Percolation Phenomena For New Magnetic Composites And Tim Nanocomposites Materials

Ahmed THABET

Nanotechnology Research Centre, Faculty of Energy Engineering, Aswan University, 81528 Aswan, Egypt

athm@aswu.edu.eg

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Abstract. *This paper presents a theoretical investigation in order to obtain new composite and nanocomposite magnetic industrial materials. The effective conductivity and thermal effective conductivity have been predicted by adding various types and percentages of conductive particles (Al_2O_3, MgO, ZnO, Graphite etc.) to the main matrices of Epoxy, Iron and Silicon for formulating new composite and nanocomposite industrial materials. The characterization of effective conductivity of new polymeric composites has been investigated with various applied forces, inclusion types and their concentrations. In addition, the effect of inclusion types and their concentrations on the effective thermal conductivities of thermal interface nanocomposite industrial materials has been explained and discussed.*

Keywords

Composites, conductivity, magnetic, nanocomposites, percolation, thermal interface materials.

1. Introduction

Percolation theory is a general model for the description of statistical processes and it has become a common method in the investigations of pre-breakdown processes in solids. Also, nanoparticle size can formulate new composite and thermal interface nanocomposite industrial materials by nanotechnology science that made huge enhancement in the magnetic properties of the composite materials which will affect the performance of the industrial applications. Polymeric composites made with particles such as conductive, ferroelectric or metal particles are some of the important engineering materials used for resistors, switching devices, conducting pastes, components in the xerographic machine and separators in polymer electrolyte membrane fuel cells. Percolation theory predicts that various characteristics of a percolating system are related to the probability of occupation of sites within the percolation lattice, by power law relations, and that the exponents of these power relations are universal regardless of the system. The previous work has shown that percolation theory is an appropriate tool for understanding finite size effects in 3D cluster films [1], [2], [3], [4], [5]. The analytical studied models have been enabled to optimize the structure and arrangement of the polymeric composite materials. Based on fundamental physical principles, it can quantify the effective conductivity of the suggested polymeric industrial composites. Such models will enable one to optimize the structure and arrangement of the material [6], [7]. The electrical characteristics of electrical conductive adhesives are close to properties of a filler. Metal particles are widely used as conductive fillers in common electrical conductive adhesives formulations due to their lower resistivity and good process. The characteristic of electrical conductivity of a composite by volume fraction of particles has already been studied by previous researchers [8], [9], [10], [11], [12]. In fact, the magnetic or dielectric loss in insulating materials can be used to dissipate the electromagnetic energy in the EM-absorbers, and the combination of high electrical conductivity and high permeability is effective to shield the EM waves. However, the high-content metal granular composite material may show metallic electrical conduction due to the percolation effect of embedded particles [13], [14], [15], [16], [17], [18].

Composite and nanocomposite industrial materials are being explored as shielding materials for electromagnetic compatibility (EMC) and electromagnetic interference (EMI) applications. In these systems, in addition to particle/matrix conductivities and volume loading of the particles in the matrix, the randomness of distribution, polydispersivity as well as interfacial thermal resistance plays a role in determining the effective conductivity of the composite material [19], [20], [21], [22], [23]. Predictive modelling based on fundamental physical principles is critical to developing new TIMs, since it can be used to quantify the effect of particle volume fractions and arrangements on the effective thermal conductivity. Such models will enable one to optimize the structure and arrangement of the material [24], [25], [26], [27]. Thermal interface materials (TIMs) have been widely adopted to minimize the thermal interface resistance between the rough surfaces of heat generating components and the heat dissipation devices. Most of TIMs are made of polymers with thermally conductive particles distributed inside to enhance the thermal conductivity. There are various kinds of approaches to calculate the effective thermal conductivity of the two-phase composite systems. The effective thermal conductivity of TIMs is affected by many factors, such as the thermal conductivity of filler particles, the thermal conductivity of the matrix, the volume fraction of filler particles, and the particle size distribution of filler particles and so on [28], [29], [30], [31], [32], [33]. For this paper we have used recent analytical models for estimating effective conductivity of new suggested polymeric composite industrial materials that have been enhanced in their characterization response with respect to particle types and their concentrations and so forces applied to these materials. A detailed analysis of the nanostructure characteristics that influence the effective thermal conductivity of TIMs is included in the goals of this paper. Thus, their characterization response with respect to types and concentrations of selected nanoparticles has been enhanced.

2. Theoretical Models

2.1. Polymetric Composites

Percolation theory, the objective of which is to characterize the connectivity properties in random geometries and to explore them with respect to physical processes consideration, the percolation types is forming continuous network of particles in conductive polymeric composite which is completely satisfied. In the technological applications, it can be predicted conductivity of polymeric composite specimen considering a spherical particle that subjected in classical mixing rules of particles with main matrices for determining the effective conductivity of composites if the inclusion phase is dispersed in the matrix phase random distribution [6], it will be as follows:

$$\sigma = \sigma_0 \cdot (x - x_c)^t, \qquad (1)$$

where σ_0 is the proportionality constant, x is the volume concentration of conducting phase, x_c is the critical concentration of conducting phase, t is the exponential factor for percolation and tunnelling percolation.

Also, there is proposed an applied force on polymeric composite material that has been used to formulate theoretical models for predicting an effective conductivity of polymeric composites; it corresponds to average sensibility [7].

$$\sigma = \frac{h}{R \cdot A} = \frac{4 \cdot h}{\pi \cdot D^2 \cdot R_0 \cdot F^{-\alpha}}, \qquad (2)$$

where h is the height of polymeric composite specimen, D is the diameter of polymeric composite specimen, R_0 is the initial resistance of polymeric composite specimen, α is the volume of particles inside the matrix. However, the variation of electric resistance due to mechanical load applied on the sample's special area of contact between particles increases and cuts the distances between particles located in parallel rows. So, Fig. 1 shows a schematic layout of the polymeric composite specimen with different volume fractions of particles.

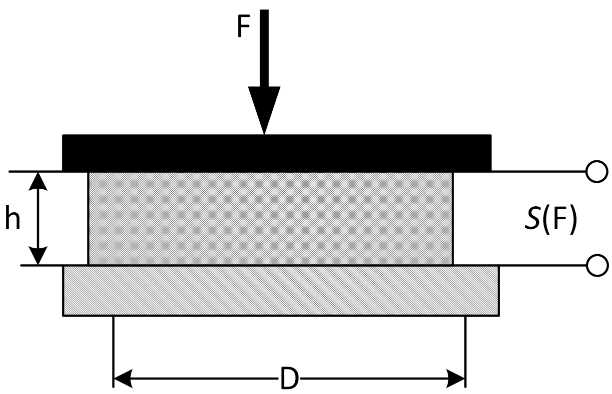

Fig. 1: Schematic layout for polymeric composite specimen with particles [7].

However, the conducting elements are in geometric contact, the theory predicts that the critical exponent t is less than two and the process is called percolation; percolation refers to the flow of current through random resistor networks. When the conducting elements are not in geometric contact, the inter-particle tunnelling is dominant. Thus, this research studies the percolation phenomenon in polymeric composites with various cost-fewer particles and configuration analytical model parameters.

2.2. Thermal Interface Materials (TIM)

This paper also focuses on applied theoretical models for estimating thermal conductivity of nanocomposite industrial materials consisting of nano-sized nanocrystalline particles embedded in different matrices.

Based on the following mathematical model [25], [26], [27], that has been used for predicting an effective thermal conductivity of thermal interface materials nanocomposites; Fig. 2 shows the cylindrical region between two spherical particles. There is proposed a point of contact between two particles in a thermal flux density across the surface of particles in random arrangement of the matrix.

Thus, there can be predicted thermal conductance between spherical particles without distortion with respect to the volume fraction of particles in the matrix ($\mathbf{\Phi}$), the thermal conductivity of particles (k_p), the thermal conductivity of matrix (k_m), radii of two local sphere surfaces (R_1 and R_2), and factors of the ability of forming continuous network of fillers in the matrix ($\mathbf{C_1}$, and $\mathbf{C_2}$) and via (0:1) as follows [26]:

$$K_{eff} = \left[\frac{5.2933}{2\cdot\pi\cdot k_p\cdot R_1} + \frac{1}{\pi\cdot k_m\cdot aln\left(1+\frac{R^2}{ha}\right)} + \frac{5.2933}{2\cdot\pi\cdot k_p\cdot R_2}\right]^{-1}, \tag{3}$$

where

$$R = \alpha\cdot a, \tag{4a}$$

$$a = \frac{2\cdot R_1\cdot R_2}{R_1+R_2}, \tag{4b}$$

$$\alpha = 5.0539\cdot\varphi^2 - 7.3994\cdot\varphi + 3.203. \tag{4c}$$

$$\log K_{eff} = \varphi\cdot\mathbf{C_2}\cdot\log k_p + (1-\varphi)\cdot\log(\mathbf{C_1}\cdot k_m). \tag{5}$$

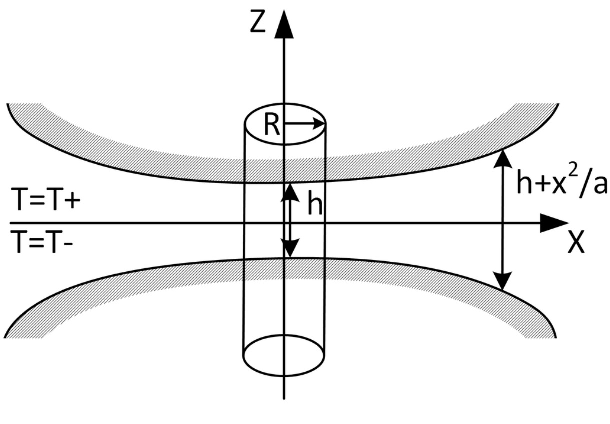

Fig. 2: Schematic diagram for cylindrical region between two spherical particles [26].

The effective thermal conductivity K_{eff} of nanoparticles/nonmagnetic matrix composite can then be calculated using the above theories based on their types and concentrations. Considering, influences of the ability of forming continuous network of fillers in base matrices will be completely satisfied, then; the performance of effective thermal conductivities for various suggested new magnetic nanocomposites has been shown in this research.

Tab. 1: Electric and thermal properties of suggested particles and industrial materials.

Materials	Conductivity ($\mathbf{S\cdot m^{-1}}$)	Thermal Conductivity K ($\mathbf{W\cdot(m\cdot K)^{-1}}$)
Graphite	$3\cdot10^5$	200
Fe	10^7	80.2
ZnO	$1.69\cdot10^7$	21
MgO	10^8	40
Al_2O_3	10^{14}	35
Si	$1.56\cdot10^{-3}$	148
Epoxy	10^{-12}	1.04
Glass	10^{-15}	1.2
PTFE	10^{-16}	0.25

3. Suggested Materials

Polymeric composites made a huge enhancement in the electric, dielectric and electromagnetic properties which will affect the performance of the industrial applications at a configuration sample of $d = h = 0.01$ m. All selected nanoparticles, in this research, have been spherically shaped and sized as 10 nm diameter for every grain size.

The main electrical and thermal description properties of the usage of particles have been depicted in Tab. 1; these particles have been used for enhancing electric properties of polymeric composite and nanocomposite industrial materials.

4. Results and Discussions

This research has used recent theoretical models for estimating effective conductivity and effective thermal conductivity of new suggested nanocomposite thermal interface industrial materials. The following results have been reported for new suggested composite and nanocomposite industrial materials that have been enhanced in their characterization response with respect to particle types and their concentrations and so forces applied to new suggested materials.

4.1. Effect of Percolation Phenomena in New Polymeric Composites

Figure 3 shows enhancing the effective conductivity of Epoxy Polymeric composite materials by adding various percentages of iron particles in random distributions to Epoxy composites. However, the effective conductivity of Iron/Epoxy polymeric composite materials decreased gradually by increasing the percolation factor of the polymeric composite materials. As shown in Fig. 4, Al_2O_3 particles have higher effectiveness for increasing the effective conductivity of Epoxy Polymeric composite materials than Iron particles. Figure 5

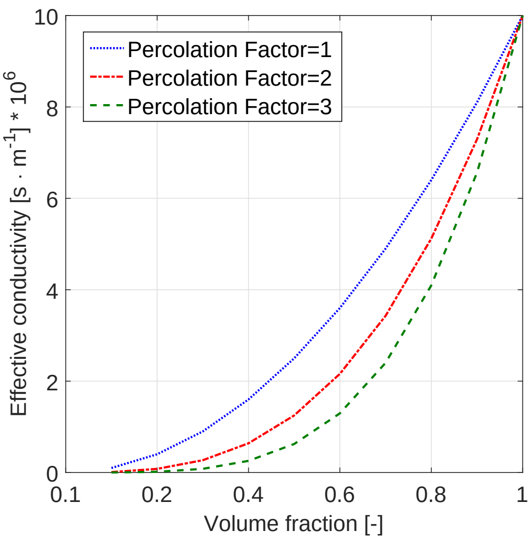

Fig. 3: Effective conductivity of Iron/Epoxy polymeric composites.

shows enhancing the effective conductivity of epoxy polymeric composite materials by adding various percentages of (Graphite, SiO_2, and MgO) particles in random distributions at a certain percolation factor 1.8. It is cleared that SiO_2 particles have increased the effective conductivity of Epoxy Polymeric composite materials higher than MgO and Graphite particles.

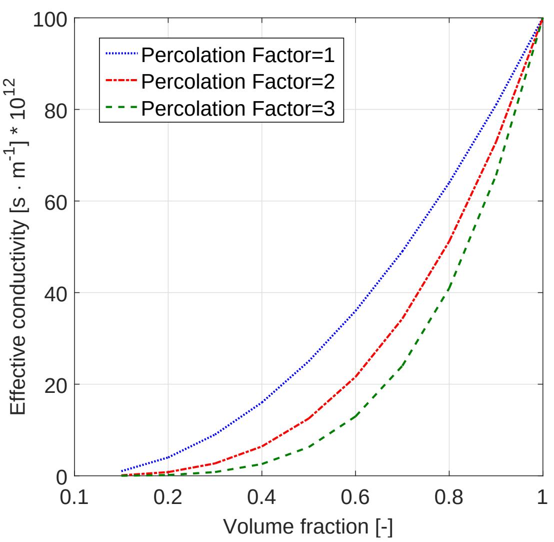

Fig. 4: Effective conductivity of Al_2O_3/Epoxy polymeric composites.

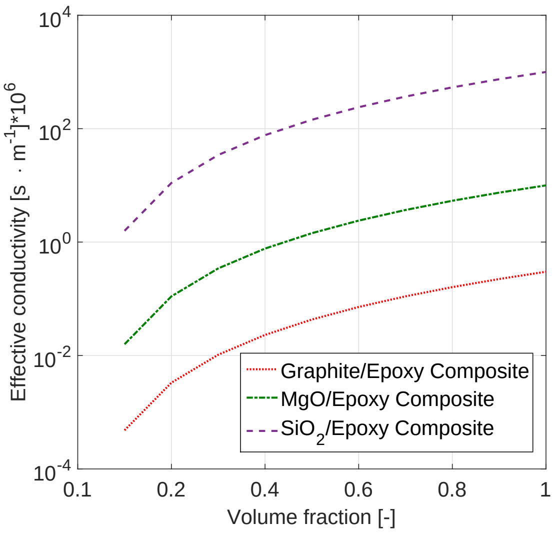

Fig. 5: Effective conductivity of Epoxy Polymeric composites.

4.2. Effect of Applied Forces on Polymeric Composites

Figure 6 shows increasing the effective conductivity of Epoxy composite materials by adding various percentages of SiO_2 particles in random distributions, also; the effective conductivity of SiO_2/Epoxy composite materials increased gradually by increasing applied force on the composite material specimens. The Effectiveness of applied forces on the effective conductivity of SiO_2/Epoxy composite materials appears whenever the percentage/s of SiO_2 increased in the polymeric composites.

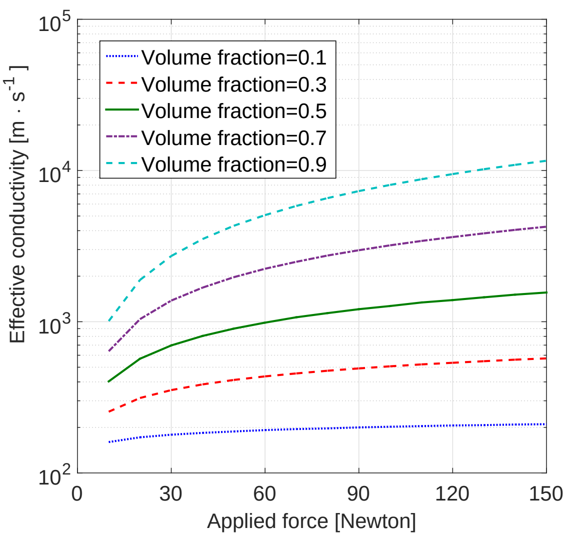

Fig. 6: Effective conductivity of SiO_2/Epoxy composites.

4.3. Effect of Nanoparticles on Magnetic TIMs

Figure 7 shows the effective thermal conductivity of TIMs iron nanocomposites that increased by adding various percentages of silicon and graphite in random distributions.

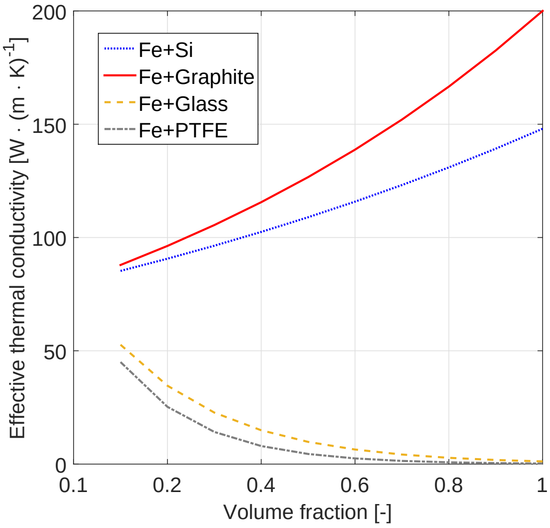

Fig. 7: Effective thermal conductivity of TIMs Iron/Polymer nanocomposites with various nanoparticles.

It is noticed that the effective thermal conductivity of TIMs iron nanocomposites decreased by adding various percentages of glass and PTFE in random distribution, but graphite nanoparticles have higher effectiveness for increasing thermal conductivity of nanocomposites in iron matrix with respect to silicon. However, PTFE has higher effectiveness for decreasing thermal conductivity of nanocomposites in iron matrix with respect to Glass nanoparticles.

Figure 8 shows the effective thermal conductivity of TIMs iron nanocomposite that decreased by adding various percentages of nanoparticles of oxides (Al_2O_3, ZnO, MgO) in random distributions to iron matrix material. But, MgO nanoparticles have higher ability for increasing thermal conductivity of nanocomposites in iron matrix with respects to Al_2O_3 and ZnO nanoparticles.

4.4. Effect of Nanoparticles on Polymeric TIMs

Figure 9 shows the effective thermal conductivity of TIMs Silicon nanocomposite materials that increased by adding various percentages of graphite nanoparticles in random distributions to iron matrix material. However, the effective thermal conductivity of TIMs Silicon nanocomposite materials

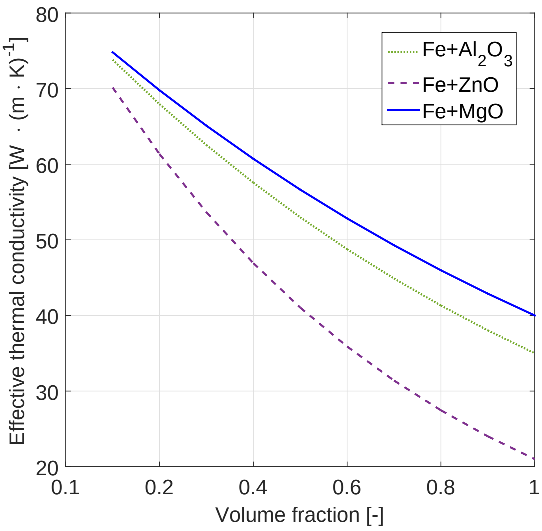

Fig. 8: Effective thermal conductivity of TIMs Iron/Oxides nanocomposites with various nanoparticles.

decreased by adding various percentages of Iron and Graphite nanoparticles in by random distributions to iron matrix material. It is cleared that Graphite nanoparticles are more effective for decreasing thermal conductivity of nanocomposites in silicon matrix with respect to Iron nanoparticles.

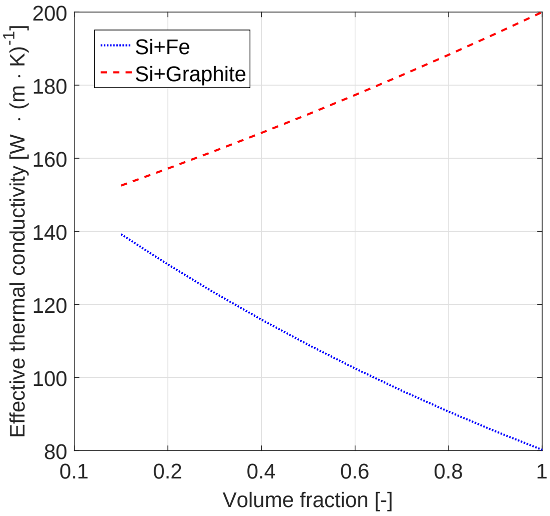

Fig. 9: Effective thermal conductivity of TIMs Silicon/Metal nanocomposites with various nanoparticles.

Figure 10 shows the effective thermal conductivity of TIMs Silicon nanocomposite materials that decreased by adding various percentages of nanoparticles of oxides (Al_2O_3, ZnO, MgO) in random distributions to silicon matrix material. However, MgO nanoparticles are more effective for decreasing thermal conductivity of nanocomposites in iron matrix with respect to Al_2O_3, and ZnO nanoparticles. Figure 11 shows the effective thermal conductivity of TIMs Epoxy nanocom-

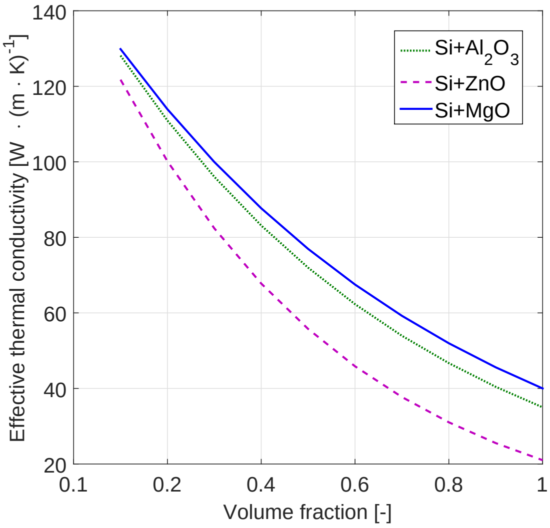

Fig. 10: Effective thermal conductivity of TIMs Silicon/Oxides nanocomposites with various nanoparticles.

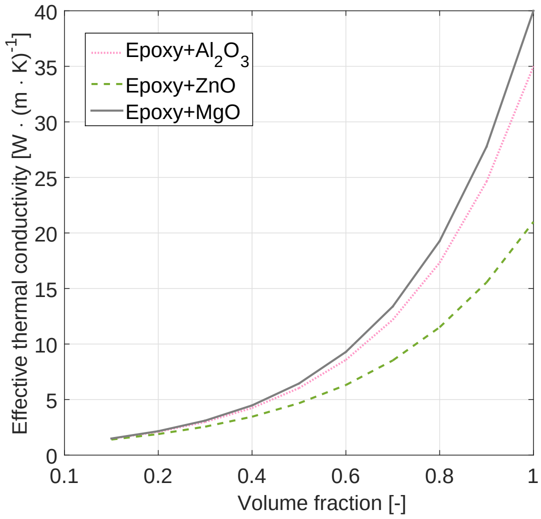

Fig. 12: Effective thermal conductivity of TIMs Epoxy/Oxide nanocomposites with various nanoparticles.

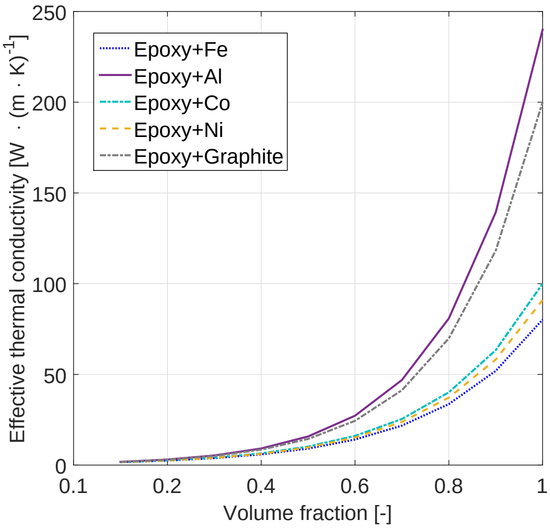

Fig. 11: Effective thermal conductivity of TIMs Epoxy/Metal nanocomposites with various nanoparticles.

posite materials that increased by adding various percentages of Aluminum, iron, silicon, graphite, cobalt, and nickel nanoparticles in random distributions to Epoxy matrix material. Whatever, iron nanoparticles are more effective for decreasing thermal conductivity of nanocomposites in Epoxy matrix with respect to other nanoparticles. Figure 12 shows the effective thermal conductivity of TIMs Epoxy nanocomposite materials that increased by adding various percentages of nanoparticles of oxides (Al_2O_3, ZnO, MgO) in random distributions to Epoxy matrix material. Note that MgO nanoparticles are more effective in Epoxy matrix for increasing thermal conductivity of nanocomposites with respect to Al_2O_3, and ZnO nanoparticles. Figure 13 shows the effective thermal conductivity of TIMs Epoxy nanocomposite materials that increased by adding various percentages of glass nanoparticles in random distributions to Epoxy matrix material. However, the effective thermal conductivity of TIMs Epoxy nanocomposite materials decreased by adding various percentages of PTFE nanoparticles in random distributions to Epoxy matrix material.

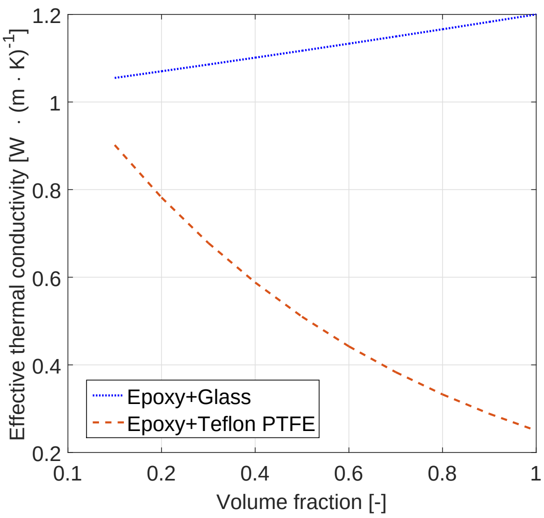

Fig. 13: Effective thermal conductivity of Epoxy/Insulator nanocomposites.

5. Conclusions

Percolation tunnelling factor is an important factor for indication of the flow of current through random resistor networks, especially the effective conductivity of polymeric composites. Compressive forces applied to the polymeric composite material specimens enhance the effective conductivity of polymeric composites materials. The effective conductivity and thermal conductivity of industrial polymeric composite materials can be controlled by using various conductive types and percentages of particles in random distributions, which depends on the types and percentages of costfewer particles. Al_2O_3 particles are more effective for increasing effective conductivity of the composite materials with respect to Iron, SiO_2, and MgO particles.

As a predicting guide for industry manufactures, it can be obvious that graphite nanoparticles are more effective for decreasing thermal conductivity of nanocomposites with respect to silicon nanoparticles; however, MgO nanoparticles are more effective for increasing thermal conductivity of nanocomposites with respect to Al_2O_3, and ZnO nanoparticles. For Epoxy TIMs nanocomposites, it can be obvious that iron nanoparticles are more effective for decreasing thermal conductivity of nanocomposites with respect to other studied nanoparticles; however, MgO nanoparticles are more effective for increasing thermal conductivity of nanocomposites with respect to Al_2O_3, and ZnO nanoparticles.

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About Authors

Ahmed THABET was born in Aswan, Egypt in 1974. He received the B.Sc. (FEE) Electrical Engineering degree in 1997 and M.Sc. (FEE) Electrical Engineering degree in 2002 both from Faculty of Energy Engineering, Aswan, Egypt. Ph.D. degree had been received in Electrical Engineering in 2006 from El-Minia University, Minia, Egypt. He joined with Electrical Power Engineering Group of Faculty of Energy Engineering in Aswan University as a Demonstrator at July 1999, until; he held Associate Professor Position at October 2011 up to date. His research interests lie in the areas of analysis and developing electrical engineering models and applications, investigating novel nano-technology materials via addition nano-scale particles and additives for usage in industrial branch, electromagnetic materials, electroluminescence and the relationship with electrical and thermal ageing of industrial polymers. On 2009, he had been a Principle Investigator of a funded project from Science and Technology development Fund "STDF" for developing industrial materials of ac and dc applications by nano-technology techniques. He has been established first Nano-Technology Research Centre in the Upper Egypt.