Al-Khwarizmi Engineering Journal, Vol. 4, No. 3, PP 85-97 (2008)

Al-Khwarizmi Engineering Journal

# Studying the Effect of Volume Fraction of Glass Fibers on the Thermal Conductivity of the Polymer Composite Materials

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(Received 11 March 2008; accepted 18 June 2008)

## Abstract

In this study the effect of fiber volume fraction of the glass fiber on the thermal conductivity of the polymer composite material was studied. Different fiber volume fraction of glass fibers were used (3%, 6%, 9%, 12%, and 15%). Specimens were made from polyester which reinforced with glass fibers .The fibers had two arrangements according to the direction of the thermal flow. In the first arrangement the fibers were parallel to the direction of the thermal flow, while the second arrangement was perpendicular; Lee's disk method was used for testing the specimens. The experimental results proved that the values of the thermal conductivity of the specimens was higher when the fibers arranged in parallel direction than that when the fibers arranged in the perpendicular direction. The percentage of increasing of experimental thermal conductivity was 96.91% for parallel arrangement and 13.33% for perpendicular arrangement comparison with its original value before the using of glass fibers.

Also the experimental results indicated that the thermal conductivity increases with the increasing of the fiber volume fraction. Minimum value was (0.172 W/m.°C) for perpendicular arrangement at fiber volume fraction 3% and maximum value was (0.327 W/m.°C) for parallel arrangement at fiber volume fraction 15%.

***Keywords:*** Polymer, Glass fibers, Thermal conductivity.

## Introduction

Thermal conductivity is a phenomena of the heat transfer phenomenon, so the thermal conductivity is defined as the transfer of heat from area of high temperature to that of low temperature. The rate of heat transfer depends upon the temperature gradient and the components of materials. The direction of heat transfer will be opposite to the temperature gradient since the net energy transfer will be from high temperature to low.

The thermal conductivity of solids materials is greater than that of liquids and gases materials.

For solid materials it is four times than that of gases material. This is due to the difference between the voids of the two materials. Gases transfer heat by direct collisions between molecules, and as would be expected, their thermal conductivity is low compared to most solids since they are dilute media. Metals have better thermal conductivity than non-metals because the same mobile electrons which participate in electrical conduction also take part in the transfer of heat. Non-metallic solids transfer heat by lattice vibrations so that there is no net motion of the media as the energy propagates through. Such heat transfer is often described in terms of "phonons", quanta of lattice vibrations [1].

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].

Zhan-Sheng et. al. [1] used the finite element formulation of transient heat transfer problem for polymeric matrix composite materials from the heat transfer differential equations to study the experimental and numerical temperature distribution of thick polymeric matrix laminates during an autoclaves vacuum bag process.

Murthy et. al. [2] studied the distribution of the temperature and the analysis of thermal stresses across the composite thick plates by using two-dimensional finite and physical model element model for this analysis in both longitudinal and transverse directions for three different filter materials with epoxy as matrix material.

Rondeaux et al. [3] improved 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 tested in the range of temperature (4.2 to 14 K) in order to extract the thermal boundary resistance for different thicknesses.

Raimund [4] studied the analysis of temperature fields for hybrid and conventional composite structures by using the two-dimensional and three-dimensional finite element formulations for the analysis of temperature fields for hybrid and conventional composite structures.

Khalaf [5] studied the thermal conductivity and the mechanical and physical properties for unsaturated polyester reinforced by fiber glass and nylon fiber composites and found that the thermal conductivity decrease with increase of nylon fiber layers and also decreases with the increase the volume fraction, for the samples of laminar reinforced system.

Pilling et. al. [6] studied the effect of orientation of fiber and the fiber volume fraction on the thermal conductivity of composite materials reinforced with fiber of carbon. They proved that the thermal conductivity increases with increasing of the fiber volume fraction and were higher in the parallel arrangement of the fibers than that for perpendicular arrangement.

Elie [7] studied the thermal conductivity and mechanical properties 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 at a weight fraction of (20 %) and for the composite material reinforced with (Al) was ( 0.407 W/m.°C) and for the composite material reinforced with ($Al_2O_3$) was (0.319 W/m.°C) at the same weight fraction.

James and Harrison [8] calculated heat flow and distribution of temperature by using the finite difference method 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

The aim of this study is to study the effect of fiber volume fraction and their direction (parallel or perpendicular to heat flow) of the reinforcement material (glass fibers) on the thermal conductivity. The specimens were made from polyester reinforced with five different volume fraction of glass fiber (3%, 6%, 9%, 12% and 15%).

The reinforcement material (glass fiber) was arranged in two methods. In the first method the glass fibers was aligned in the parallel direction to the heat flow while in the second method the glass fibers was aligned perpendicular to its.

## Theoretical analysis

The volume fraction of matrix and reinforcement material is calculated from the following equations [9].

**a-** Volume fraction of matrix

$$V_m = \frac{v_m}{v_c}\% \qquad ...(1)$$

**b-** Volume fraction of glass fibers

$$V_f = \frac{v_f}{v_c}\% \qquad ...(2)$$

The electric power pass through the heating coil is calculated by the following formula.

$$P=V.I \qquad …(3)$$

The transferring of the thermal energy is carried out in two ways. These are:

1- The vibrating waves of the lattice.
2- The movement of the free electrons.

The thermal conductivity is defined by the following formula [9]:

$$q= -k\, dT/dx \qquad ...(4)$$

The equation (4) used only for steady state of thermal flow and when the thermal flux is fixed and does not change with time. The minus sign means that the transfer of heat is starting from hot part to the cold part. The direction of heat transfer will be opposite to the temperature gradient since the net energy transfer will be from high temperature to low. This direction of maximum heat transfer will be perpendicular to the equal-temperature surfaces surrounding a source of heat.

The theoretical thermal conductivity is calculating by the following equation [9, 10].

$$K\cdot\left[\frac{T_2-T_1}{d_s}\right]=e\cdot\left[T_1+\frac{2}{r}\cdot\left(d_1+\frac{1}{2}d_s\right)\cdot T_1+\frac{1}{r}\cdot d_s\cdot T_2\right] \qquad ...(5)$$

The heat loss (e) through the unit time (second) and through the area ($m^2$) is calculated by the following formula [11]:

$$I\cdot V=\pi\cdot r^2\cdot e\cdot\left(T_1+T_3\right)+2\cdot\pi\cdot r\cdot e\cdot\left[d_1\cdot T_1+\frac{1}{2}\cdot d_s\left(T_1+T_2\right)+d_2\cdot T_2+d_3\cdot T_3\right] \qquad ...(6)$$

The theoretical thermal conductivity of composite materials is estimated from the following equations [12, 13, 14]:-

1-heat flow is parallel to the glass fibers:

$$K_{c1} = K_f \cdot V_f + K_m \cdot V_m \qquad ...(7)$$

2- heat flow is perpendicular to the glass fibers:

$$K_{c2} = \frac{K_f \cdot K_m}{K_f \cdot V_m + K_m \cdot V_f} \qquad ....(8)$$

## Experimental Work

The samples were manufactured from unsaturated polyester (thermosets) which reinforced with different values of fiber volume fraction of fiber glass.

The hardener type of MEKP (Methyl Ethyl Keto Peroxide ) was added by 2% of resin and the Cobalt Octeate also added by 0.5% to speed up the reaction and increases the solidification of the samples.

In this studying, the Lee's disk method is used for measuring the thermal conductivity. Figure (1) shows the electric circuit which used for this method. Figure (2) shows the instrument used for this method. The instrument is consist of heating coil and three brass disks (1, 2, 3). The specimen was fixed between brass disks (1,2) while the heating coil was fixed between brass disks (2,3) as shown in figure (1).

The cylindrical specimens were made from polyester matrix material which reinforced by glass fibers, the geometry of the specimens are r =0.02m, ds =0.007m.

The first group of specimens reinforced with the glass fibers parallel to the direction of thermal flow and the second group of the specimens are perpendicular to the thermal flow. The experimental temperature $T_1$, $T_2$, and $T_3$ were measured by means of Lee`s disk method. The applied voltage across the terminal of the heating coil is (6 Volt) and the current is (0.2 Amper). The heating coil was used to heat the brass disks (1, 2, 3) and heat transfer across the specimen from the bass disk (2) to brass disk (1).The temperatures of all disks increases gradually and the temperatures recorded every (5 minutes) by using thermometers until reach the equilibrium temperature of all disks (i.e. $T_2$=$T_3$).

The losses in heat (e) was calculated from equation (6).The thermal conductivity (k) was calculated from equation (5) by using the experimental temperatures ($T_1$, $T_2$, $T_3$) and the dimension of specimen (r,ds).

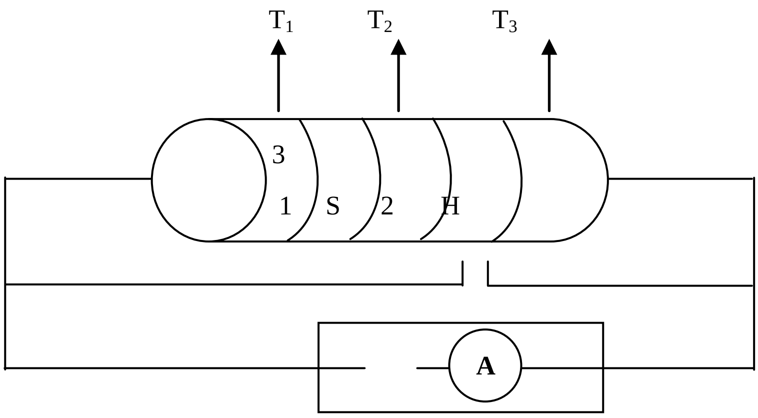



**Fig.1. Thermal Conductivity Measurment.**

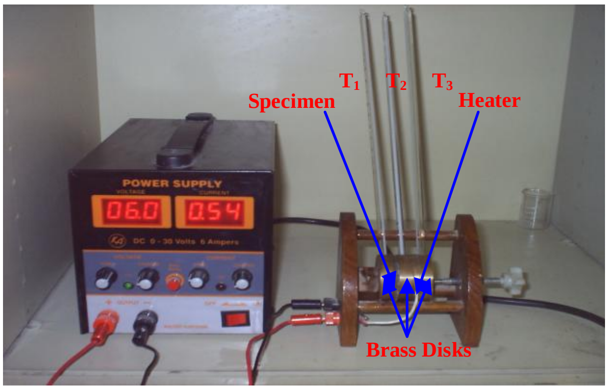



**Fig. 2. Test Apparatus with Specimens Test.**

## Results and Discussions

The properties of the unsaturated polyester and glass fibers are presented in table (1). Table (2) illustrates the theoretical thermal conductivity of composite material for parallel and perpendicular arrangement and the difference between them. This table indicated that the difference increase with the increasing the fiber volume fracture and this leads to that the thermal conductivity of composite materials improve with the addition of glass fibers.

Tables (3, 4) show some properties of the manufactured composite specimens at different fiber volume fraction for both directions parallel and perpendicular respectively. These tables show that the properties of manufactured specimens were improved and increase with the increasing of the fiber volume fraction of glass fibers.

Figure (3) shows the relationship between the experimental temperature of the wall surface ($T_1$and $T_2$) of the tested specimens and the time for the unsaturated polyester. It is clear from these figures that the experimental temperatures of wall surface ($T_2$ and $T_3$) increase with time until it reach the equilibrium temperature ($T_2$=$T_3$).

**Table 1**
**Properties of Unsaturated Polyester and Glass Fibers[12].**

| Material Type | Density ($g/cm^3$) | Modulus of Elasticity (GPa ) | Tensile Stress (MPa.) | Thermal conductivity (W/m. °C) | Poisson's Ratio | Percent Elongation % |
|---|---|---|---|---|---|---|
| Glass Fiber | 2.58 | 72.5 | 3450 | 1.3 | 0.22 | 4.3 |
| Unsaturated Polyester | 1.04-1.46 | 2.06-4.41 | 70.3-103 | 0.17 | 0.33 | < 2.6 |

**Table 2**
**Theoretical Thermal Conductivity For the Parallel and the Perpendicular Arrangement Composite Materials.**

| Fiber Volume Fraction % | Theoretical Thermal Conductivity ($K_c$) (W/m. °C) | | The Difference Between Parallel and Perpendicular Arrangement |
|---|---|---|---|
| | Parallel Arrangement | Perpendicular Arrangement | |
| 0 | 0.170 | 0.170 | 0.000 |
| 3 | 0.204 | 0.175 | 0.029 |
| 6 | 0.238 | 0.179 | 0.059 |
| 9 | 0.272 | 0.184 | 0.088 |
| 12 | 0.306 | 0.190 | 0.116 |
| 15 | 0.340 | 0.195 | 0.145 |

**Table 3**
**Properties of the Manufactured Composite Specimens When the Fiber are Arranged in the Parallel Direction to the Heat Flow.**

| Properties | Fiber Volume Fraction | | | | |
|---|---|---|---|---|---|
| | 3% | 6% | 9% | 12% | 15% |
| $\rho(g/cm^3)$ | 1.086 | 1.32 | 1.179 | 1.225 | 1.271 |
| $K_x$(W/m-C°) | 0.175 | 0.179 | 0.184 | 0.190 | 0.195 |
| $K_y$(W/m-C°) | 0.175 | 0.179 | 0.184 | 0.190 | 0.195 |
| $K_z$(W/m-C°) | 0.204 | 0.238 | 0.272 | 0.306 | 0.340 |

**Table 4**
**Properties of the Manufactured Composite Specimens When the Fiber are Arranged in the Perpendicular Direction to the Heat Flow.**

| Properties | Fiber Volume Fraction | | | | |
|---|---|---|---|---|---|
| | 3% | 6% | 9% | 12% | 15% |
| $\rho$ ($g/cm^3$) | 1.086 | 1.32 | 1.179 | 1.225 | 1.271 |
| $K_x$(W/m-C°) | 0.204 | 0.238 | 0.272 | 0.306 | 0.340 |
| $K_y$(W/m-C°) | 0.204 | 0.238 | 0.272 | 0.306 | 0.340 |
| $K_z$(W/m-C°) | 0.175 | 0.179 | 0.184 | 0.190 | 0.195 |

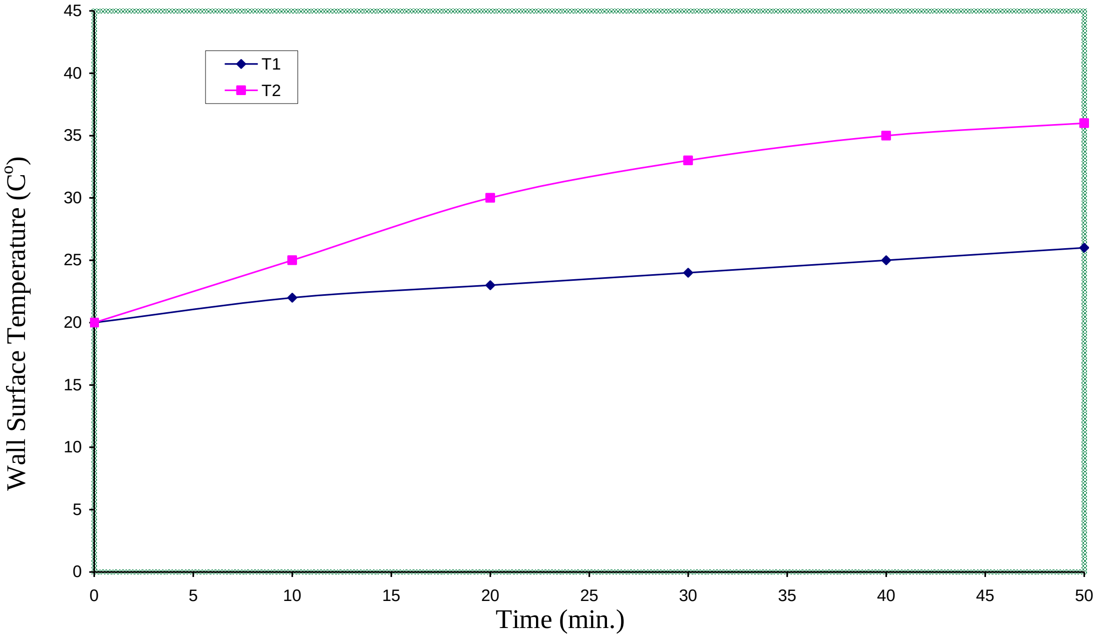



**Fig.3. Relationship between the Experimental Wall Surface Temperatures ($T_1$and $T_2$) of the Tested Specimens and the Time for the Unsaturated Polyester**.

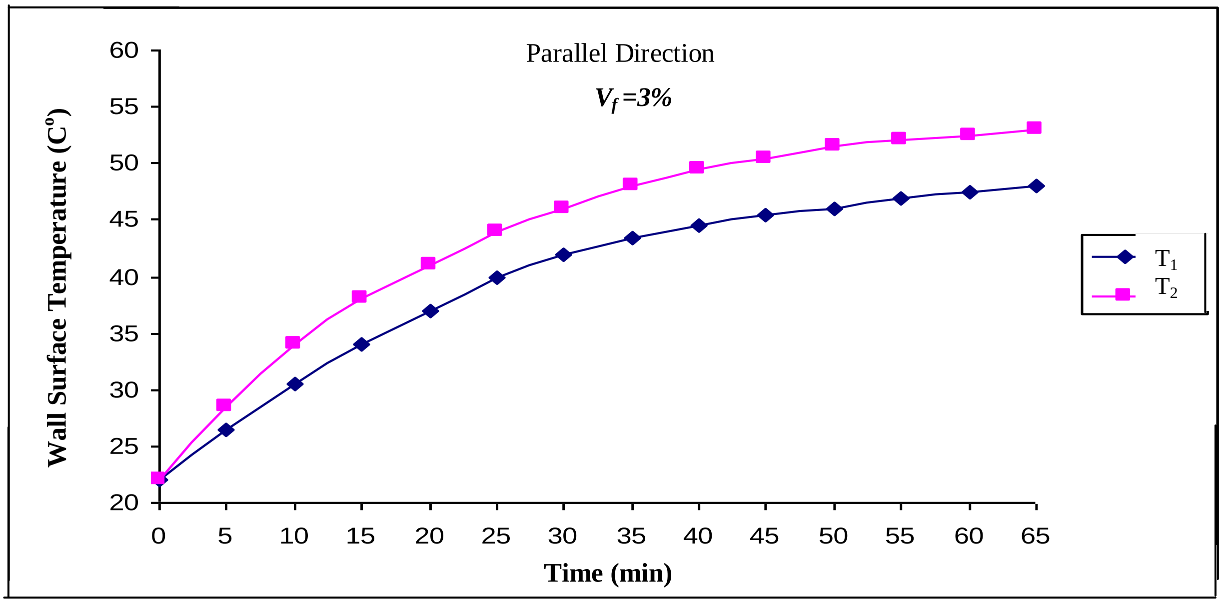
Figure (4) shows the relationship between the temperature of the wall surface ($T_1$and $T_2$) of the tested specimens and the time for the different fiber volume fraction ($V_f$=3%and15%) for experimental work when the thermal flow in the parallel direction to the glass fibers.

Figure (5) shows the relationship between the temperature of wall surface ($T_1$and $T_2$) and time for the different fiber volume fraction ($V_f$=3%, and15%) for experimental work when the thermal flow in the perpendicular direction to the direction of the glass fibers.

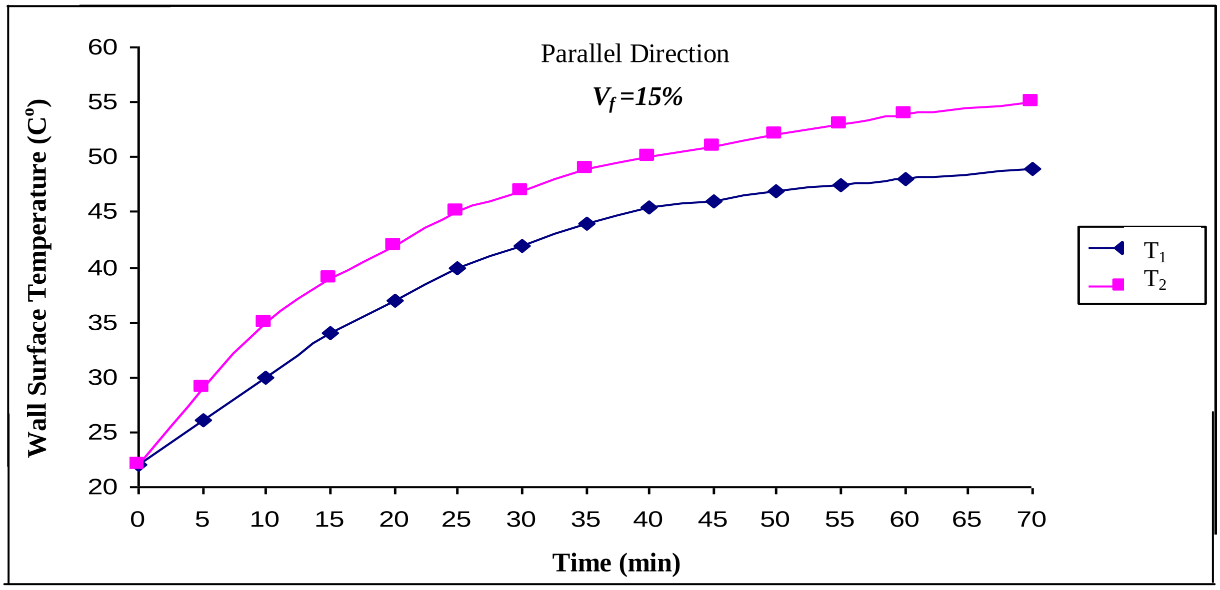
The figures (4 and 5) indicated that the experimental temperatures ($T_2$and $T_3$) reach the equilibrium state ( $T_2$=$T_3$ ) at different time.

The relationship between the theoretical thermal conductivity and the fiber volume fraction ($V_f$) for parallel and perpendicular direction of glass fibers is presented in figure (6), it can be seen that the results of the parallel direction was higher than the results when the fiber arranged in the perpendicular direction to the heat flow. It can be seen that the difference between the parallel and the perpendicular direction increases with increasing the fiber volume fraction as shown in the table (2). Also it was found that the maximum difference between the theoretical results of the parallel direction and the perpendicular direction was (42.6%) at the fiber volume fracture ($v_f$=15%) and the minimum difference was 14.2% at fiber volume fracture ($v_f$=3%). The experimental results indicated that the maximum percentage of improvement of the experimental thermal conductivity for parallel arrangement was96.9% at the $v_f$=15%, and the maximum improvement for perpendicular was 13.77% at the $v_f$=15% this difference is due to the arrangement and orientation of the glass fibers.

Figure (7) shows the relationship between the theoretical and experimental thermal conductivity with different values of volume fraction of glass fibers for parallel direction, while the relationship for perpendicular direction is illustrated in figure (8). The relationship between the theoretical and the experimental thermal conductivity with the different values of the fiber volume fraction (3% and 15% ) for parallel and perpendicular arrangement is illustrated in figure (9), while the same relationship different values of the fiber volume fraction (9% and 15% ) is illustrated in figure (10). Figures (6, 7, 8, 9 and 10) indicated that the theoretical thermal conductivity is greater than the experimental conductivity. The difference between the theoretical and the experimental conductivity is due to the fact that the theoretical conductivity is real values and obtained from the equations while the experimental values depend on the properties of matrix material , fibers, the precision of instrument, reading, and environmental condition. From the experimental and the theoretical results found that for the parallel direction the maximum difference theoretical and experimental values was (3.82%) at ($V_f$ = 15%) while the minimum value was (2.94 %) at ($V_f$ = 3 %). For the perpendicular direction it was found that the maximum difference of thermal conductivity between the theoretical value and experimental value was (2.56%) at ($V_f$ =15%) while the minimum value was (1.71%) at ($V_f$ =3 %). It is clear from the results of the this research that the thermal conductivity increases with increasing fiber volume fraction of the glass of thermal conductivity between the fibers but the percentage of increase for parallel direction is more than that for perpendicular direction for both theoretical and experimental work. All the results of the theoretical and experimental results prove that the parallel arrangement is the best for application and the improvement of the thermal conductivity depend on the properties of the matrix and the reinforcement material and the orientation of the fibers.

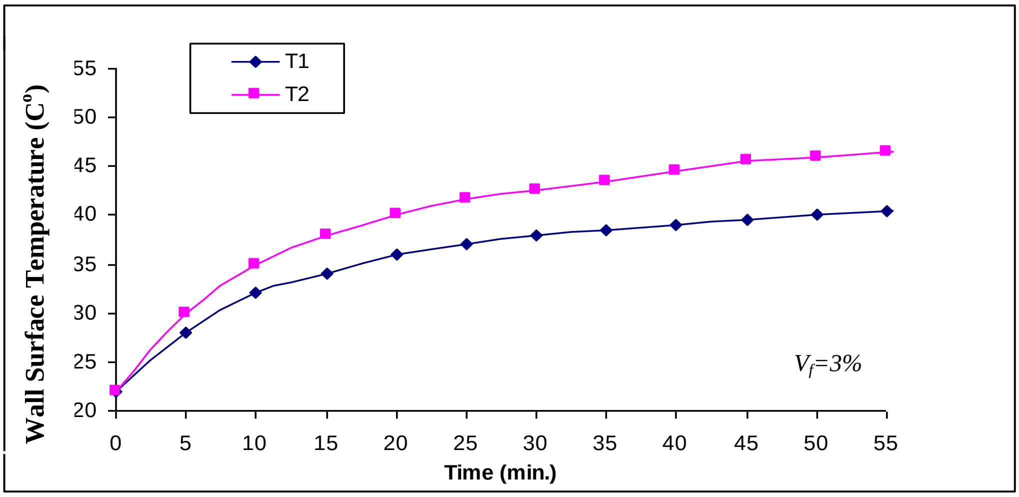



**(a)**

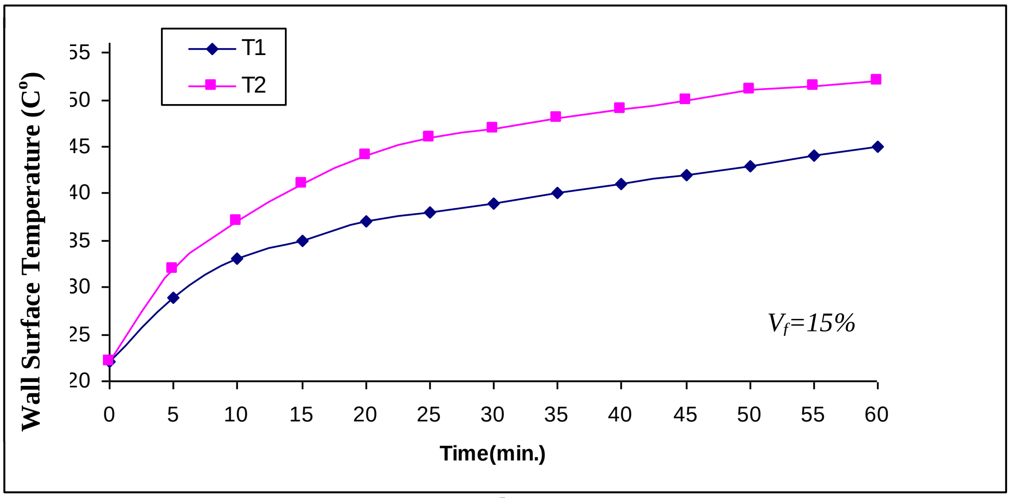



**(b)**

**Fig.4. Relationship between the Experimental e Wall Surface Temperature ($T_1$and $T_2$) of the Tested Specimens and the Time When the Fiber Arranged in the Parallel Direction at:**
**a) Volume Fraction of Fiber 3% b) Volume Fraction of Fiber 15%.**




**(a)**




**(b)**

**Fig.5. Relationship between the Experimental Wall Surface Temperature ($T_1$and $T_2$) of the Tested Specimens and the Time When the Fiber Arranged in the Perpendicular Direction at: a) Volume Fraction of Fiber 3%. b) Volume Fraction of Fiber %15.**

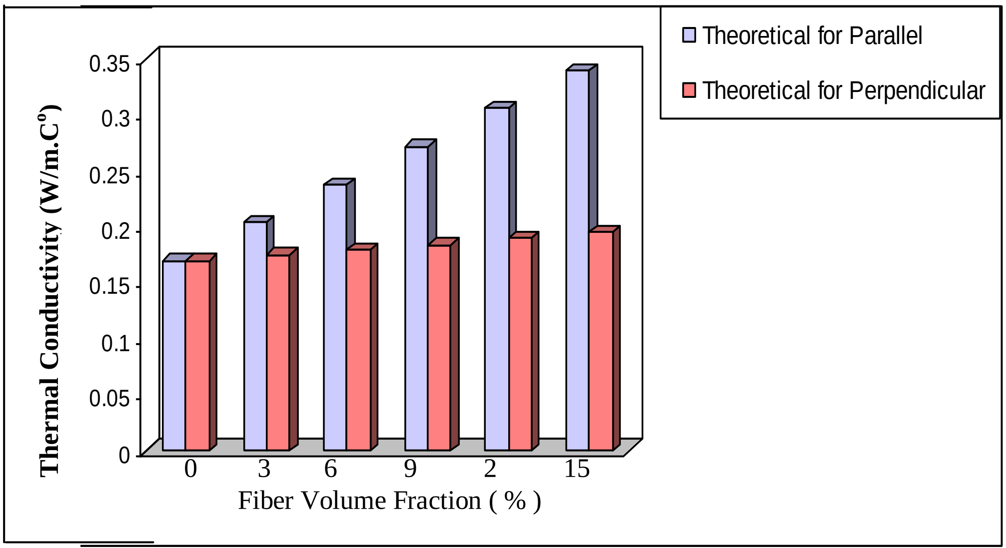



**Fig.6. The Relation between the Theoretical Thermal Conductivity and the Fiber Volume Fraction ($V_f$) for Parallel and Perpendicular Direction of Manufactured Specimens.**

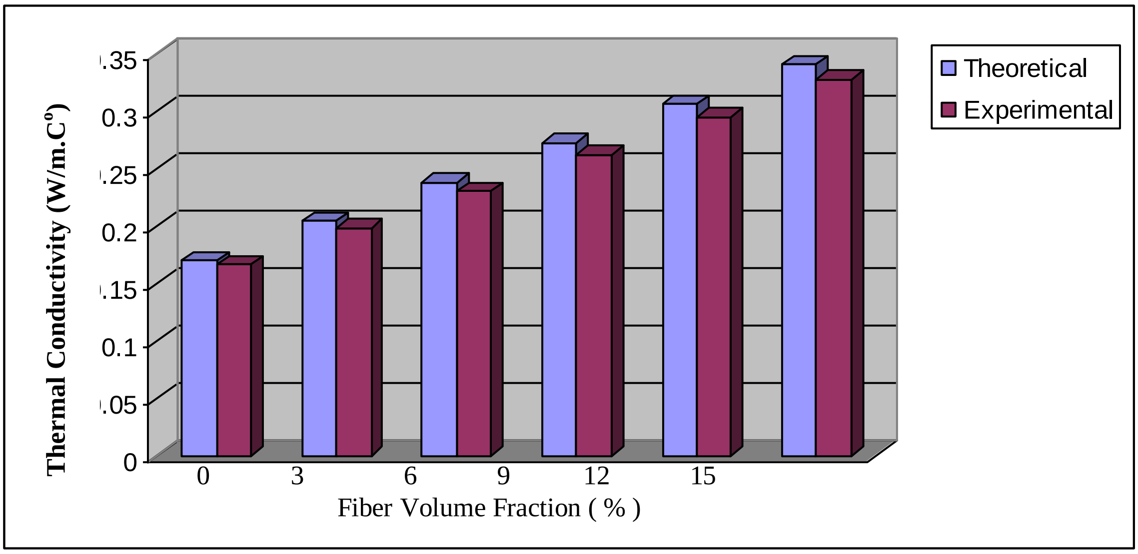



**Fig.7. The Relation between the Theoretical and Experimental Thermal Conductivity with the Fiber Volume Fraction ($V_f$) for Parallel Direction of Manufactured Specimens.**

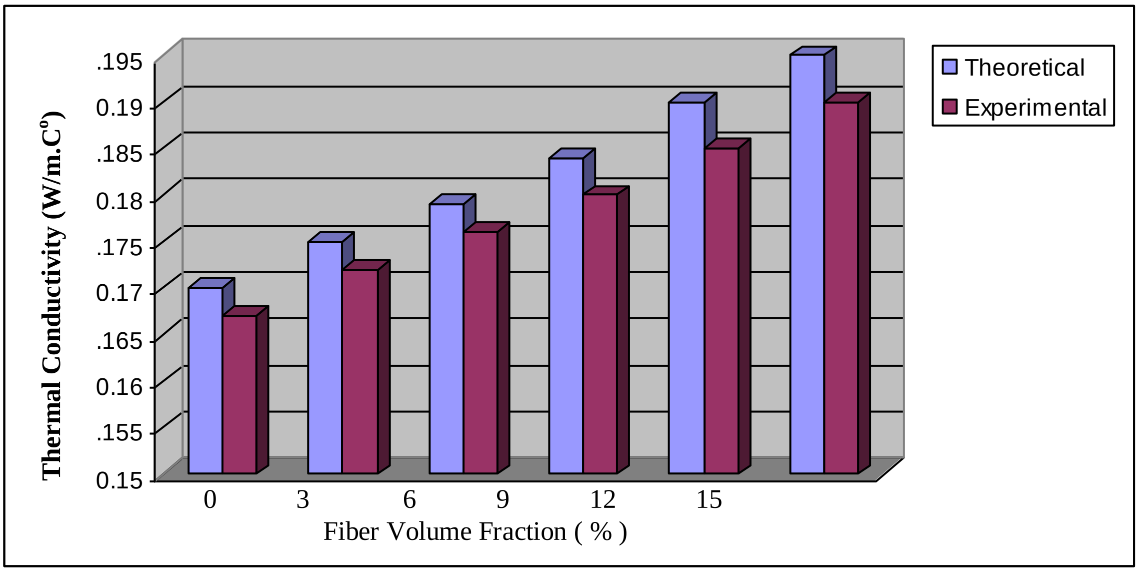
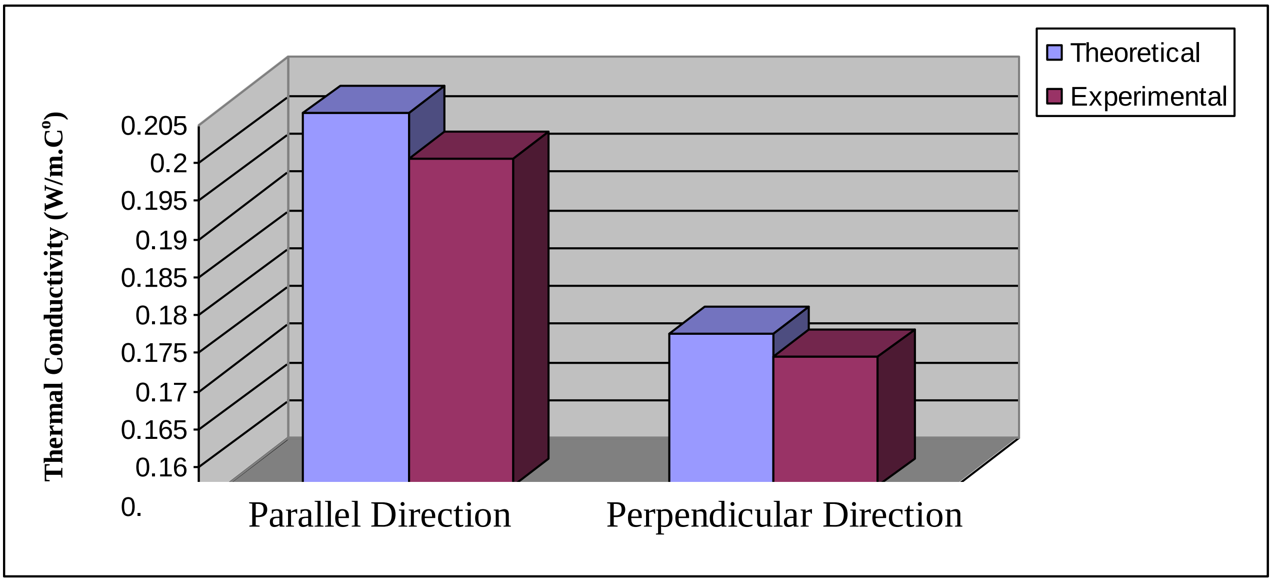
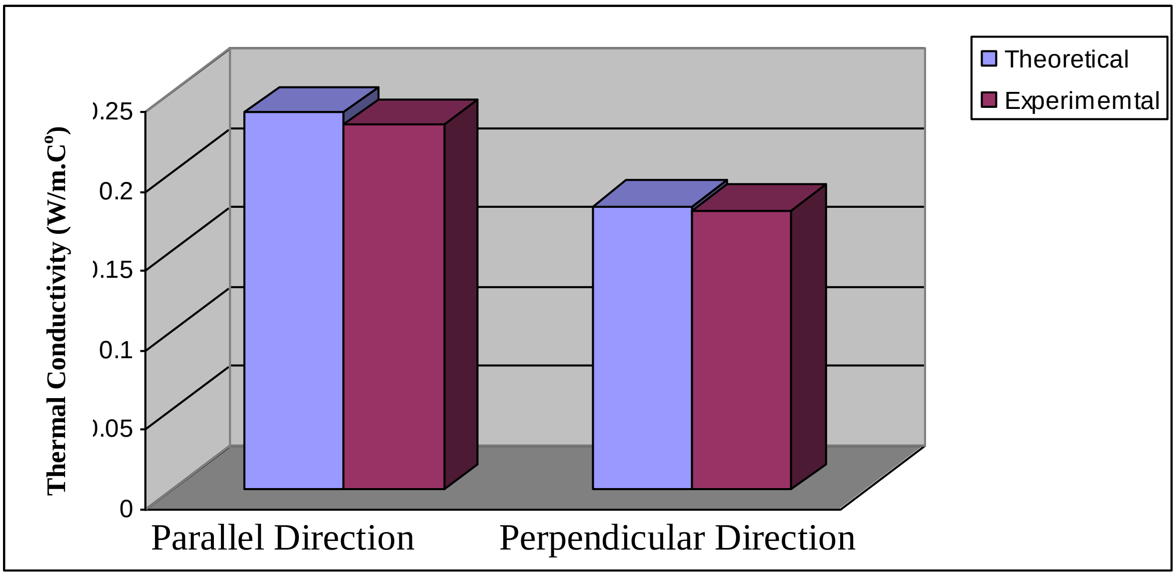



**Fig.8. The Relation between the Theoretical and Experimental Thermal Conductivity with the Fiber Volume Fraction ($V_f$) for Perpendicular Direction of Manufactured Specimens.**

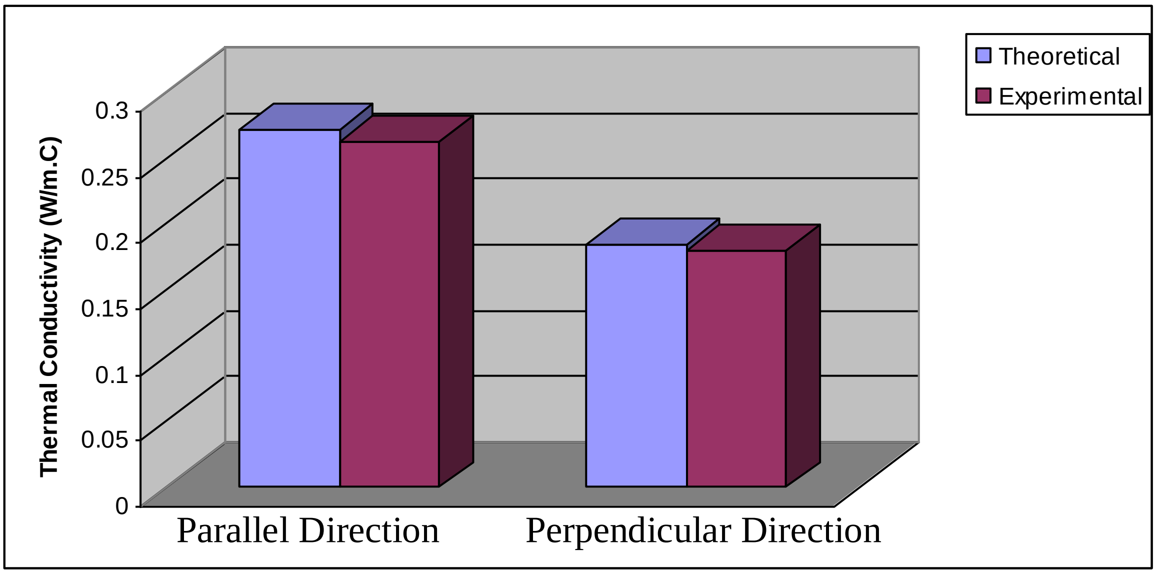



$V_f$ = 3%

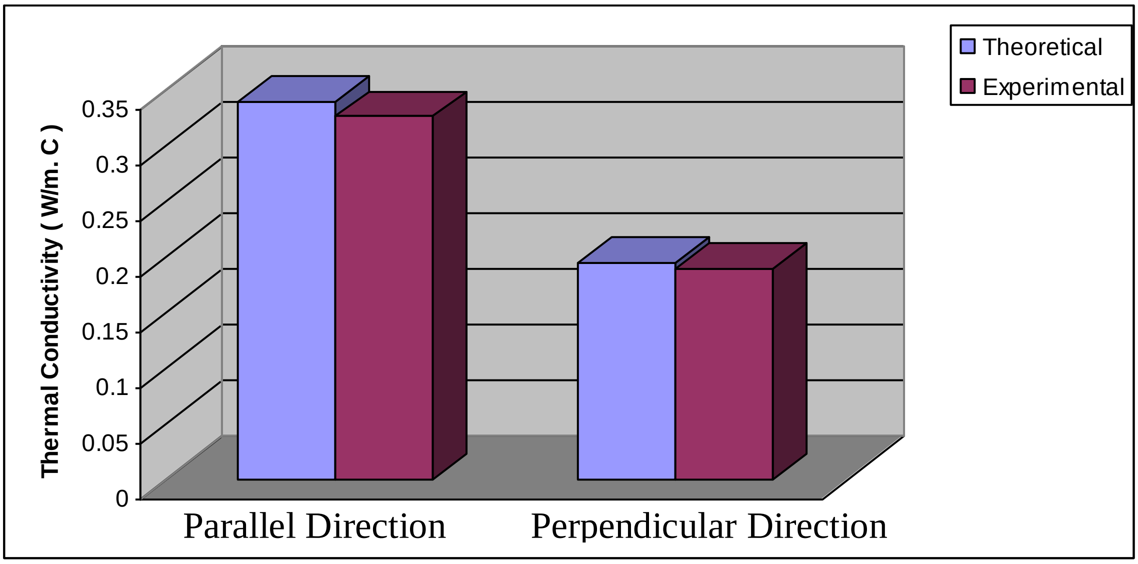



Vf = 6%

**Fig.9. The Relation between the Theoretical and Experimental Thermal Conductivity with the Different Value of Fiber Volume Fraction ($V_f$ = 3% and 6%) for Parallel and Perpendicular Direction of Manufactured Specimens.**




Vf= 9 %




Vf= 15 %

**Fig.10. The Relation between the Theoretical and Experimental Thermal Conductivity with the Different Value of Fiber Volume Fraction ($V_f$ = 9% and 15%) for Parallel and Perpendicular Direction of Manufactured Specimens.**

## 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 minimum value of experimental thermal conductivity for perpendicular arrangement was (0.172 W/m. °C) at fiber volume fraction (3%) and the percentage of improvement and the increasing of the experimental thermal conductivity was 13.77% while the maximum value of experimental thermal conductivity for parallel arrangement was (0.237 W/m. °C) at fiber volume fraction (15%) and the percentage of improvement and the increasing of the experimental thermal conductivity was 96.9%.

**3-** For parallel. Arrangement, the maximum difference between the experimental and theoretical values of the thermal conductivity was (3.82%) at fiber volume fraction (15%) and the minimum difference was 2.94% at fiber volume fraction (3%).

**4-** For perpendicular arrangement, the maximum difference between experimental and theoretical thermal conductivity was 2.56% at fiber volume fraction (15%) and the minimum difference was 1.71% at fiber volume fraction (3%).

## 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). |
| $\mathbf{v_c\ v_m, v_f}$ | Volume of composite, matrix and reinforced material (m$^3$). |
| $\mathbf{V_f, V_m}$ | Fiber volume fraction of matrix and fiber (%). |
| dT/dx | Temperature gradient (%). |
| p | Power pass though heating coil (watt) |
| I | Electric current pass though heating coil(Ampere) |
| V | Voltage across the terminal of heating coil(volt) |

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# دراسة تأثير الكسرالحجمي لألياف الزجاج علىالموصلية الحرارية للمواد المتراكبة البوليمرية

**محمد صلاب حمزة**
قسم هندسة المواد/ الجامعة التكنولوجية

**الخلاصة**

تم في هذا البحث دراسة تأثير الكسر الحجمي لالياف الزجاج وبنسب مختلفة (15%، 12%، 9%، 6%، 3% ) على التوصيلة الحرارية للمادة المتراكبة. حيث صنعت العينات من مادة البولي أستر غير المشبع المقواة بالياف الزجاج. العينات صنعت في مجموعتين المجموعة الاولى كانت فيها الياف الزجاج مرتبة بشكل موازي للانسياب الحراري، اما المجموعة الثانية نضمت بترتيب الالياف بشكل عمودي على الانسياب الحراري.

استخدمت طريقة قرص لي ( Leeś disk ) في فحص العينات. اثبتت النتائج العملية ان الترتيب الموازي للالياف يعطي موصلية حرارية اعلى من الترتيب العمودي وان الموصلية الحرارية للمادة المتراكبة تزداد مع زيادة الكسر الحجمي للالياف. حيث كان مقدار الزيادةفي الموصلية الحرارية بسبب التقوية بالالياف هو 96.91% للترتيب الموازي و 13.33% للترتيب العمودي كذلك اثبت النتائج العملية ان اقل قيمة للموصلية الحرارية كانت ( 0.172w/m.°C) للترتيب العمودي عند الكسر الحجمي ( $V_f$=3%) اما اعلى قيمة كانت (0.327W/m.°C) للترتيب الموازي عند كسر حجمي ($V_f$ = 15%).