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Study the Effect of Carbon Fiber Volume Fraction and their Orientations on the Thermal Conductivity of the Polymer Composite Materials.

Dr. Mohammed Sellab Hamza
Mat. Eng. Depart
University of Technology

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Abstract

The effect of fiber volume fraction of the carbon fiber on the thermal conductivity of the polymer composite material was studied. Different percentages of carbon fibers were used (5%, 10%, 15%, 20%, and 25%). Specimens were made in two groups for unsaturated polyester as a matrix and carbon fibers, first group has parallel arrangement of fibers and the second group has perpendicular arrangement of fibers on the thermal flow, Lee's disk method was used for testing the specimens. This study showed that the values of the of thermal conductivity of the specimens when the fibers arranged in parallel direction was higher than that when the fibers arranged in the perpendicular direction

The results indicated that the thermal conductivity increases with the increasing the fiber volume fraction. Minimum value was (0.64 W/m.°C) for parallel arrangement and (0.1715 W/m.°C) for perpendicular arrangement at (V_f = 5%) .Maximum value for parallel and perpendicular were (2.65 W/m. °C) and (0.215 W/m.°C) at (V_f = 25%) respectively.

Keyword: Carbon Fiber, Thermal Conductivity, Polymer, Composite Materials.

Introduction

Thermal conductivity is defined as the transfer of heat from area of high temperature to that of low temperature. The thermal conductivity of solids materials is greater than that of liquids and gases materials. The thermal conductivity of solid material is four times than that of gases material. This is due to the difference between the voids for two materials. The transfer of the thermal power is depending upon the component of materials. The free electrons are responsible for the transferring the thermal power through the conduct materials, while for the insulating materials such as polymers, the photons is responsible for this phenomena [1].

The fiber volume fraction and their orientation have greater effect on the thermal analysis of the composite specimens. The ability of the composite material to resist or conduct the heating depends on the quantities and qualities of the constituents.

The typical applications of epoxy-based fiber-reinforced composite materials are as insulators, mechanical supports and composite tubes in combination with metal tubes as thermal standoffs in large size super-conducting underground energy storing magnets to take up compressive loads with minimum thermal loss [2].

Oronizo Manca et. al. [1] studied the thermal response of the composite materials by evaluating the thermal response of the specimens to different heating conditions.

M.W. Gaglord [3] said that the composite materials have anisotropic properties; therefore it has high thermal conductivity along the fiber direction and low thermal conductivity in a direction perpendicular to the fiber direction.

Charles A. Sorrell [4] tried to develop new high – performance materials for use in industrial heating application, including glass melting, steel production, …. etc., and the major focus of this project was on optimizing a specific aerogel composite material to the precise thermal mechanical and chemical requirements of a given industrial process.

B.W. James and P. Harrison [5] used the finite difference method in the calculation of temperature distribution and heat flow in composite materials made from anisotropic materials by taking in to account the local re-orientation of the grid and the temperature distribution. Heat flow was derived for a composite material made from two materials with anisotropic thermal conductivities.

Zhan-Sheng Guo et. al. [6] studied the experimental and numerical temperature distribution of thick polymeric matrix laminates during an autoclaves vacuum bag process. The finite element formulation of transient heat transfer problem was carried out for polymeric matrix composite materials from the heat transfer differential equations.

F.Rondeaux et.al. [7] developed a specific thermal conductivity measurement facility for solid materials at low temperature where the thermal conductivity measurements on pre-impregnated fibers glass epoxy composite are presented in the temperature of 4.2 K to 14 K for different thicknesses in order to extract the thermal boundary resistance.

Lamees A. Khalaf [8] studied the mechanical and physical properties for unsaturated polyester reinforced by fiber glass and nylon fiber composites and found that the thermal conductivity decreases with the increase the volume fraction, it also decrease with increase of nylon fiber layers for the samples of laminar reinforced system.

Saad M. Elie [9] studied the mechanical properties and thermal conductivity for polymer composite material reinforced by aluminum and aluminum oxide particles and found that the thermal conductivity increased with the increase of the weight fraction of metallic and ceramic particles and reach a maximum value of (0.319 W/m.°C) for the composite material with (Al_2O_3) reinforced at a weight fraction of (20 %) and reached to (0.407 W/m.°C) for the composite material with (Al) reinforcement at the same weight fraction.

The aim of this research is to study the effect of fiber volume fraction and their orientation (parallel and perpendicular to heat flow) of the reinforcement material (carbon fibers) on the thermal conductivity. The specimens were made from polyester reinforced with five different volume fraction of carbon fiber which is equal to (5%, 10%, 15%, 20% and 25 Vol. %).

The reinforcement material (carbon fiber) was arranged in two groups. The first group the carbon fibers was aligned in the parallel direction to the thermal flow while the second group the carbon fibers was aligned perpendicular to the thermal flow .

Theoretical analysis

There are two ways for transfer of the thermal energy,

1- The vibrating waves of the lattice.

2- The movement of the free electrons.

The thermal conductivity is defined by the following formula:

$$q= -k\ dT/dx \tag{1}$$

The equation (1) used only for study state of thermal flow and when the thermal flux does not change with time. The minus sign means that the transfer of heat is starting from hot part to the cold part.

The theoretical thermal conductivity is calculated by the following equation [2]:

$$K\cdot\left[\frac{T_2-T_1}{d_s}\right]=e\cdot \left[T_1+\frac{2}{r}\cdot\left(d_1+\frac{1}{2}d_s\right)\cdot T_1+\frac{1}{r}\cdot d_s\cdot T_2\right] \tag{2}$$

The loss in heat (e) through the unit time (second) and through the area (m^2) is calculated by the following formula [6]:

$$I\cdot V=\pi\cdot r^2\cdot e\cdot\left(T_1+T_3\right)+ 2\cdot\pi\cdot r\cdot e\cdot\left[d_1\cdot T_1+\frac{1}{2}\cdot d_s\left(T_1+T_2\right)+d_2\cdot T_2+d_3\cdot T_3\right] \tag{3}$$

The theoretical thermal conductivity of composite materials is estimated from the following equations [2, 10]:-

1-when the direction of the thermal flow is parallel to the reinforced material, it is calculated from following equation:-

$$K_{c1}=K_f\cdot V_f+K_m\cdot V_m \tag{4}$$

2-when the direction of the thermal flow is perpendicular; it is obtain from the following formula:

$$K_{c2} = \frac{K_f \cdot K_m}{K_f \cdot V_m + K_m \cdot V_f} \quad .....(5)$$

Experimental work

In this research, the Lee's disk method is used for measuring the thermal conductivity. Figure (1) shows the instrument was used for this method. The specimens were made from carbon fibers – polyester matrix materials that have specification illustrated in table (1), and using Hand Lay-up method for preparation the specimens, the geometry of the specimens are (r=0.02 m), (ds =0.005 m).

The specimens reinforced with the carbon fibers parallel to the direction of thermal flow and perpendicular to the thermal flow. Temperature of T1, T_2, T_3 were measured by means of Lee`s disk method.

The applied voltage and current were (6v) (I=0.2A), to heat the brass disks (2,3) and the temperatures of all disks increases gradually where temperatures recorded every (5 minutes) until reach the equilibrium temperature of all disks.

The losses in heat (e) was calculated from equation (3).The thermal conductivity (k) was calculated from equation (2) by using the experimental reading (T_1, T_2, T_3) and the dimension of specimen(r, ds). The theoretical values of the thermal conductivity were obtained from equations (4) and (5).

Results and Discussion

Table (2) shows the thermal conductivity of the composite specimen when the direction of the thermal flow is parallel to the direction of the carbon fibers. While results of the perpendicular group are shown in table (3).

Figure (2 and 3) show the relationship between wall surface temperature of the specimen and the time for the fiber volume fraction (V_f=5% and V_f=25%) respectively for experimental work when the thermal flow in the parallel direction to the direction of the carbon fibers.

Figure (4&5) show the relationship between wall surface temperature and time for the fiber volume fraction (V_f=5% and V_f=25%) for experimental work when the thermal flow in the perpendicular direction to the direction of the carbon fibers.

It is clear from these figures that the wall surface temperature (T_1 and T_2) increases in nonlinear relationship with time until it reachs the equilibrium temperature.

The relationship between the theoretical thermal conductivity and the volume fraction (V_f) for parallel and perpendicular direction of carbon fibers is presented in figure (6), while the relationship for experimental thermal conductivity and the volume fraction shown in figure (7). It can be seen that the results in case of the parallel direction was higher than the results when the fiber arranged in the perpendicular direction to the heat flow. Also it can be seen that the difference between the parallel direction and the perpendicular direction increase with increasing the fiber volume fraction

Figure (8) shows the relationship between the theoretical and experimental thermal conductivity with the volume fraction of carbon fibers for parallel direction, while the relationship for perpendicular direction is illustrated in figure (9). It was found that the maximum difference between the theoretical and the experimental results was (8%) for the parallel direction, this difference is accepted and it is due to the working conditions of the preparation and test of the specimens in the experimental work, while the equation of the theoretical thermal conductivity based on the ideal case.

Conclusion

The main conclusions of this research are:

1- the thermal conductivity of composite materials is increasing with increasing of fiber volume fraction(V_f), and for the parallel direction was higher than that for the perpendicular direction.

2- The Maximum difference between the experimental and theoretical values of the thermal conductivity was (8%) at fiber volume fraction (25%).

3- For parallel arrangement, The maximum experimental and theoretical values of the thermal conductivity were (2.65 W/m. °C) and (2.8775 W/m. °C) respectively ,while for perpendicular were (0.215 W/m. °C) and (0.2265 W/m. °C) at (V_f = 25%).

4- The results indicated that the thermal conductivity depends on the method of the arrangement of reinforcement materials.

5- The using of reinforcement material (carbon fibers) increased the thermal conductivity of polyester from (0.17 W/m. °C) to value (2.8775 W/m. °C) at (V_f = 25%) of fibers for parallel arrangement, and to (0.2265 W/m. °C) for perpendicular arrangement.

Table (1) The Properties of Polyester and Carbon Fiber[12].

	Density (g/cm3)	Modulus of Elasticity (GN/m2)	Poisson's Ratio	Modulus of Rigidity (GN/m2)	Thermal Conductivity (W/m. c°)
Polyester	1.04-1.46	2.06-4.41	0.33	0.774-1.657	0.17
Carbon Fiber	1.78	400	0.32	107.954	15

Table (2) Thermal Conductivity of the Composite Specimen when the direction of the thermal flow is parallel to the direction of the carbon Fibers.

Thermal conductivity (Kc) (W/m. c°)	Fiber Volume Fraction				
	5%	10%	15%	20%	25%
Theoretical (Kc)	0.7115	1.253	1.7945	2.336	2.8775
Expermintal(Kc)	0.64	1.13	1.65	2.15	2.65

Table (3) Thermal Conductivity of the Composite Specimen when the direction of the thermal flow is Perpendicular to the direction of the carbon Fibers.

Thermal conductivity (Kc) (W/m. c°)	Fiber Volume Fraction				
	5%	10%	15%	20%	25%
Theoretical (Kc)	0.1788	0.1885	0.201	0.21468	0.2265
Expermintal(Kc)	0.1715	0.1805	0.192	0.1203	0.215

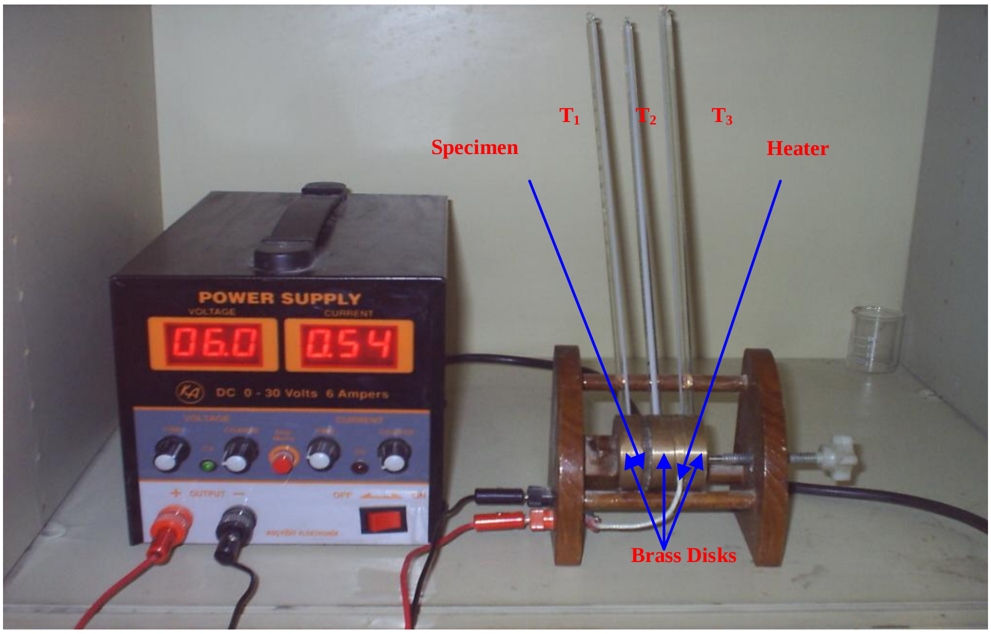

Figure (1): Test Apparatus with Specimens Test.

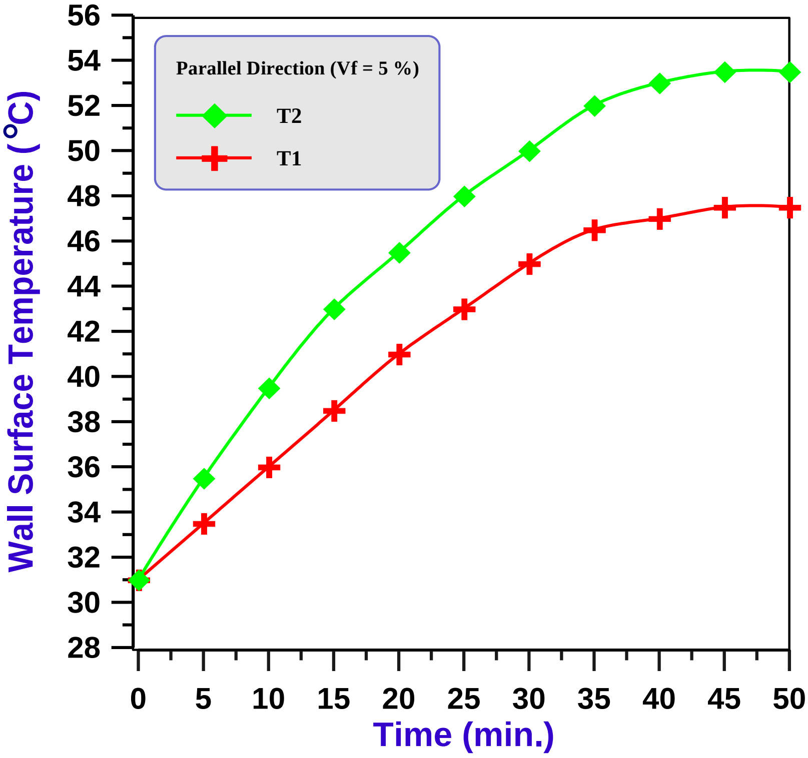

Figure (2): Relationship Between Wall Surface Temperature and Time When the Fibers Arranged in the Parallel Direction at Fiber Volume Fraction (Vf = 5%) for Experimental Work.

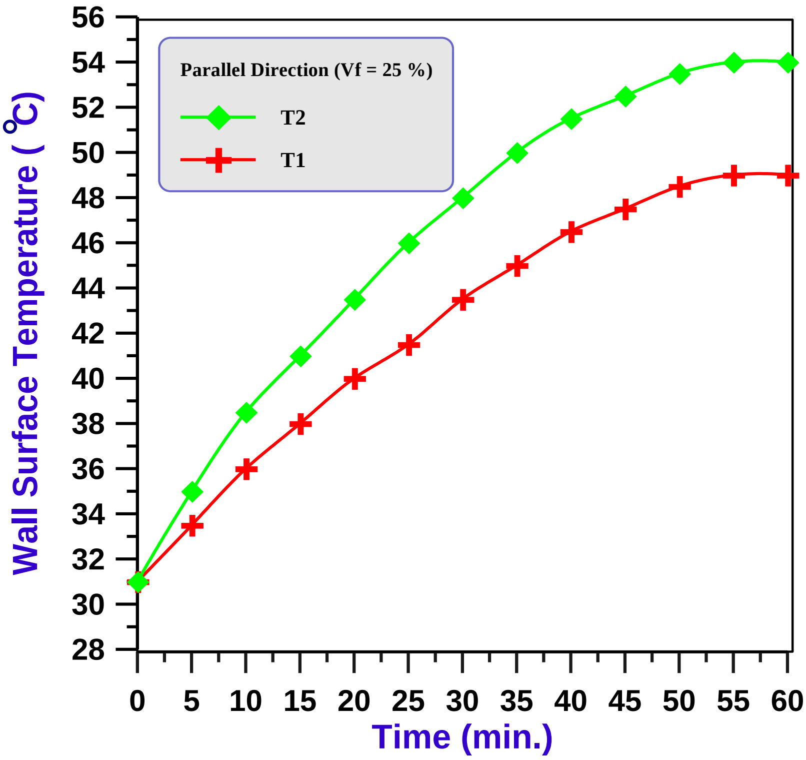

Figure (3): Relationship Between Wall Surface Temperature and Time When the Fibers Arranged in the Parallel Direction at Fiber Volume Fraction (Vf = 25%) for Experimental Work.

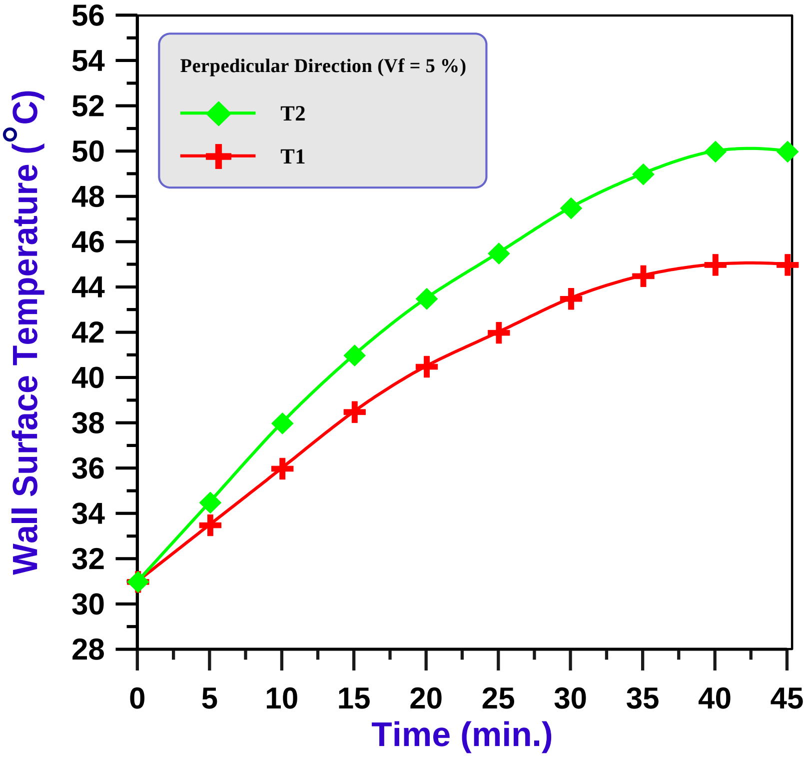

Figure (4): Relationship Between Wall Surface Temperature and Time When the Fibers Arranged in the Perpendicular Direction at Fiber Volume Fraction (Vf = 5%) for Experimental Work.

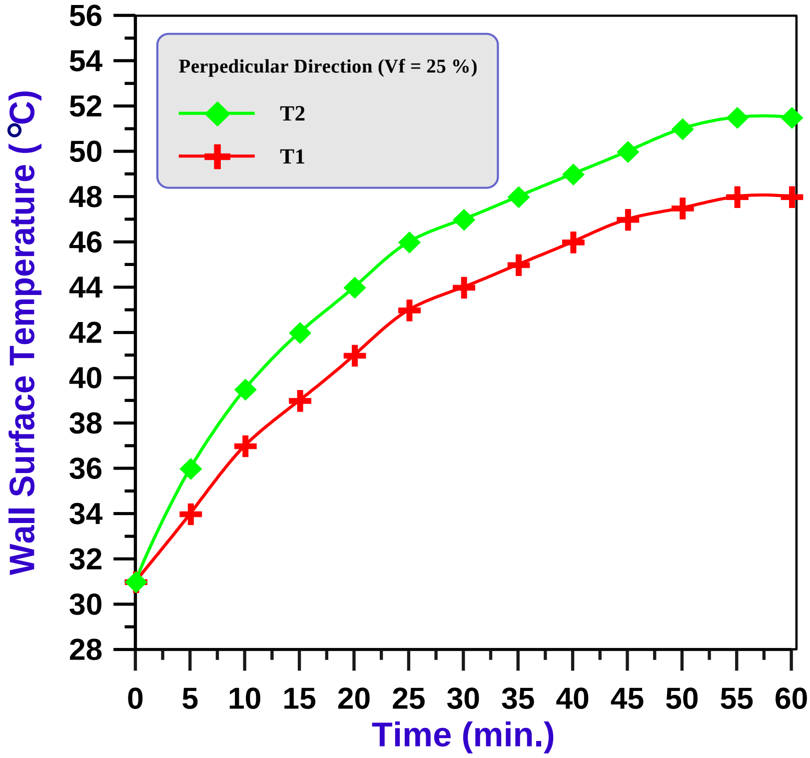

Figure (5): Relationship Between Wall Surface Temperature and Time When the Fibers Arranged in the Perpendicular Direction at Fiber Volume Fraction (Vf = 25%) for Experimental Work.

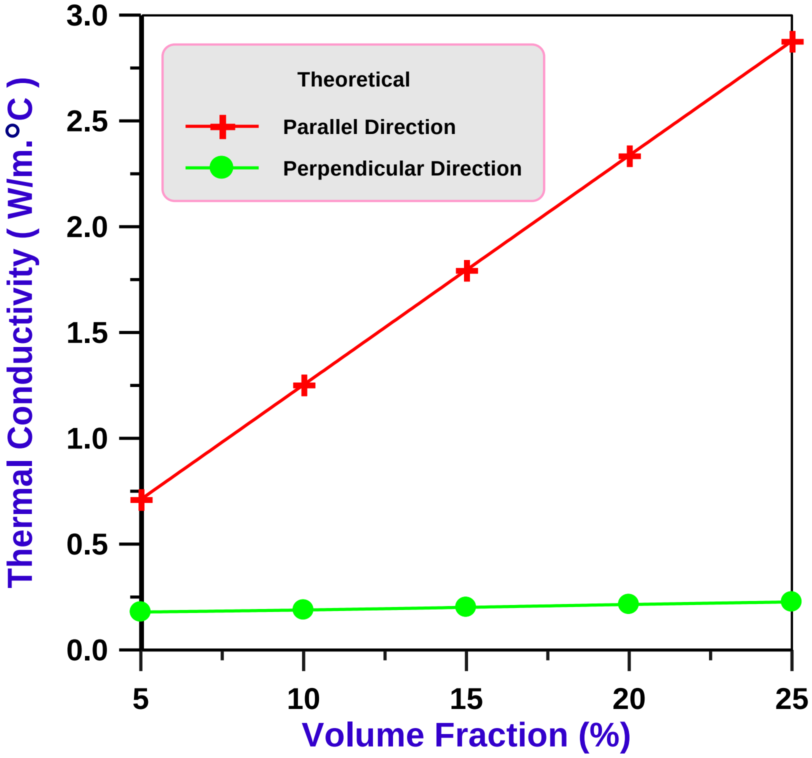

Figure (6): Relationship Between the Theoretical Thermal Conductivity and the Volume Fraction for Parallel and Perpendicular Direction.

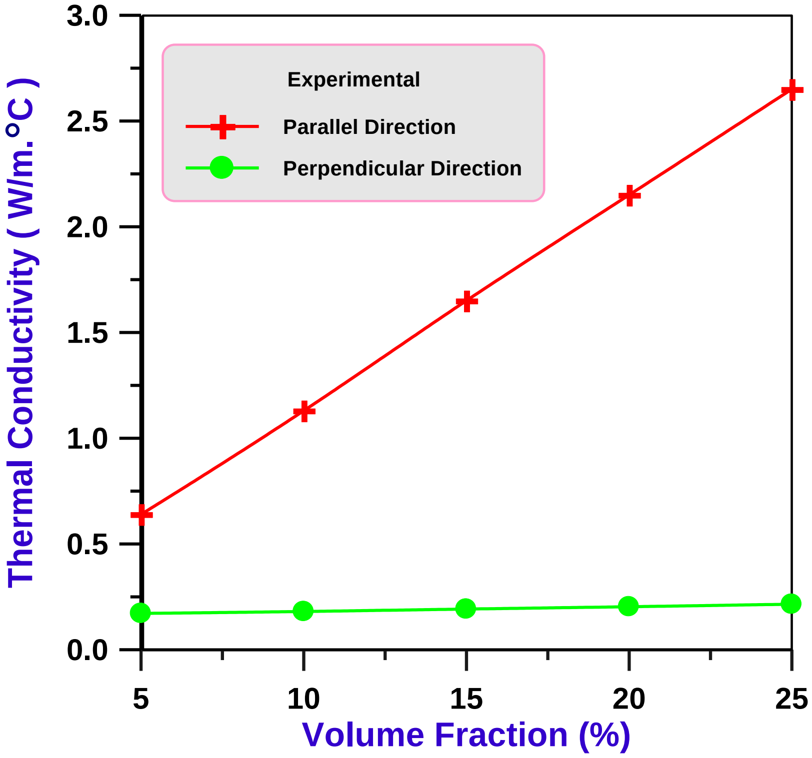

Figure (7): Relationship Between the Experimental Thermal Conductivity and the Volume Fraction for Parallel and Perpendicular Direction.

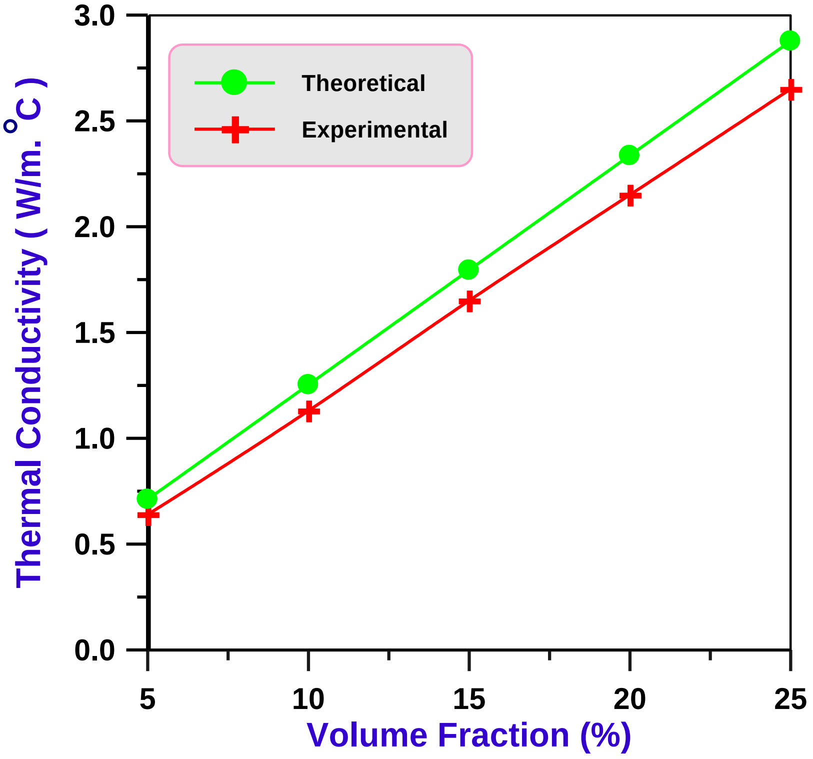

Figure (8): Relationship Between the Thermal Conductivity and the Volume Fraction for Parallel Direction.

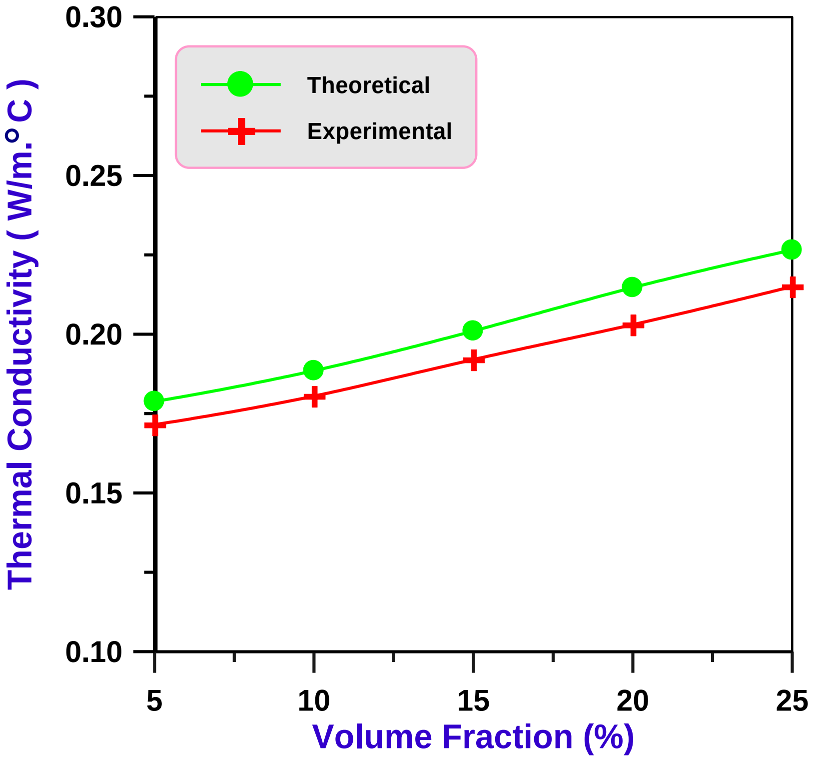

Figure (9): Relationship Between the Thermal Conductivity and the Volume Fraction for Perpendicular Direction.

Notation

$\mathbf{d_1, d_2 \& d_3}$	Thickness of the brass disks (m)
$\mathbf{d_s}$	Thickness of the composite specimen (m)
e	Convection heat transfer Coefficient (W/m^2. °C)
K	Thermal conductivity (W/m. °C)
$\mathbf{K_{c1}}$	Thermal conductivity of the composite specimen in the parallel direction of the fibers (W/m. °C)
$\mathbf{K_{c2}}$	Thermal conductivity of the composite specimen in the perpendicular direction of the fibers (W/m. °C)
$\mathbf{K_f, K_m}$	Thermal conductivity of fibers and matrix (W/m. °C)
q	Heat flux.
r	Radius of specimen (m)
$\mathbf{T_1, T_2, T_3}$	Temperature across the copper disks(1,2,3) (°C)
$\mathbf{V_f}$	Volume fraction of fibers (%)
$\mathbf{V_m}$	Volume fraction of matrix (%)
dT/dx	Temperature gradient

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دراسة تأثير الكسر ألحجمي لألياف الكربون واتجاهها على الموصلية الحرارية للمواد المتراكبة البوليمرية

الدكتور المهندس محمد صلاب حمزة
الجامعة التكنولوجية
قسم هندسة المواد

الخلاصة:

تم في هذا البحث دراسة تأثير الكسر الحجمي لالياف الكاربون وبنسب مختلفة (25%، 20%، 15%، 10%، 5%) على التوصيلة الحرارية للمادة المتراكبة. حيث صنعت العينات من مادة البولي أستر غير المشبع المقواة بالياف الكاربون . العينات صنعت في مجموعتين المجموعة الاولى كانت فيها الياف الكاربون مرتبة بشكل موازي للانسياب الحراري، اما المجموعة الثانية نظمت بترتيب الالياف بشكل عمودي على الانسياب الحراري .

استخدمت طريقة قرص لي (Leeś disk) في فحص العينات. اثبتت الدراسة ان الترتيب الموازي للالياف يعطي موصلية حرارية اعلى من الترتيب العمودي. وبينت النتائج بان الموصلية الحرارية للمادة المتراكبة تزداد مع زيادة الكسر الحجمي للالياف. وان اقل قيمة للموصلية الحرارية كانت (0.64 w/m.°C) للترتيب الموازي و (0.1715 w/m.°C) للترتيب العمودي عند الكسر الحجمي (V_f=5%) اما اعلى قيمة كانت (2.65 w/m.°C) للترتيب الموازي و (0.215 w/m.°C) للترتيب العمودي عند كسر حجمي (V_f = 25%) .