Study of Thermal Characteristics of a Composite Specimen Experimentally and by Using Finite Element Method

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Abstract

This research deals with the study of the effect of fibers volume fraction and fibers orientation on the thermal conductivity and wall surface temperatures for composite specimen in form of Lee's disk by using experimental work and finite element technique. The results show that the thermal conductivity increases with increasing fiber volume fraction of the composite specimen, and in the longitudinal direction is larger than in the lateral fiber direction.The experimental results indicated that the largest value of the thermal conductivity for the composite specimen was (0.611 W/m.°c) at (V_f = 40 %) in the longitudinal direction, while the lowest value was (0.195 W/m.°c) at (V_f = 10 %) in the lateral direction. Also the results show that the maximum difference for the thermal conductivity between the experimental work and finite element method was (7 %) at (V_f = 10 %) in the lateral direction while the minimum value was (3.5 %) at (V_f = 40 %) in the longitudinal direction.

Key words: composite specimens, thermal conductivity, Temperature distribution

تناول هذا البحث دراسة تأثير كل من الكسر الحجمي للألياف وأتجـاه الأليـاف علـى الموصلية الحرارية ودرجات حرارة سطح الجدار لعينة مادة مركبة علـى شـكل قـرص لـي.
بينت النتائج بانه بزيادة الكسر الحجمي تزداد الموصـلية الحراريـة للمـادة المركبـة وبالاتجاه الطولي للالياف وتكون اكبر من الموصلية الحرارية بالاتجاه العمودي على الاليـاف.
كما بينت النتائج العملية بأن اعلى موصلية حرارية للعينة المركبة كانت (0.611 W/m.°c) عند كسر حجمي (V_f = 40 %) وبأتجاه موزاي للألياف بينما أقل قيمـة للموصـلية الحراريـة للعينة المركبة كانت (0.195 W/m.°c) عند كسر حجمي (V_f =10 %) وبأتجاه عمودي على الألياف. وأظهرت النتائج ايضا" بان اعلى فرق للموصلية الحرارية بين النتائج العملية والنتـائج النضرية هو (7 %) عند كسر حجمي (10 %) وبالأتجاه العمودي على الألياف. بينمـا أقـل فرق للموصلية الحرارية بين النتائج العملية والنتائج النضرية هو (3.5 %) عند كسر حجمـي (40 %) وبالأتجاه الطولي للألياف.

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Notation

A	Cross-sectional area of the disk (m^2)
C_p	Specific heat (J/kg.^{o}c)
d_1, d_2 and d_3	Thickness of the brass disks (m)
d_s	Thickness of the composite specimen (m)
E_f, E_m	Modulus of elasticity of fibers and matrix (GPa.)
E	Convection heat transfer coefficient (W/m^2.^{o}c)
K	Thermal conductivity (W/m.^{o}c)
K_{c1}	Thermal conductivity of the composite specimen in the longitudinal direction of the fibers (W/m.^{o}c)
K_{c2}	Thermal conductivity of the composite specimen in the lateral direction of the fibers (W/m.^{o}c)
K_f, K_m	Thermal conductivity of fibers and matrix (W/m.^{o}c)
K_x, K_y and K_z	Thermal conductivity in x, y and z direction (W/m.^{o}c)
R	Radius of disk (m)
T_1, T_2	Temperature across the sample sides (^{o}c)
V_f	Volume fraction of fibers (%)
V_m	Volume fraction of matrix (%)
α_{c1}	Thermal expansion coefficient of the composite specimen in the longitudinal direction of fibers (1/^{o}c).
α_{c2}	Thermal expansion coefficient of the composite specimen in the lateral direction of fibers (1/^{o}c).
α_f, α_m	Thermal expansion coefficient of the fibers and matrix (1/^{o}c)
α_x, α_y, α_z	Thermal expansion coefficient in the x, y and z direction (1/^{o}c)
ρ	Density (kg/m^3)
υ_{12}	Poisson's ratio of the composite specimen
υ_f, υ_m	Poisson's ratio of the fibers and matrix.

Introduction

Nowdays the composite materials have a wide range of applications depend on the temperature therefore it is necessary to study the thermal characteristic of the materials. Very often composite materials results in anisotropic media and their thermal conductivity changes along the axes because of the presence of reinforcing fibers embedded in the matrix [1].

The thermal response of an anisotropic medium subject to thermal disturbance can be determined by means, numerical procedures or experimental setups [1]. The fiber volume fraction and their orientation have a greater effect on the thermal analysis of the composite specimens. The ability of the composite material to resist or conduct heating depends on the quantities and qualities of the constituents. Most of the work was concentrated on determining the thermal conductivity of the composite specimens at different boundary conditions are presented here. Pilling et.al [2] studied the effect of fiber volume fraction and the fiber orientation on the thermal conductivity of carbon fiber-reinforced composites. Gaglord [3] mentioned 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. Manca et.al [1] studied the thermal response of the composite materials by evaluating the thermal response of the specimens to different heating conditions. James and P. Harrison [4] used the finite difference method in the calculation of temperature distribution and heat flow in composite materials made from anisotropic materials. Zhan-Shang Guo et.al

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[5] studied the experimental and numerical temperature distribution of thick polymeric matrix laminates. The finite element formulation of transient heat transfer problem was carried out for polymeric matrix composite materials from the heat transfer differential equations. BSR Murthy et.al [6] studied the analysis of thermal stresses, temperature distribution across the composite thick plates by using physical model and two-dimensional finite element model for three different filter materials with epoxy as matrix material. Rondeaux etal. [7] developed a specific thermal conductivity measurement facility for pre-impregnated fibers glass epoxy composite, where the thermal conductivity measurements are presented in the temperature of 4.2 K to 14 K for different thicknesses.

In this research the specimens was made from four different volume fractions which are equal to (10 %, 20 %, 30 %, and 40 %) and the fibers were arranged in two directions, the first, in the lateral direction (perpendicular) to the heat source, and the second, in the longitudinal direction (parallel) to the heat source.

The purpose of this work is to study the effect of fiber orientation on the thermal characteristics of the composite material for different fiber volume fractions and make comparison between the experimental results and finite element results.

Theory

The large use of composite materials in many applications is related to the increment of the mechanical and thermal properties and the reduction of weight with respect to the traditional materials.

Thermal properties of the composite material are very important they indicate how the material will expand for a particular change of temperature, how much the temperature of a piece of material will change when there is a heat input into it, and how good a conductor of heat it is [8].

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 [6].

The rule of mixture accurately predicts the thermal conductivity of fiber reinforced composite in both directions [9]:

When the fibers are arranged in the Longitudinal Direction, then:-

$$K_{c1} = K_f \cdot V_f + K_m \cdot V_m \tag{1}$$

While when the fibers are arranged in the Lateral Direction:-

$$K_{c2} = \frac{K_f \cdot K_m}{K_f \cdot V_m + K_m \cdot V_f} \tag{2}$$

Also the thermal expansion coefficient can be calculated in both directions by the following formulii [10]:

When the fibers are arranged in the Longitudinal Direction

$$\alpha_{c1} = \frac{\alpha_m \cdot E_m \cdot V_m + \alpha_f \cdot E_f \cdot V_f}{E_m \cdot V_m + E_f \cdot V_f} \tag{3}$$

When the fibers are arranged in the Lateral Direction

$$\alpha_{c2} = \alpha_m \cdot V_m \cdot (1-\upsilon_m) + \alpha_f \cdot V_f \cdot (1-\upsilon_f) - \upsilon_{12} \cdot \alpha_{c1} \tag{4}$$

Where:

$$\upsilon_{12} = \upsilon_f \cdot V_f + \upsilon_m \cdot V_m \tag{5}$$

Experimental Work

The experimental part was carried out in the laboratory to determine experimentally the thermal conductivity of many composite specimens.

Figure (1) represents the test apparatus (Lee's disc apparatus) type (Griffin and George) with tested composite specimen and some accessories to measure the temperature of both sides of the composite specimen in order to calculate the thermal conductivity.

The heater is switch on from the power supply with (V = 6 V and I = 0.2 A) to heat the brass disks (2,3) and the temperatures of the all disks increases in nonlinear relationships and at different rates with the time according to its position from the heat source. And the temperatures were recorded every (5 minutes) until reach to the equilibrium temperature of all disks.

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This composite specimen was made from glass fiber-epoxy matrix composite under the following conditions.

V_f = 10%, 20%, 30% and 40 %

And the fibers were arranged in the lateral direction and in the longitudinal direction as shown in figure (2).

The sample used to measure the thermal conductivity using the Lee's Disk method is in the form of a disk whose thickness (d_s = 0.0035 m) is small relative to its diameter (D = 0.04 m). Using a thin sample means that the system will reach thermal equilibrium more quickly.

The heat transfer (Q) across the thickness of the sample is given by:

$$Q = K \cdot A \cdot \frac{T_2 - T_1}{d_s} \quad (6)$$

And the thermal conductivity can be calculated by using the following equation [6].

$$K \cdot \left[\frac{T_2 - T_1}{d_s}\right] = e \cdot \left[T_1 + \frac{2}{r} \cdot \left(d_1 + \frac{1}{2} d_s\right) \cdot T_1 + \frac{1}{r} \cdot d_s \cdot T_2\right] \quad (7)$$

And the value of (e) can be calculated from the following equation [7].

$$I \cdot V = \pi \cdot r^2 \cdot e \cdot \left(T_1 + T_3\right) + 2 \cdot \pi \cdot r \cdot e \cdot \left[d_1 \cdot T_1 + \frac{1}{2} \cdot d_s \left(T_1 + T_2\right) + d_2 \cdot T_2 + d_3 \cdot T_3\right] \quad (8)$$

Element Selected and Mesh generation

For the finite element analysis of thermal characteristics of a composite specimen, the ANSYS 8 package program is adopted. This program has very efficient capabilities to perform finite element analysis of most engineering problems. From the ANSYS 8 element library the solid 70 (3-D thermal solid) element is adopted to perform this type of analysis. This element has a three-dimensional thermal conductivity capability. The element has eight nodes with single degree of freedom, temperature, at each node. The element is applicable to a three-dimensional, steady-state or transient thermal analysis. The geometry, node locations, and coordinate system for this element are shown in figure (3) [11].

As for the mesh generation of the composite specimen see figure (4), the specimens are treated as a three-dimensional problem with different glass fiber volume fraction and different orientation.

Results and Discussions

The composite specimens were made from glass fiber-epoxy matrix composite with different fiber volume fraction and different fiber orientation and the study was made experimentally and by using finite element technique.

The thermal constants of the composite specimens at different volume fraction and for both directions are illustrated in table (1 and 2) which are based on thermal characteristics of the constituents (fiber and matrix) of the composite materials [12].

Figure (5) shows the temperature distribution contours of the composite specimens under a given case studies of glass fiber volume fraction and for two types of fiber arrangement parallel to heat source.

Figures (6 and 7) show the relationship between wall surface temperature (T_1 and T_2) and the time for different fiber volume fractions (V_f = 10 %, 20 %, 30 % and 40 %) and for experimental work and finite element analysis when the fiber arranged in the lateral direction and in the longitudinal direction to heat source, respectively.

It is clear from these figures that the wall surface temperature increases in nonlinear relationship with time required to reach equilibrium temperatures. And the results of (T_1 and T_2) for finite element method are closer than the results of (T_1 and T_2) of the experimental work.

Figures (8,a and b) show the relationship between the wall surface temperature (T_1 and T_2) and fiber volume fraction in both directions (lateral and longitudinal).

It is clear from figure (8, a) that the wall surface temperature (T_1 and T_2)

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increase in linear relationship with fiber volume fraction. While it is clear from figure (8, b) that the wall surface temperature (T_1 and T_2) increase in nonlinear relationship with fiber volume fraction. This difference is due to fiber orientation.

It was found that the maximum difference between the results of finite element method and experimental work for (T_1) was (2.8 °c) at (V_f = 10 %) while the minimum difference for (T_1) was (3 °c) at (V_f = 40 %) when the fibers are arranged in the lateral direction.

Figures (9,a and b) show the relationship between the thermal conductivity and the fiber volume fraction when the fibers are arranged in the lateral direction and longitudinal direction, respectively.

It is clear from these figures that the thermal conductivity increases with increasing volume fraction but the rate of increase for longitudinal direction is more than that for lateral direction for both experimental work and finite element analysis.

Also it was found that the max. difference of thermal conductivity between the theoretical value and experimental value was (7 %) at (V_f = 10 %) while the minimum value was (3.5 %) at (V_f = 40 %) when the fibers are arranged in the longitudinal direction.

Figure (10) shows the relationship between thermal conductivity and type of arrangement of fibers for theoretical analysis and experimental work.

It is clear that the thermal conductivity for the specimens in which the fibers are arranged in longitudinal direction is more than that when the fibers are arranged in lateral direction for both experimental and theoretical analysis.

Also it was found that the maximum difference in the thermal conductivity between longitudinal direction and thermal and lateral direction was (57 %) at (V_f = 40 %) while the minimum value was (32 %) at (V_f = 10 %) for experimental work.

Conclusions

The main conclusions of the thermal characteristics of the composite specimens using experimental work and finite element analysis are:

(1-) Thermal conductivity increases with fiber volume fraction in different rates (slope). For longitudinal direction is higher than for lateral direction.

(2-) Maximum value of experimental thermal conductivity was (0.611 W/m.°c) at (V_f = 40 %) when the fibers are arranged in the longitudinal direction. But the minimum value of the thermal conductivity was (0.195 W/m.°c) at (V_f = 10 %) when the fibers are arranged in lateral direction.

(3-) Maximum difference between the theoretical and experimental results of the thermal conductivity was (7 %) at (V_f = 10 %) for lateral arrangement of fibers, while the minimum difference was (3.5 %) at (V_f = 40 %) for longitudinal arrangement of fibers.

(4-) The maximum difference between the experimental thermal conductivity of the composite specimen when the fibers are arranged in the lateral direction to the heat source was (57 %) at (V_f = 40 %) and (32 %) at (V_f = 10 %).

(5-) Final equilibrium surface temperatures (T_1) and (T_2) of the composite specimen increase in linear relationship with fiber volume fraction when the fibers are arranged in lateral direction to the heat source. While it increases in nonlinear relationship with fiber volume fraction when the fibers are arranged in the longitudinal direction to heat source.

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Table (1): Thermal Properties of the Composite Specimen when the Fibers are Arranged in the Lateral (Perpendicular) Direction to the Heat Source [12].

	Fiber Volume Fraction			
	10 %	20 %	30 %	40 %
ρ (k_g/m^3)	1383	1515	1649	1782
K_x (W/m. $^\circ$c)	0.301	0.412	0.523	0.634
K_y (W/m. $^\circ$c)	0.301	0.412	0.523	0.634
K_z (W/m. $^\circ$c)	0.21	0.23	0.255	0.2889
α_x (1/°c)	114.5e-6	104e-6	92.67e-6	80.46e-6
α_y (1/c°)	114.5e-6	104e-6	92.67e-6	80.46e-6
α_z (1/°c)	26.87e-6	16.15e-6	11.83e-6	9.51e-6
C_p (J/k_g.°c)	1020	995	972	954

Table (2): Thermal Properties of the Composite Specimen when the Fibers are Arranged in the Longitudinal (Parallel) Direction to the Heat Source [12].

	Fiber Volume Fraction			
	10 %	20 %	30 %	40 %
ρ (k_g/m^3)	1383	1515	1649	1782
K_x (W/m.$^\circ$c)	0.21	0.23	0.255	0.2889

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K_y (W/m.°c)	0.21	0.23	0.255	0.2889
K_z (W/m.°c)	0.301	0.412	0.523	0.634
α_x (1/°c)	26.87e-6	16.15e-6	11.83e-6	9.51e-6
α_y (1/°c)	26.87e-6	16.15e-6	11.83e-6	9.51e-6
α_z (1/°c)	114.5e-6	104e-6	92.67e-6	80.46e-6
C_p (J/kg.°c)	1020	995	972	954

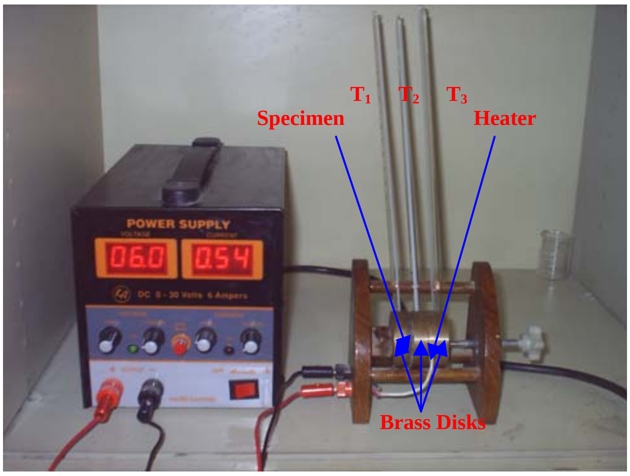
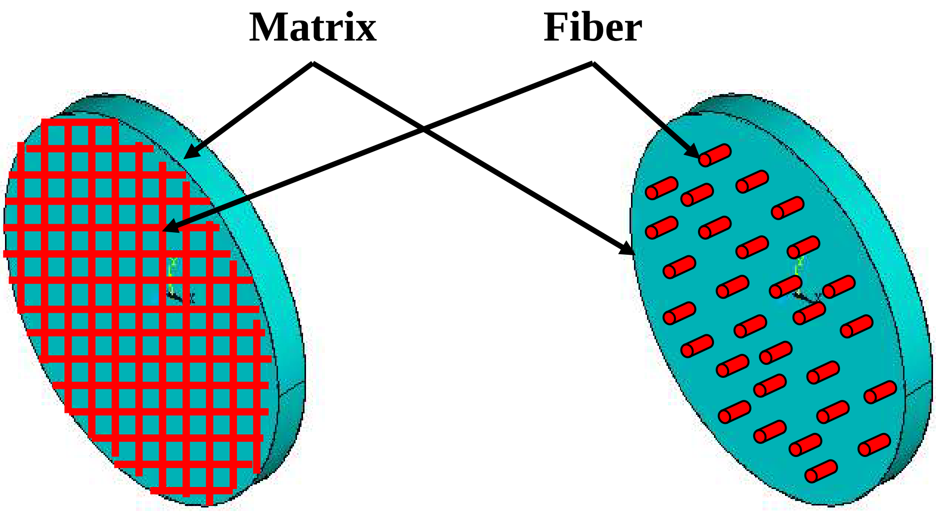


Figure (1): Test Apparatus with Specimens Test.



(a) Lateral (Woven) Arrangement (Perpendicular to heat source)

(b) Longitudinal (Unidirectional) Arrangement (Parallel to heat source)

Figure (2): Fiber Arrangement in the Specimen.

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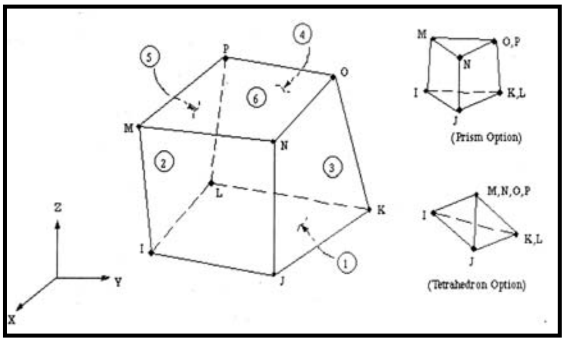

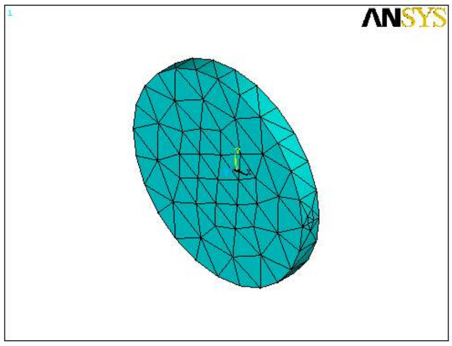

Figure (3): 3-Dimensional Element (Thermal Solid 70) [11]

Figure (4): Mesh Generation of the Composite Specimen.

(a) **(b)**

Figure (5): Temperature Distribution Contours for the Test Specimens at:

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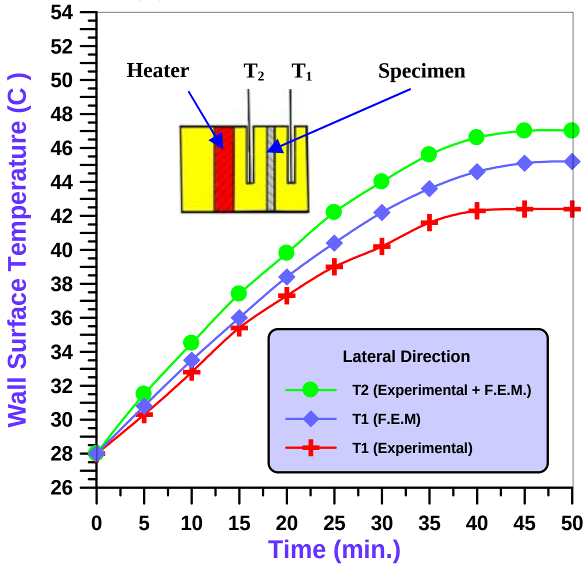
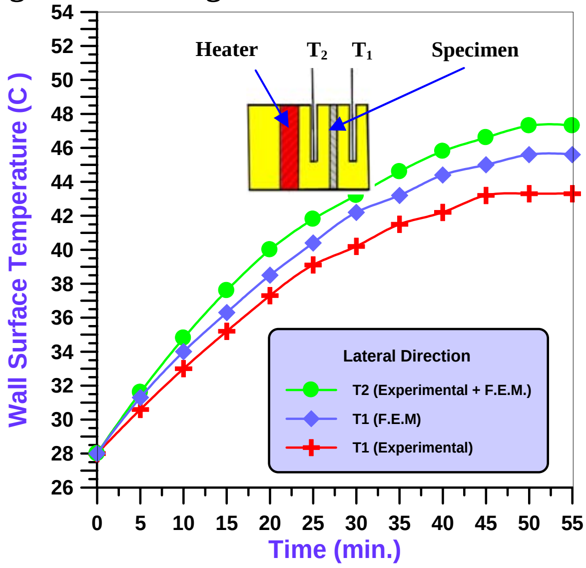
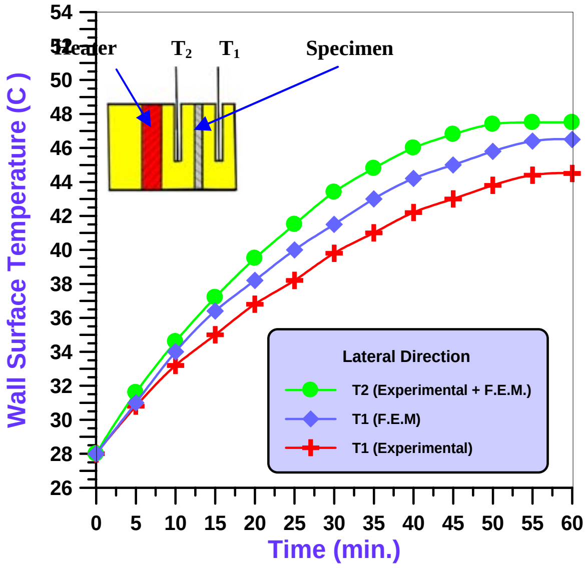
(a) V_f = 30 % and the Fiber arranged in the lateral Direction.
(b) V_f = 30 % and the Fiber arranged in the Longitudinal Direction.



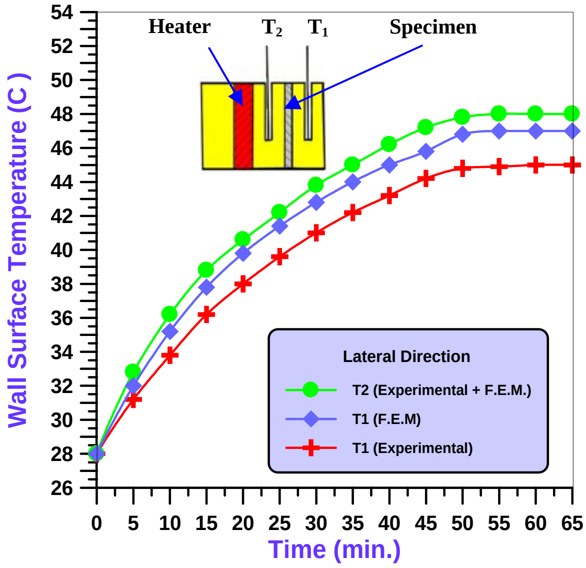
(a) V_f = 10 %



(b) V_f = 20 %



(c) V_f = 30 %



(d) V_f = 40 %

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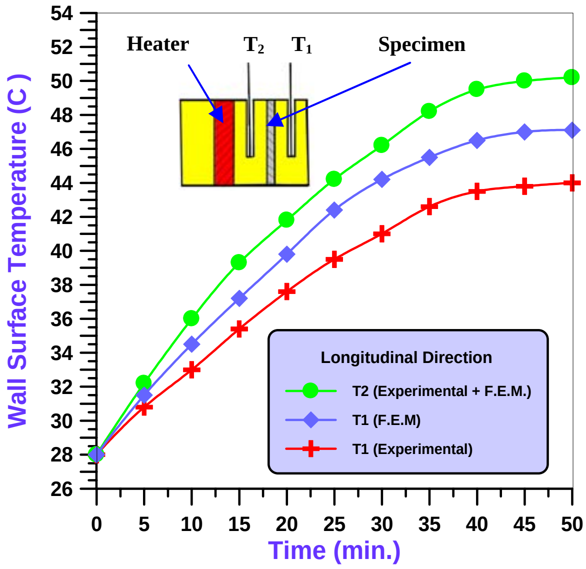
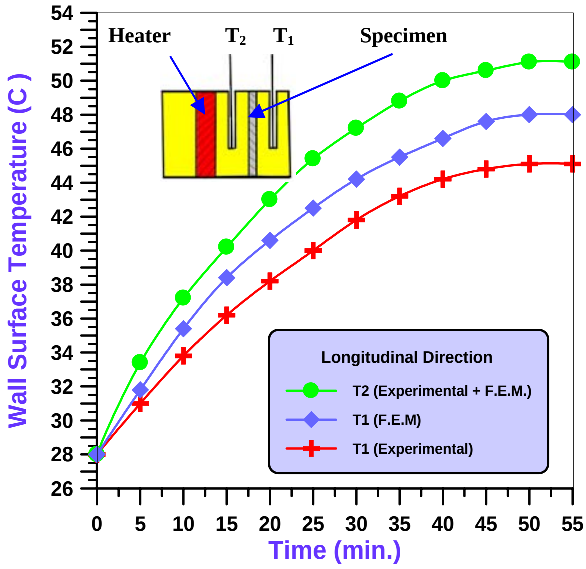
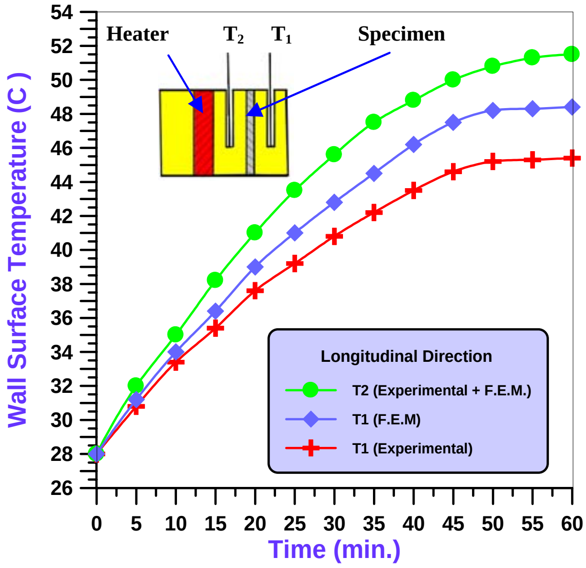
Figure (6): Relationship Between Wall Surface Temperature and the Time When the Fiber arranged in the Lateral Direction at Different Volume Fibers Fraction.



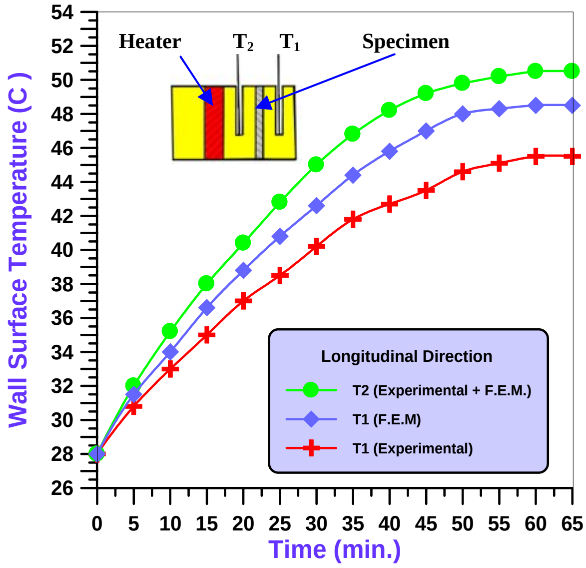
(a) V_f = 10 %



(b) V_f = 20 %



(c) V_f = 30 %



(d) V_f = 40 %

Figure (7): Relationship Between Wall Surface Temperature and the Time When the Fiber arranged in the Longitudinal Direction at Different Volume Fibers Fraction.

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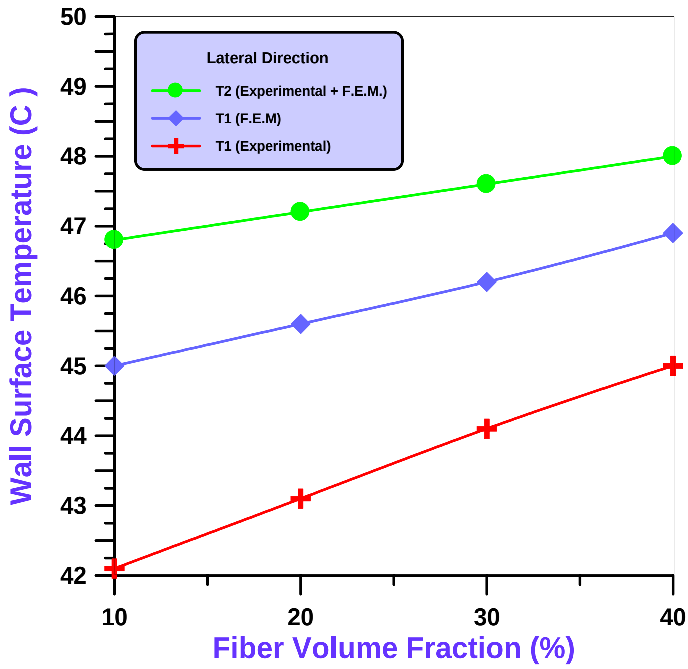
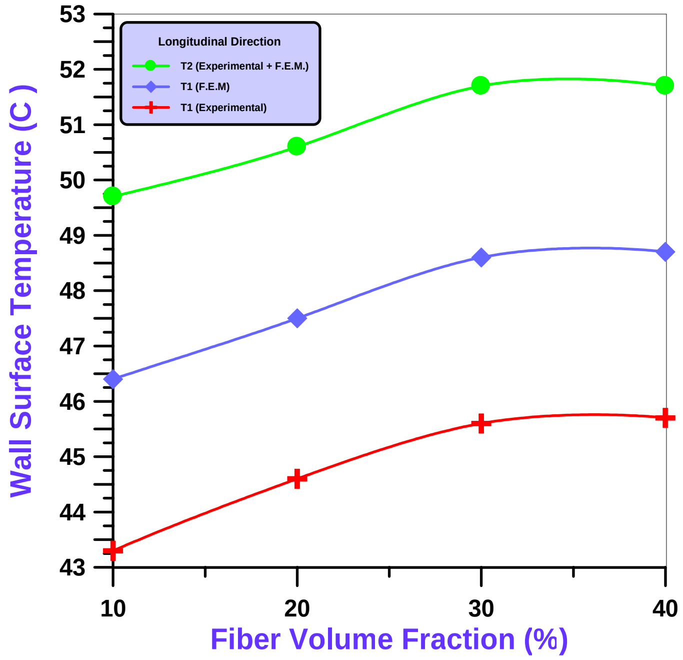


(a) Lateral Direction



(b) Longitudinal Direction

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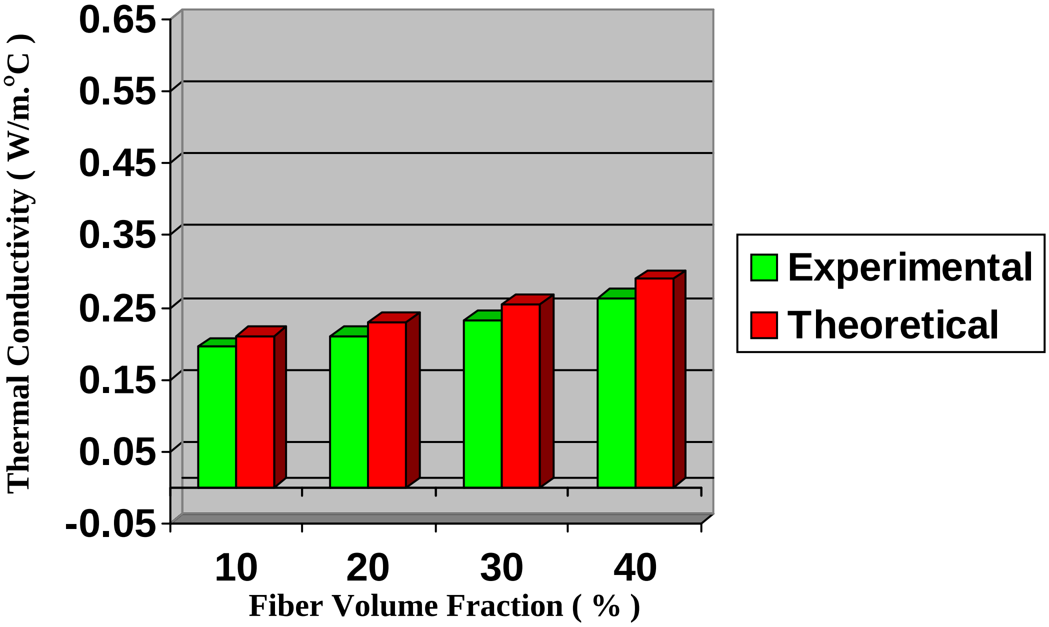
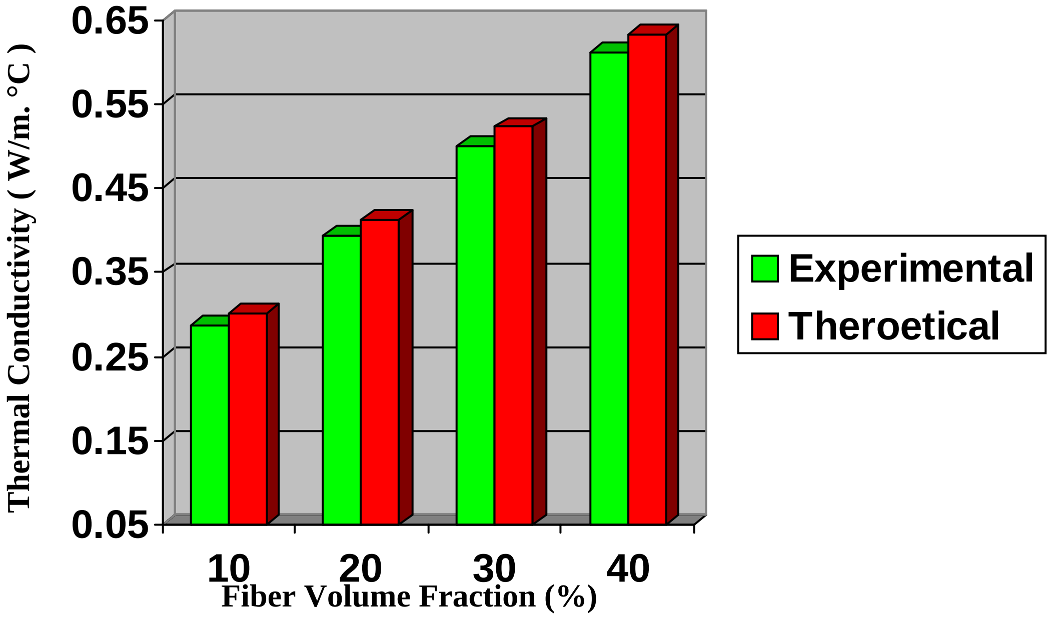
Figure (8): Relationship Between the Wall Surface Temperature and the Fiber Volume Fraction When the Fiber Arranged in both Direction.



(a) Lateral Direction



(b) Longitudinal Direction

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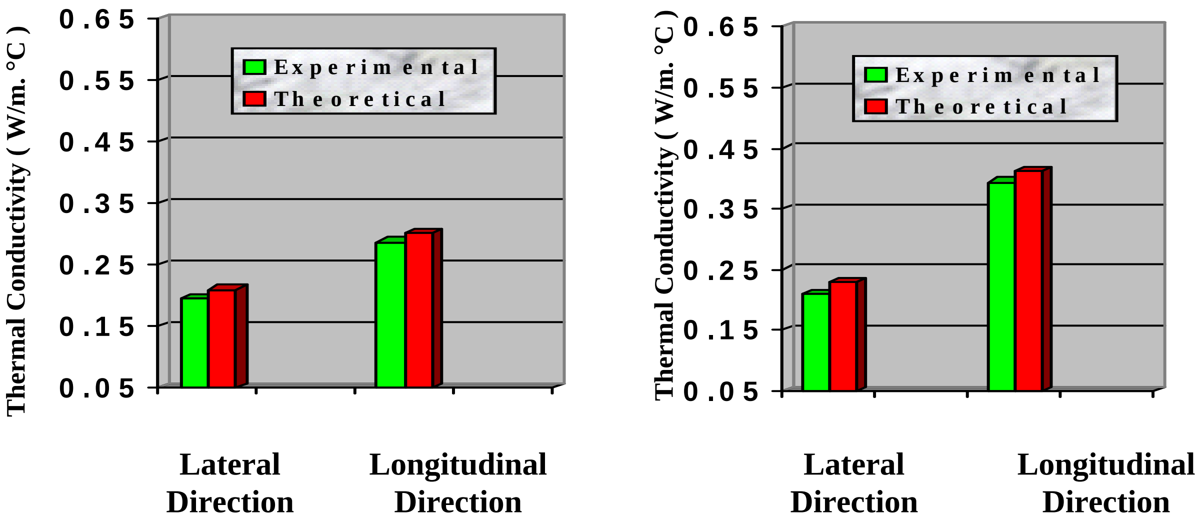
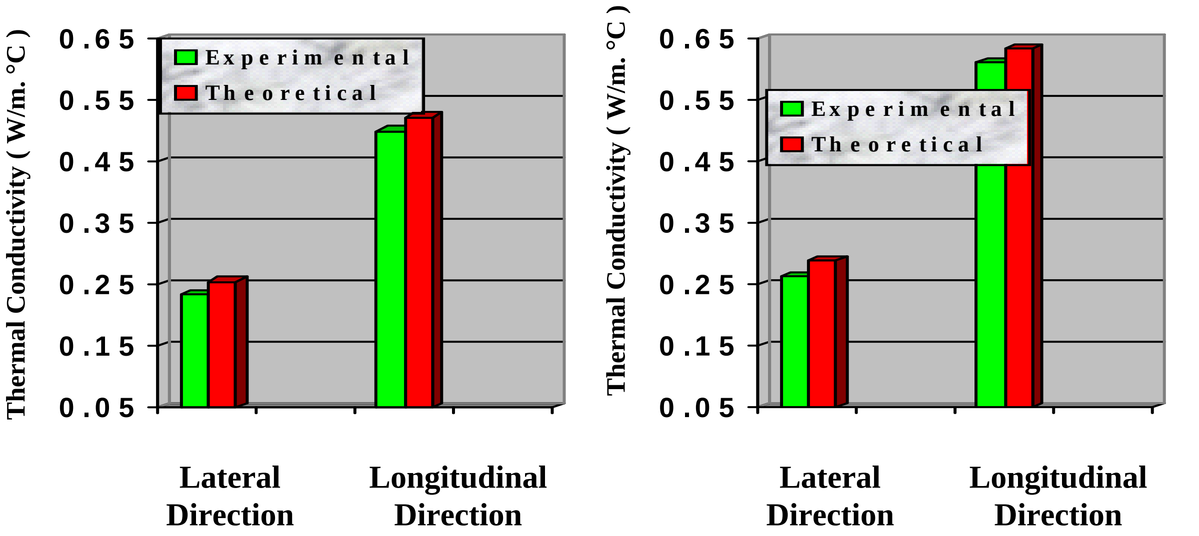
Figure (9): Relationship Between the Thermal Conductivity and Fiber Volume Fraction in both Direction.



(a) $V_f = 10$ % (b) $V_f = 20$ %



(c) $V_f = 30$ % (d) $V_f = 40$ %

Figure (10): Relationship Between the Thermal Conductivity and Type of Fiber Arranged at Different Fiber Volume Fraction.

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