manufacturing in a vacuum oven for 24 hour at 80 °C in order to remove moisture. The mixture (epoxy filled with PWD) was slowly powered into the respective mould. Convectional hand lay-up technique was used to cast the composite in the respective mould so as to get composite pipe (22/26 mm solid pipe diameter and 37 mm inner diameter of outer pipe with length 300 mm), respectively. Composites of four different compositions with (6.5, 11.3, 26.8, and 35.9 vol.% of PWD were made, fig. 2. Silicon spray was used to facilitate easy removal of the composite from the mould. The cast of each composite was cured under a load of about 50 kg for 24 hours before it was removed from the mould. Then this cast was post cured in air for another 24 hours after removing out from the mould. All these tests were carried out for epoxy/wood dust composites.

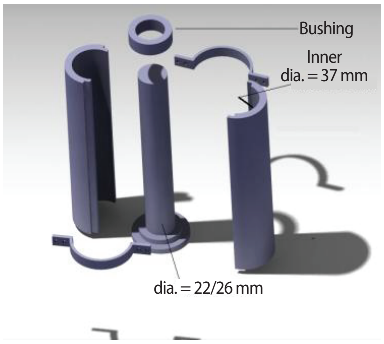

Figure 1. Mould to prepare specimen (pine wood tube) to measure thermal conductivity

Specification of instruments

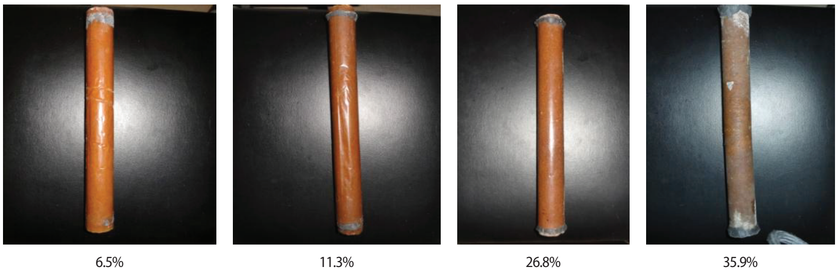

Figure 2. Samples of pine wood tube (size -150 μm, 22 mm diameter)

- Test section: composite tube of 22/26 mm inner diameter, 37 mm outer diameter, and 300 mm length.
- Manometer: U-tube as mercury as working fluid.
- Blower: centrifugal ½ Hp, 220 V a. c.
- Dimmer stat: 230 V, 2 A.
- Heater: externally heated, nichrome band type (250 W).
- Voltmeter: digital voltmeter of range 0-300 V a. c.
- Ammeter: digital ammeter of range 0-5 A a. c.
- Temperature indicator: digital temperature indicator of range 0-400 °C with Tss.
- Thermocouples: teflon coated Cr-Al (K-type)-4No.
- Orifice diameter: d =16 mm.
- Coefficient of discharge: C_d = 0.64.
- Electric supply: 230 V, 5 A a. c, 50 Hz, single phase electric supply with proper earthing.

Experimental set-up

The thermal conductivity test is carried out with forced convection apparatus shown in fig. 3. The apparatus consists of a blower, orifice meter, and thermally insulated composite pipe heated over approximately 30 cm of its length and provided with thermocouples, selector switches, Manometer: U-tube as mercury as working fluid, dimmer stat: 230 V, 2 A, digital voltme-

Figure 3. Experimental set-up of forced convection apparatus

ter of range 0-300 V a. c, digital ammeter of range 0-5 A a. c., heater [externally heated, nichrome band type (250 W)], and digital temperature indicator of range 0-400 °C with Tss. This apparatus is modified in order to incorporate the different types of composite pipes of different dimension. The outer diameter being same does not pose any problems in design but the real modifications are targeted towards the accommodation of the internal diameter. To hold the composite pipes in place with the inlet and the outlet portions two adapter sockets were designed such that they fit over the inlet and outlet pipe. To place the composite pipe an internal ring is projected internally in the adapter, of internal diameter of (hole) 22/26 mm. Here the pipes are a perfect fit and the joint between the inlet/outlet and composite pipes are sealed with epoxy bond (m-Seal) for rendering it air tight and not let the air from blower leak to the surrounding. The nichrome heating element is such that it covered two third of the circumferential area was used over the composite pipe and was press fitted longitudinally over it. Thus after being set over the designated pipe it left a small strip of uncovered portion along the axis of the pipe. Hence the pipe was made such that the holes or the perforations for the thermocouples are in a straight line and the pipe is fit in such a manner so as to keep the holes uncovered so that the thermocouples may be inserted into them. Thermocouples were inserted into the pipes for measurement of temperatures. After the previous set-up was complete the whole assembly of composite pipe and nichrome element was insulated by winding asbestos coated ropes of course by taking into account the projecting thermocouples. A blower was fitted with a test pipe. Four thermocouples were embedded in the test section. Out of four thermocouples, the two thermocouples were placed in the air stream at the entrance and exit of the test section to measure inlet and outlet temperature of air. The rest two were placed in between the entrance and exit of the test section to measure surface temperature (average value of temperature measured by these two thermocouples). The readings were taken when the steady-state was reached. Test pipe was connected to the delivery side of the blower along with an orifice to measure flow of air through the pipe. The air flow was measured with the help of orifice meter and the water with the manometer fitted on the board. Input to the heater was given through a dimmerstat measured by voltmeter and ammeter. It was noted that only a part of the total heat supplied was utilized in heating the air.

Working procedure

- The blower was started and the flow was adjusted by means of gate valve to some desired difference of 80 mm in manometer level.
- The heating of test section was started with the help of dimmer stat and desired input (voltage – 120 V, current – 1.2 A) was adjusted with the help of voltmeter and ammeter.
- Readings of all thermocouples were taken at an interval of ten minutes until steady-state was reached. The thermocouple reading values of composite (22/26 mm diameter) at steady-state of varied composition are shown in tab. 1 and tab. 2, respectively.

Table 1. Thermocouple reading values of composites (22 mm diameter) of varied composition

Sample	Particulate content [vol. fraction, %]	Thermocouple readings		
		Inlet temperature of air in [°C]	Outlet temperature of air in [°C]	Surface temperature in [°C] $T_s = (T_3+T_4)/2$
1	6.5	30	35	58
2	11.3	32	37	62
3	26.8	33	37	63
4	35.9	34	38	65

Table 2. Thermocouple reading values of composites (26 mm diameter) of varied composition

Sample	Particulate content [vol. fraction, %]	Thermocouple readings in °C		
		Inlet temperature of air in [°C]	Outlet temperature of air in [°C]	Surface temperature in [°C] $T_s = (T_3+T_4)/2$
1	6.5	33	38	50
2	11.3	34	39	52
3	26.8	36	40	53
4	35.9	37	41	56

Here T_3 and T_4 are the surface temperatures measured by thermocouples at different sections placed in between inlet and outlet side of air in order to find out the surface temperature of air which is the average of these two values.

Thermal conductivity measurement

The thermal conductivity of a material can be defined as a rate at which heat is transferred by conduction through a given unit area of a given material, when the temperature gradient is normal to the cross sectional area.

The pressure head of air (h_a):

$$h_a = \frac{\rho_w}{\rho_a} h \tag{6}$$

$$v_a = \sqrt{2gh_a} = \sqrt{2g\frac{\rho_w}{\rho_a}h} \tag{7}$$

$$a = \frac{\pi}{4} d^2 \tag{8}$$

$$V_{th} = av_a = \frac{\pi}{4} d^2 \sqrt{2g\frac{\rho_w}{\rho_a}h} \tag{9}$$

$$V_a = C_d V_{th} = C_d \frac{\pi}{4} d^2 \sqrt{2g\frac{\rho_w}{\rho_a}h} \tag{10}$$

where h_a [m] is the pressure head of air, h [m] – the pressure head of water, v_a [m/s] – the velocity of air, a [m^2] – the area of cross section of the orifice, d [m] – the diameter of the orifice, V_{th} [m^{3}s^{-1}] – the theoretical air flow rate, V_a [m^{3}s^{-1}] – the actual air flow rate, C_d – the coefficient of discharge = 0.64, ρ_a – the density of air = 1.128 kg/m^3, and ρ_w – the density of water = 1000 kg/m^3.

Mass flow rate of air:

$$m_a = \rho_\mathrm{a} V_\mathrm{a} = \rho_\mathrm{a} C_d \frac{\pi}{4} d^2 \sqrt{2g \frac{\rho_\mathrm{w}}{\rho_\mathrm{a}} h} \tag{11}$$

$$Q_\mathrm{a} = m_\mathrm{a} c_{pa} (T_1 - T_2) \tag{12}$$

$$Q_c = h_{ac} A_i (T_\mathrm{s} - T_1) \tag{13}$$

$$A_i = \pi D_\mathrm{i} L \tag{14}$$

Comparing eqs. (10) and (11):

$$h_{ac} = \frac{m_\mathrm{a} c_{pa} (T_1 - T_2)}{A_i (T_\mathrm{s} - T_1)} \tag{15}$$

where m_a [kgs^{-1}] is mass flow rate of air, Q_a [W] – the rate of heat given by air, Q_c [W] – the rate of convective heat transfer of air, A_i [m^2] – the inner area of cross section of pipe, D_i [m] – the inner diameter of pipe, D_o [m] is the outer diaeter of pipe, L [m] – the length of pipe, c_{pa} [kJkg^{-1}K^{-1}] – the specific heat of air, T_1 [K] – the inner temperature of air, T_2 [K] – the outlet temperature of air, T_s [K] – the surface temperature, and h_{ac} [Wm^{-2}K^{-1}] – the convective heat transfer coefficient.

The thermal conductivity of composite material, K [Wm^{-1}K^{-1}]:

$$K = h_{ac} x \tag{16}$$

where x is the thickness of the composite material:

$$x = \frac{D_\mathrm{o} - D_\mathrm{i}}{2} \tag{17}$$

Results and discussion

The thermal conductivity obtained from the experimental study (composite pipe with 22 and 26 mm diameter) for the particulate filled epoxy composite with varied proportion of PWD is shown in fig. 4. On comparison it is found that the thermal conductivities of neat epoxy calculated by all models are same *i. e.* 0.363 W/mK. After that as the volume fraction of the reinforcement increases, the thermal conductivities are reduced but the distribution of the thermal conductivities are slightly higher in case of experimental study of composite pipe with 26 mm diameter in comparison to experimental study of composite pipe with 22 mm diameter. This is because the core of the filler is porous and air voids are created during preparation of composite. It is also interesting to note that the incorporation of PWD results in reduction of thermal conductivity of epoxy resin and there by improves its insulation capability.

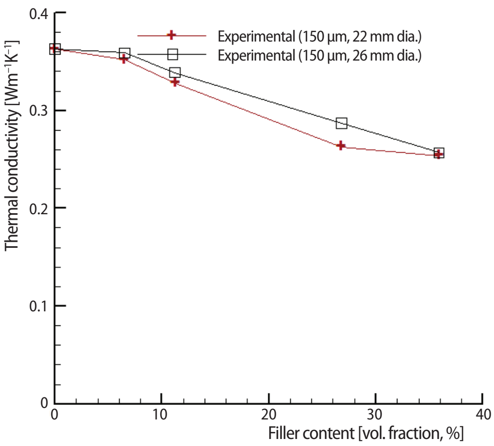

Figure 4. Thermal conductivity of epoxy composites as a function of filler content

Figure 5 presents a comparison on the thermal conductivity values obtained from the experimental work with several thermal conductivity models like Rule of mixture model, Maxwell model, Russel model, and Baschirow and Selenew model. It is found that the results obtained from the experimental work are closer to the all four thermal conductivity models at low fibre content. After that as the volume fraction of PWD increases (6.5% to 35.9% volume fraction), the thermal conductivity values of experimental work along with all the four theoretical models are decreased gradually. It is further noted that the Rule of mixture model and Baschirow and Selenew model underestimate the value of thermal conductivity with respect to the experimental one (22 mm diameter). On the other hand, Maxwell model and Russel model underestimate the value of thermal conductivity except at 26.8% volume fraction where they overestimate with respect to experimental one (22 mm diameter). On comparison, it has been found that the errors associated with all the previous mentioned four models with respect to experimental ones (22 mm diameter) lie in the range of 19.60 to 44.10%, 0.76 to 12.10%, 1.86 to 5.12%, and 8.24 to 19.68%, respectively. The values of thermal conductivities and percentage of errors associated with each method for individual composite with two components *i. e.* epoxy and PWD are given in tabs. 3 and 4, respectively.

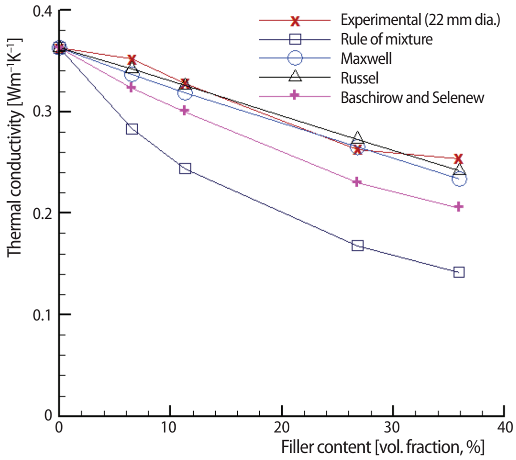

Figure 5. Comparison of thermal conductivity of different models with experimental values and varying filler content (PWD)

Figure 6 shows a comparison of thermal conductivity values obtained from Lee's apparatus method and present experimental work (forced convection apparatus

Table 3. Thermal conductivity values of composites obtained from different methods

Sample	Particulate content [vol.%]	Effective thermal conductivities of composites [Wm^{-1}K^{-1}]					
		Rule of mixture	Maxwell	Russel	Baschirow and Selenew	Experimental 26 mm diameter	Experimental 22 mm diameter
1	0 (Neat epoxy)	0.363	0.363	0.363	0.363	0.363	0.363
2	6.5	0.283	0.337	0.342	0.323	0.359	0.352
3	11.3	0.244	0.319	0.326	0.300	0.339	0.328
4	26.8	0.168	0.265	0.273	0.230	0.287	0.263
5	35.9	0.142	0.234	0.241	0.204	0.257	0.254

Table 4. Percentage errors with respect to the experimental value

Sample	Particulate content [vol.%]	Percentage of errors with respect to the experimental value, 22 mm diaeter			
		Rule of mixture	Maxwell	Russel	Bashirow and Selenew
1	0 (Neat epoxy)	0	0	0	0
2	6.5	19.60	12.10	2.84	8.24
3	11.3	25.61	2.74	1.86	8.53
4	26.8	36.12	0.76	3.8	12.54
5	35.9	44.10	7.87	5.12	19.68

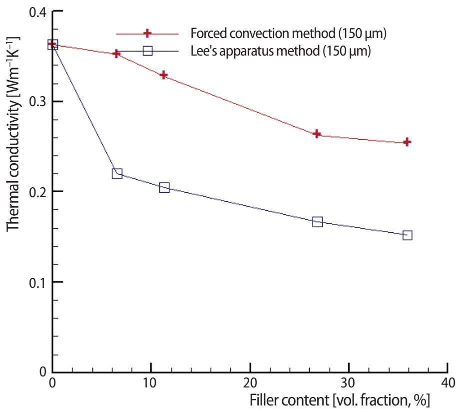

Figure 6. Comparison of thermal conductivity of different methods with varying filler content

method) for same size of PWD and same filler contents *i. e.* 6.5%, 11.3%, 26.8%, and 35.9% volume fraction, respectively. On comparison, it is found that the thermal conductivity values are reduced as the filler contents (6.5% to 35.9% volume fraction) are increased, but the values of thermal conductivities are much higher in case of experimental work (forced convection apparatus method) on comparison to Lee's apparatus method. This is because of direction of heat flow to the composite. The thermal conductivity in the longitudinal direction is greater than the thermal conductivity in transverse direction (Suleiman *et al.* [4]). In case of forced convection apparatus (present experimental work) the measurements are done on the longitudinal direction and for Lee's apparatus the measurements are done in transverse direction. For this reason the thermal conductivity values of experimental work are higher than Lee's apparatus method. It is also found that the addition of PWD results in reduction in thermal conductivity of epoxy resin and thereby improves its thermal insulation property. The values of thermal conductivity and their ratios associated with each method are shown in tab. 5.

Table 5. Thermal conductivity comparison between two experimental methods

Sample	Particulate content [vol.%]	Thermal conductivity values [Wm^{-1}K^{-1}]		Ratio of thermal conductivity with respect to forced convection apparatus method
		Lee's apparatus method	Forced convection apparatus method	
1	6.5	0.220	0.352	1.60
2	11.3	0.205	0.328	1.60
3	26.8	0.167	0.263	1.57
4	35.9	0.152	0.254	1.67

In fig. 7 the PWD filler with two different particle sizes (150 μm and 250 μm) are compared and found that the thermal conductivity values of 250 μm (PWD filler) at same filler contents is least. Hence, it shows that when the size of the filler increases, the thermal conductivity decreases for the same volume fraction. From the previous discussion it is concluded that choosing 250 μm size is most advantages one as it has best insulation properties on comparison to 150 μm particle size of PWD filler. The values of thermal conductivity associated with each size of filler are shown in tab. 6.

Conclusions

The PWD is an environmental friendly waste products which can be gainfully utilized for preparation of composites. Composites made of PWD posses less thermal conductivity and this can be used as insulators. It has been found that the thermal conductivity of composites made of PWD is decreased with increase in filler content. As the size of the filler increases the thermal conductivity decreases for the same volume fraction, as a result of which it's insulation capability is improved. Due to improved insulation capability these composites can be used for applications such as insulation boards, air craft components, ceiling of roofs, automotive com-

Table 6. Measured thermal conductivity values of composites of varied composition and particle size of PWD

Sample	Particulate content [vol.%]	Thermal conductivity values of composites [Wm^{-1}K^{-1}]	
		150 µm	250 µm
1	6.5	0.352	0.347
2	11.3	0.328	0.295
3	26.8	0.263	0.257
4	35.9	0.254	0.246

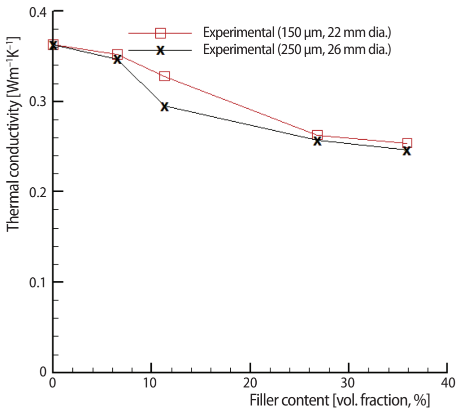

Figure 7. Comparison of thermal conductivity of different sizes with varying filler content

ponents and furniture's, *etc.* The present experimental work is compared with Lee's apparatus method and found that the values of thermal conductivities are 1.57 to 1.67 time higher in case of experimental work (forced convection apparatus method) on comparison to Lee's apparatus method. This is because of direction of heat flow to the composite.

Nomenclature

A_i – inner area of cross-section of pipe, [m^2]
a – area of cross section of orifice, [m^2]
C_d – coefficient of discharge, [–]
c_{pa} – specific heat of air, [kJkg^{-1}K^{-1}]
D_i – inner diaeter of pipe, [m]
D_o – outer diaeter of pipe, [m]
d – orifice diaeter, [m]
h – pressure head of water, [m]
h_a – pressure head of air, [m]
h_{ac} – convective heat transfer coefficient, [Wm^{-2}K^{-1}]
K – thermal conductivity, [Wm^{-1}K^{-1}]
L – length of pipe, [m]
Q_a – rate of heat given by air, [W]
Q_c – rate of convective heat transfer of air, [W]
T_1 – inner temperature of air, [K]
T_2 – outlet temperature of air, [K]
T_s – surface temperature, [K]
V_a – actual air flow rate, [m^{3}s^{-1}]
V_{th} – theoretical air flow rate, [m^{3}s^{-1}]
v_a – velocity of air, [ms^{-1}]

Greek symbols

ρ_a – density of air, [kgm^{-3}]
ρ_w – density of water, [kgm^{-3}]
ϕ – volume fraction, [–]

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