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ORIGINAL ARTICLE

Hybrid nanofluid based on CuO nanoparticles and single-walled Carbon nanotubes: Optimization, thermal, and electrical properties

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Abstract

The purpose of this study is to use the thermal and electrical conductivities of copper oxide nanoparticles and carbon nanotubes for the preparation of high-performance nanofluids for achieving better heat transfer properties. These nanofluids consist of a water/Ethylene Glycol solution containing single-wall carbon nanotubes (SWCNTs) and copper oxide nanoparticles (CuONPs). The effects of such independent variables as CuONPs and SWCNT concentrations, Ethylene Glycol ratio and solution pH were optimized to enhance the Thermal conductivity by the response surface method. The experimental results revealed that adding small amounts of nanoparticles to water/Ethylene Glycol mixtures would improve the thermal and electrical conductivity of nanofluids. The morphology of the nanoparticles was investigated by Scanning and Transmission Electron Microscopy (SEM & TEM) and Energy-Dispersive X-ray Spectroscopy (EDS). For the first time, the electrical conductivity of nanofluids was investigated by electrical impedance spectroscopy. The combined effects of both nanoparticles and nanotubes on thermal and electrical properties of the base fluid were compared to the influence of each on the same base fluid. The electrical and thermal conductivities could be enhanced by 18000 % and 157 % by addition of 0.41 % wt of SWCNT and 1.15 % wt of CuONPs to a 44:56 Ethylene Glycol-water mixture.

Keywords: *Copper Oxide Nanoparticle; Ethylene Glycol; Hybrid Nanofluids; Single-Wall Carbon Nanotube; Thermal Conductivity.*

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INTRODUCTION

Heat transfer is one of the most important issues in industries such as car manufacturing, aerospace, electronics, heat exchangers, and refrigeration systems [1-3]. The engineering applications of heat transfer are of great importance and interest due to the increasing need to optimize energy consumption in modern industries [4]. Over the past few decades, the energy crisis and environmental issues led many researchers to adopt more economical and environmentally friendly methods to increase heat transfer rates [5].

Commercial fluids such as water, Ethylene Glycol, and various oils are widely used as common coolants in most industrial units [6]. However, the main problem of these fluids is their weak Thermal conductivity and consequently low heat transfer rate. The addition of nanoscale particles to the carrier liquids is an effective method of increasing their Thermal conductivity and heat transfer rate [7]. Many researchers have acknowledged that the dispersion of nanoparticles in conventional fluids can improve their heat transfer properties [8-9].

Moreover, the number of nanoparticles, the particle sizes, the base fluids, the temperature, and ultrasonic waves have interactions together

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and the influence of the value of the Thermal conductivity coefficient [10]. Nanofluids are usually prepared by adding carbon nanotubes or metal (metal oxide) nanoparticles such as copper, alumina, copper oxide, and titanium dioxide to a base fluid [11]. The main reason for choosing nanoparticles rather than larger particles is their greater stability, a higher rate of heat exchange, and lower weight to surface ratio [12-14]. Most studies in this regard have been carried out on nanofluids including a single type of nanoparticles.

In another study, calcium carbide nanoparticles with spherical and cylindrical shapes were added to water and Ethylene Glycol. It was observed that the cylindrical nanoparticles enhance the conductivity coefficient of nanofluids more greatly, but the Thermal conductivity of nanofluids would be affected better by spherical nanoparticles [15].

Recently, researchers have considered the use of hybrid nanofluids by mixing more than one type of nanoparticles with the base fluids. This has further improved the properties of nanofluids, such as heat transfer and pressure drop during the advantages and disadvantages of each nanoparticle [16-17]. In this regard, attempts have been made to prepare nanofluids based on F-MWCNTs-Fe_3O_4 in Ethylene Glycol [18], GO-Ag nanoparticles in water [19], MWCNTs Al_2O_3 nanoparticles in water-Ethylene Glycol [20] and Cu-Al_2O_3 nanoparticles in water [21].

Generally, the Thermal conductivity of nanofluids largely depends on the mass flow rate, nanoparticles volume concentration, and most importantly, the Thermal conductivity of nanoparticles. For constant volume concentrations of the particles and a specific flow rate, heat transfer only depends on the Thermal conductivity of the nanoparticles [21]. The other key feature of the nanofluids is their electrical conductivity. The electrical conductivity is the ability of charged particles to transport the charges toward corresponding electrodes during applying an electric potential to the fluid [15]. Application of copper nanoparticles which possess a Thermal conductivity, 700 times larger than water, and 3000 times higher than engine oil, is considered as an appropriate option for improving the heat transfer rate of water-based nanofluids [22]. Additionally, due to their high surface-to-volume ratio and inherent Thermal conductivity [23], carbon nanotubes are one of the most suitable materials for improving the nanofluid performance in heat transfer. It should be noted that the use of the mentioned nanoparticles not only improves the heat transfer rate of the nanofluid but also increases its electrical conductivity.

On the other hand, excessive nanoparticles can also affect the viscosity and density of nanofluids along with their thermal properties [24]. It is obvious that the viscosity is a critical factor in fluid dynamics because the pumping power and pressure drop are directly related to it. Also, the heat transfer coefficient of the flow depends strongly on the Prandtl and Reynolds numbers, which are vastly influenced by the viscosity [25]. The density of nanoparticle-based fluids also has a direct impact on the pressure drop and pumping power of the system [26]. Higher viscosity and density of nanofluids could be a drawback for the heat transfer performance [25].

Ramachandran *et al.* [27] investigated the effects of volume concentration of particles on density and specific heat capacity of CNC-Ethylene Glycol-water mixture. They stated that the density was higher in fluids with higher concentrations of particles. Alrashed *et al.* [28] (2018) produced nanofluids by dispersion of modified carbon nanotubes in water without adding any surfactants or additives. The results showed that using nanoparticles in a reasonable volume of fraction, has a slight influence on the density, but a great effect on Thermal conductivity and viscosity of studied nanofluids. Selvaraj *et al.* [29] reported that the nanofluids prepared by using BeO nanoparticles possess higher Thermal conductivity and specific surface area compared to water and Poly Ethylene Glycol. Moreover, the viscosity of the nanofluid decreased with the increment of the temperature and increased with an augmentation in nanoparticle concentration.

Concerning economic considerations and the high cost of heat transfer facilities in the industry, using a comprehensive method to examine all effective factors on the heat transfer rate and their importance is vital [30]. One of the techniques for modeling and dealing with these issues is the Response Surface Method (RSM). The RSM has plays an important role in designing, developing, and formulating the new products, and also in improving existing products [31]. The method is able to determine the optimal value of variables with the lowest number of experiments and data. Meanwhile, it presents a mathematical model to be applied in the statistical analyses and modeling processes [32-33].

Thus far, the enhancement of the thermal performance of heat exchangers and cooling systems is an important issue that can lead to an increase in the profitability of many industries. Hence, this study aims to use the unique properties of copper oxide nanoparticles and carbon nanotubes to produce various hybrid nanofluids, evaluate their thermal, electrical, and physical properties, and optimize the parameters affecting the performance of these nanofluids. The Response Surface Method was first applied to optimize the Thermal conductivity of nanofluids as a dependent variable by changing the independent variables such as the Ethylene Glycol-to-water volume ratio, the concentration of CuO nanoparticles, and SWCNT as well as the solution pH. The modeling of these data was performed by the Design-Expert software version 11.0.1. Then, the test fluids were prepared in optimum conditions in the presence and absence of nanoparticles and they were compared in terms of their Thermal conductivity, electrical conductivity, viscosity, and density.

MATERIALS AND DEVICES

Preparation of nanofluids

The nanofluids used in this research consisted of a mixture of water and Ethylene Glycol (Merck product, Germany) as the base fluid and SWCNT (Nanolab, USA) and CuO nanoparticles (US Research, USA) as the nano-additives. To achieve the highest Thermal conductivity (CHT), the effects of the water-to-Ethylene Glycol volume ratio, the concentrations of SWCNT and CuO nanoparticles, and the solution pH were optimized with the RSM. The opted levels of these variables are presented in Table 1. In fact, via this statistical method, an investigation was performed on the simultaneous effects of these four significant variables on the Thermal conductivity of the prepared nanofluids with the lowest number of experiments.

The hybrid nanofluid samples were prepared according to the amounts defined in Table 2. Indeed, under optimum conditions, 10 mL of the nanofluid, 1.15 mg of CuO nanoparticles (1.15 % wt), and 0.41 mg of SWCNT (0.41 % wt) were added to Ethylene Glycol/Water (44:56) mixture. Then, 2 mL of a 0.1 M phosphate buffer solution (pH = 5.0) was added to this dispersion. Next, the nanodispersion was exposed to an ultrasonic processor (Vicenza S.P.A model, 4D, Euronda Co. Italia) with the power of 400 W and frequency of 24 kHz for two hours. This was done to break down the agglomeration of the particles, which led to a stable suspension and a uniform dispersion. The morphology of the nanoparticles was characterized using a Transmission Electron Microscope (TEM, JEOL JEM-2100F) and a Field Emission Scanning Electron Microscope (FESEM, MIRA 3 Tescan).

Property Analysis of the nanofluids

The Thermal conductivity of the nanofluid samples was measured by KD2 Pro thermal properties analyzer (Decagon Devices, USA). In this study, a sensor of the KD2 Pro analyzer was placed in the nanofluids, then CHT of fluid was recorded. All the measurements were performed for at least five times with the accuracy of ±5% and the average values of the measurements were reported.

The electrical conductivity of the nanofluid samples was measured using an EMCEE Model 1152 conductivity meter. The device was able to estimate both temperature (^{o}C) and electric conductivity (µS cm^{-1}) of the sample, simultaneously. The prepared nanofluids were transferred to a measuring cup, and the electrode was dipped in it. Finally, the average values of three independent measurements were presented.

Furthermore, it is well known that the Electrochemical Impedance Spectroscopy (EIS) is a suitable method for studying electrode surface and electrolyte properties [34]. For EIS studies, 5.0 mL of the nanofluid (prepared in an optimal condition) was moved to an electrochemical cell connected to a potentiostat/galvanostat model PGSTAT 110 (EcoChemic, Utrecht, Netherlands), and then 2 mL of a 0.1 M phosphate buffer solution (pH = 5.0) containing 1.0 mM $K_3[Fe(CN)_6]$ as an electrolyte was added to it. The Nyquist plot corresponding to each fluid is depicted in Fig. 4. The viscosity of the prepared nanofluids was determined using a DV1 Digital Viscometer (Brookfield Eng., USA). The densities of the fluids were also calculated employing precision scales and through the volumetric flask method. To guarantee the repeatability of experiments, they were all repeated three times, and the average of the measurements was then recorded.

Table 1. Experimental range and levels of the independent variables.

Parameters	Unit	Symbol	Levels				
			-α	-1	0	1	**α**
Ethylene Glycol	% v/v	A	30	40	50	60	70
SWCNT	% wt	B	0.01	0.26	0.51	0.75	1
CuNPs	% wt	C	0.1	0.58	1.05	1.58	2
pH	-	D	2	4	6	8	10

Table 2. Central composite design for maximum Thermal conductivity of hybrid nanofluid.

Run	A:EtG v/v%	B:CNT %wt	C:CuNP %wt	D:pH -	CHT W per m °C
1	50	0.505	0.1	6	0.337
2	40	0.7525	1.525	4	0.563
3	50	0.505	1.05	6	0.348
4	50	0.505	1.05	6	0.344
5	40	0.7525	1.525	8	0.381
6	60	0.2575	1.525	8	0.382
7	50	0.505	1.05	6	0.346
8	50	0.505	1.05	10	0.328
9	60	0.2575	0.575	8	0.319
10	40	0.7525	0.575	4	0.419
11	50	0.01	1.05	6	0.485
12	40	0.2575	0.575	8	0.517
13	60	0.7525	0.575	8	0.363
14	50	0.505	1.05	6	0.458
15	60	0.7525	1.525	4	0.428
16	60	0.7525	1.525	8	0.462
17	60	0.7525	0.575	4	0.396
18	60	0.2575	0.575	4	0.309
19	50	0.505	1.05	6	0.442
20	50	0.505	1.05	2	0.353
21	50	1	1.05	6	0.417
22	50	0.505	1.05	6	0.413
23	40	0.2575	1.525	8	0.449
24	60	0.2575	1.525	4	0.355
25	40	0.7525	0.575	8	0.327
26	40	0.2575	0.575	4	0.333
27	50	0.505	2	6	0.412
28	40	0.2575	1.525	4	0.425
29	70	0.505	1.05	6	0.304
30	30	0.505	1.05	6	0.479

RESULTS AND DISCUSSION

EDS, SEM and TEM studies

In order to investigate the morphology of SWCNT and CuO nanoparticles, FESEM and TEM analysis were applied. Figs. 1a and 1b depict the TEM images of CuONPs and SWCNT used in the nanofluid. As can be seen in Fig. 1a, the CuONPs are spherical, and the pure SWCNT in Fig. 1b has an almost tubular structure.

Fig. 1c shows the FESEM images of the Ethylene Glycol/water (44:56 % v/v) nanofluid made from 0.41 % wt SWCNTs and 1.25 % wt CuO nanoparticles. Before the imaging process, the nanofluid was dried, and the remaining solid was examined. From this figure, one can clearly see the presence of agglomerated nanospheres of CuONPs on highly tangled tubes. Also, as shown in Fig. 1d, EDS analysis demonstrates the presence of CuONPs in the nanofluid.

Optimization of the preparation conditions for hybrid nanofluids

Designing experiments is a significant stage in laboratory tests. It involves determining a test type and the selection of the factors to deal with. Response Surface Methodology (RSM) is of benefit

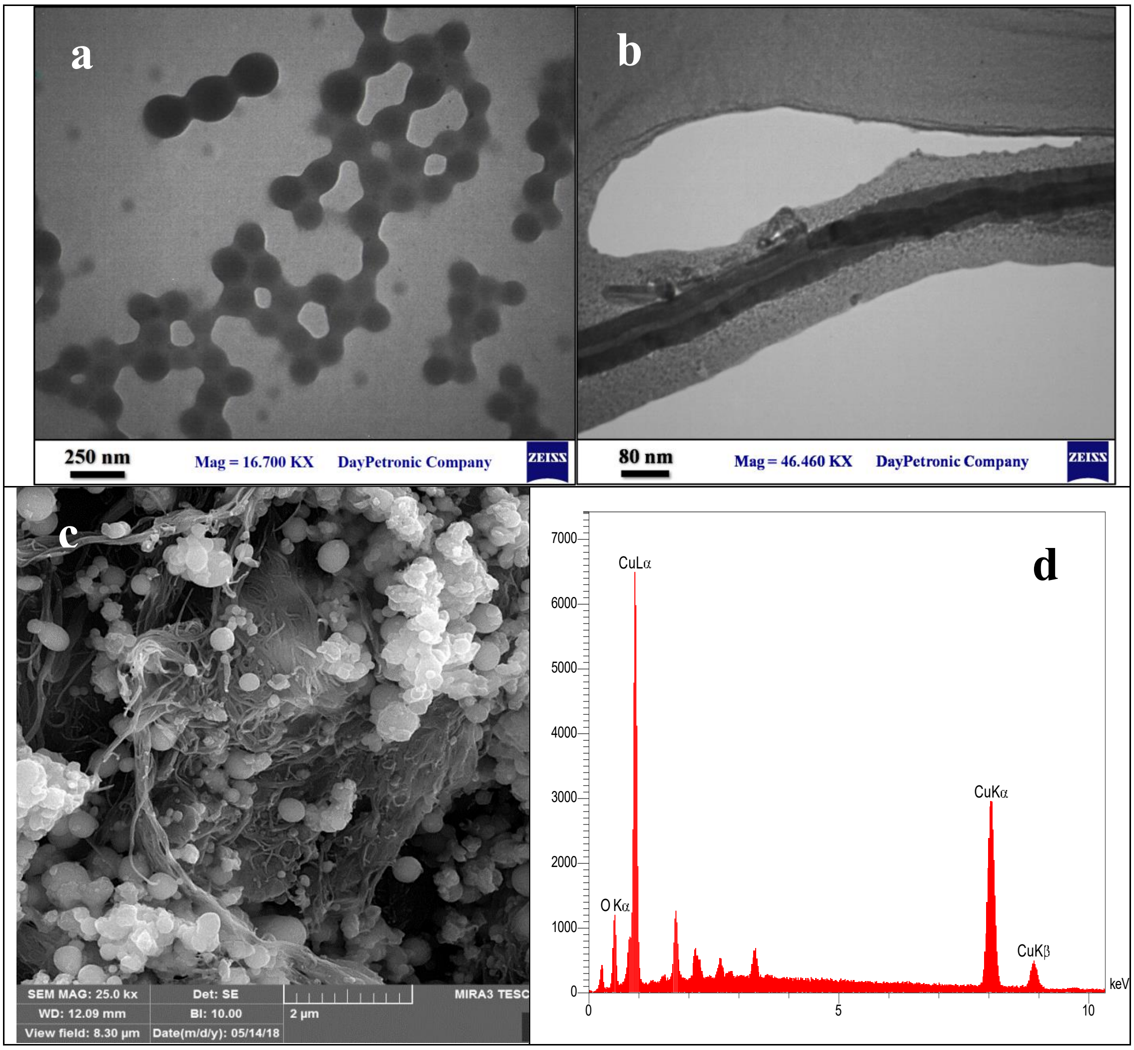

Fig. 1. TEM Images of (a) CuNPs (b) SWCNT. (c) FESEM image and d) EDS analysis of SWCNT/ CuNPs hybrid Nanofluid.

in this regard [35]. The main advantage of RSM is the reduction of test repetitions to ascertain the interrelations of multiple parameters and their effects on the response. The two commonly used techniques for designing experiments by RSM are Central Composite Design (CCD) and Box-Behnken Design (BBD) [36]. In this study, using these statistical methods, the conditions for the preparation of the nanofluid were optimized to achieve the highest Thermal conductivity. The optimization was done by changing the independent variables including the volume ratio of EG to water (factor A), amount of SWCNT (factor B), the concentration of CuONPs (factor C), and the solution pH (factor D). The proposed test plan and its results are presented in Table 2.

Analysis of variance was done on the data to assay their main effects and the interactions among them. The analysis took place using the Design Of Experiment (DOE) software version 11.0.1 (Table 3). A p-value of less than 0.05 in the ANOVA table indicates that the statistical significance of the proposed model is at the confidence level of 95%. Afterward, the F test was also applied to evaluate the statistical significance of all terms in the polynomial equation at the confidence level of 95%. The results presented in this table show that the encoded parameters A, B, C, and D are the variables that affect the Thermal conductivity. Besides, the interactions among variables AB, AC, AD, BC, BD, and CD have significant effects on the heat transfer rate. Based on the reported

Table 3. ANOVA for response surface of evaluation of Thermal conductivity prepared using hybrid nanofluid.

Source	*Sum of Squares*	*df*	*Mean Square*	*F Value*	*p-value Prob > F*	
Model	0.125	10	0.125	5.66	< 0.0001	significant
A-EtG	0.103	1	0.103	46.38		
B-CNT	0.029	1	0.029	13.16		
C-Metal NP	0.034	1	0.034	15.65		
D-pH	0.013	1	0.013	6.19		
AB	0.013	1	0.013	6.01		
AC	0.017	1	0.017	8.07		
AD	0.020	1	0.020	9.18		
BC	0.013	1	0.013	5.94		
BD	0.012	1	0.012	5.48		
CD	0.016	1	0.016	7.49		
Residual	0.042	19	0.0022			
Lack of Fit	0.041	14	0.0029	2.16	0.0003	Not significant
Pure Error	0.000331	5	0.00005			
Cor Total	0.16	29				

F values, A (EG ratio to water), C (CuONPs) and B (SWCNT) variables have the highest influence on the Thermal conductivity.

The DOE software presented a second-order fitting equation and the model suitability using the ANOVA test. Therefore, the second-order polynomial equation was expressed by Equation (1):

$$\text{Thermal conductivity (CHT)} = 0.414 - 0.065A + 0.011B + 0.012C - 0.004D - 0.001AB + 0.026AC - 0.005AD - 0.011BC + 0.008BD - 0.008CD \tag{1}$$

In this equation, variables B and C have positive effects on the Thermal conductivity, but the effect of C is greater, which means that copper oxide nanoparticles have a more pronounced effect on CHT. However, as shown in Fig. 2, variables A and D have a negative influence on the Thermal conductivity. In other words, Thermal conductivity is reversely related to A and D. The above equation can be applied to predict Thermal conductivity within a certain range of variables.

Effects of the model parameters

Another important advantage of the DOE lies in the production of three-dimensional (3D) response surface plots to present the influence of each variable and its interaction with the response [37]. The interactions between four independent variables (i.e. the amount of SWCNT, the amount of CuONPs, the volume ratio of Ethylene Glycol to water, and the solution pH) and CHT as a dependent variable are shown in Fig. 2. Fig. 2a illustrates the 3D plot for the interaction of the Ethylene Glycol to water volume ratio (A) and SWCNT amount (B) with CHT. The pH and the CuONPs were fixed at 6.3 % w/v and 1.3 % w/v, respectively.

As can be seen in the plot, there is an increase in CHT with augmentation of SWCNT from 0.01 - 0.4 % wt, but then it decreases in the range of 0.5 – 1 % wt. This implies that adding SWCNTs improves the Thermal conductivity of EG/water carrier. Many researchers have confirmed that, once the amount of conductive nanoparticles, especially CNTs, is increased, the number of suspended nanoparticles grows too, which leads to successive collisions among the particles [38-39]. Furthermore, the presence of CNTs in fluids can cause the formation of conductive particle chains in the base fluid, which will facilitate the Thermal conductivity enhancement [40]. Thus it can be concluded that increasing the number of CNTs (up to 0.5 % wt) has a positive impact on the Thermal conductivity. However, when more CNT (> 0.5 % wt) is added, due to the accumulation of SWCNTs, the effective surface area of the nanotubes is not further increased, and hence the Thermal conductivity of the nanofluid remains almost constant. On the other hand, the CHT decreases from 0.42 to 0.08 $W\ m^{-1}\ {}^{\circ}C^{-1}$ as the amount of Ethylene Glycol is increased in the range of 40 - 70 % v/v in the base fluid. Ethylene Glycol has a lower Thermal conductivity (0.267 $W\ m^{-1}\ {}^{\circ}C^{-1}$) compared to water (0.715 $W\ m^{-1}\ {}^{\circ}C^{-1}$). So as expected, the Thermal conductivity of the Water/Ethylene Glycol fluid was reduced when the Ethylene Glycol volume ratio was increased. Other authors have also reported this observation [41].

In Fig. 2b, the Ethylene Glycol ratio (A) and the

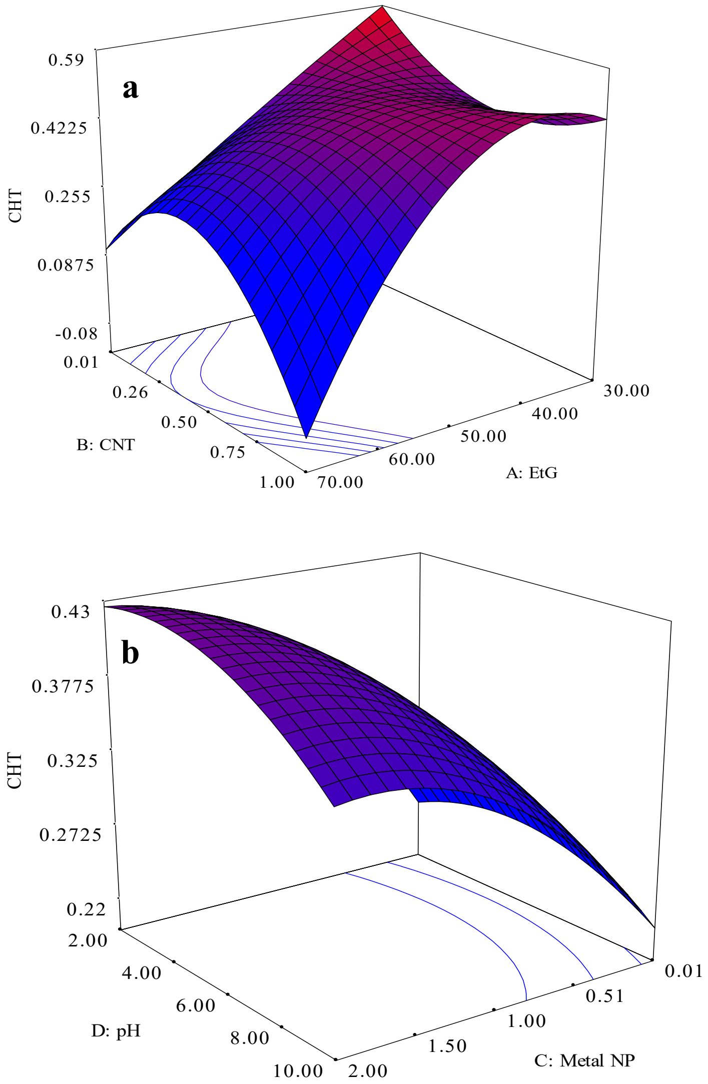

Fig. 2. Three-dimensional response surface graph for the Thermal conductivity of hybrid nanofluids with changing of EtG, SWCNT, CuNPs and pH.

SWCNT (B) were kept constant at 58 % v/v and 0.38 % wt, respectively, and a plot is presented for variations of the amount of CuONPs (C) and the solution pH (D). As the plot indicates, the increase of the CuONPs value in the range of 0.01 – 1.5 % wt will lead to an increment in the CHT, but then the CHT remains almost constant when the CuONPs concentration was further increased. The maximum CHT of 0.341 W m^{-1} °C^{-1} was obtained at 1.15 % wt CuONPs. As indicated above, a rise in the number of conductive particles inside the solution would lead to an increase in the collision of particles, which consequently augments the probability of the collision of nanoparticles. Basically, an increase in the number of collisions can give rise to the contact surface and improve the Thermal conductivity [42]. In our study, however, adding more CuONPs (> 1.2 % wt) had no significant effect on the CHT. Some authors have suggested that a high concentration of nanoparticles can lead to an easy and early agglomeration, through which heat transfer performance is affected, significantly [43].

Moreover, the CHT increased as the pH raised in the range of 2.0 - 5.0, and then it decreased at pH values higher than 5.0. It should be noted that the Thermal conductivity of fluids is nearly constant with different doses of electrolyte salt, acid, or base, as mentioned in the literature [41-44]. The enhancement of CHT seems to be related only to the particles [45]. When the nanoparticles are dispersed through a base fluid, the overall particle-water interactions depend on the properties of the particle surface [46]. The surface charge of the nanoparticles increases due to the frequent attacks on surface hydroxyl groups and phenyl sulfonic groups by potential-determining ions (i.e. H^+, OH^- and phenyl sulfonic group) at an optimum pH. This leads to increased electrostatic repulsion force between the particles, significantly reduced agglomeration rate, enhanced mobility of the suspensions, and ultimately, improved heat transfer rate. In mild and strong alkaline environments, the concentration of the pH-adjusting reagent, i.e. hydroxyl anion (OH^-), increases in the system, which causes the compression of the electrical double layer [47-48]. This phenomenon leads to a decrease in the electrostatic repulsion force and the dispersion of nanoparticles in the solution. The process ends up with a decrement of the contact surface and the Thermal conductivity.

It is safe to say that the surface charge of nanoparticles affects the Thermal conductivity of nanofluids [49]. Once the solution pH changes from the isoelectric point (PZC), the particles acquire a stronger charge, and the particle-particle repulsion increases. This makes the suspension more stable and results in higher Thermal conductivity. Therefore, it sounds reasonable to infer that pH optimization and surface charge enhancement can facilitate phonon transport by enhancing transport efficiency. In addition, when the solution pH is increased, the stabilizing agents of the nanoparticle in the solution are eliminated (their aggregation and clustering rates are increased), and hence the Thermal conductivity of the nanofluid is decreased.

Finally, the optimization results obtained by the analysis were as follows: Ethylene Glycol at 44 % v/v, SWCNT at 0.41 % wt, CuONPs at 1.15 % wt, and pH solution of 5.0. These optimum conditions were then applied to the experiments.

Comparison of the hybrid nanofluid with mono nanofluids

To demonstrate the influence of nanoparticles addition to a base fluid on the enhancement of the Thermal conductivity, a comparison of the Thermal conductivity of 1. Pure base fluid (EG, water, EG-water at the ratio of 44:56), 2. A mono nanofluid (SWCNT/EG-water, CuONPs/EG-water), and 3. a hybrid nanofluid (SWCNT/CuONPs/EG-water) is presented in Table 4.

It is observed from the table that the CHT of the EG-water coolant (0.358 W m^{-1} $°C^{-1}$) could be enhanced to 9.4 % when SWCNT was added to it with a solid proportion of 0.41 % wt (0.392 W m^{-1} $°C^{-1}$). However, when 1.15 % w/v CuONPs were added to the EG/water coolant in the same conditions, its CHT rose to 22.3 % (0.438 W m^{-1} $°C^{-1}$). This might be related to the larger surface-to-volume ratios and higher Thermal conductivity of SWCNTs. It goes without saying that the specific surface area (SSA) of CNTs is more than that of CuONPs.

However, the presence of both nanoparticles in the base solution led to a CHT enhancement (0.563 W m^{-1} $°C^{-1}$), which was 57.2 % and 209 % higher than those of Ethylene Glycol/Water (0.272 W m^{-1} $°C^{-1}$) and Ethylene Glycol (0.358 W m^{-1} $°C^{-1}$) pure fluid, respectively. Also, the CHT of SWCNT-CuONPs Ethylene Glycol/Water hybrid nanofluid (0.563 W m^{-1} $°C^{-1}$) was higher than that for 0.41 % wt SWCNT (0.392 W m^{-1} $°C^{-1}$) and 1.15 % wt CuONPs (0.438 W m^{-1} $°C^{-1}$) mono nanofluids. This synergetic effect could be due to the less formation of larger SWCNT nano-clusters. Also, due to the presence of CuONPs in the base fluid, the Thermal conductivity was enhanced, significantly. The same results have been reports by other researchers for the development of a new hybrid nanofluid composed of FMWCNT and MgO [50]. It is worth mentioning that adding and dispersing nanoparticles in base fluids can increase the amount of the transferred heat without changing the size of the heat transfer surface. This means that there is no need to increase the fluid speed and the surface of the heat exchanger, which will result in lower costs. Also, the destructive effects of the fluid on the pumps and the wall of the converters will be reduced due to the existence of a favorable heat transfer using a lower fluid volume. Above all, the use of nanofluids leads to reduced consumption of fuel or electricity, which is both environmentally and economically important.

Electrical and impedance characterization

The electrolytic property of a base fluid gets altered when nanoparticles are dispersed through it. In this section, the electrical properties of mono and hybrid nanofluids were investigated, as presented in Table 4. The electrical conductivities of DI water and Ethylene Glycol, as base fluids, were found to be 6.0 and 1.07 µS cm^{-1},

Table 4. The obtained results for thermal, electrical conductivity, viscosity and density of base, mono and hybrid nanofluids at optimum condition.

Fluids	Thermal conductivity (W per m °C)	electrical conductivity (µS per cm)	Viscosity (kg per ms)	Density (kg per m^3)
DI water (w)	0.711±0.0033	6±1.03	0.0009	997
Ethylene glycol (EtG)	0.272±0.001	1.07±0.02	0.00165	1110
EtG:W (44:56)	0.358±0.0029	3.7±2.00	0.00113	1041.2
SWCNT-EtG:W	0.392±0.0021	515.2±13.32	0.00115	1056.8
CuNPs-EtG:W	0.438±0.0032	571.8±5.97	0.00131	1160.1
SWCNT-CuNPs-EtG:W	0.563±0.0029	697±11.96	0.00138	1174.6

respectively. The electrical conductivity of the water-based nanofluid rose when either one or both nano additives were added. A surface charge was created on the nanoparticles once they were dispersed in the fluid. Due to the less availability of free ions in DI water, a net charge density was produced on the surface of the particles. Generally, identical charges repel each other; thus, the particles were suspended stably in the fluid. Also, since no surfactant was added to the suspension, the enhancement of the electrical conductivity of the mono or hybrid nanofluids could be attributed merely to the presence of particles with electrical double layers.

The electrical conductivity of the nanofluid containing SWCNT (545.2 µS cm^{-1}) was higher than that of the nanofluid containing CuONPs (487.8 µS cm^{-1}). This can be attributed to the special properties of SWCNT as compared to metal oxide nanoparticles [51]. Besides, many authors have stated that the Thermal conductivity of SWCNT (300 W m^{-1} °C^{-1}) is 50 to 100 times higher than that of copper nanoparticles (38 W m^{-1} °C^{-1}) [52-53].

Here, the electrical conductivity of the hybrid nanofluids (697 µS cm^{-1}) was higher than that of the mono nanofluids. As discussed above, this is due to the synergetic effect of both nanoparticles in the base fluid. It has been also found that the presence of metal nanoparticles in the vicinity of SWCNT prevents CNTs accumulation in the fluid and leads to their higher stability in the base fluid. Therefore, as a result of the uniform distribution of nanoparticles in the base fluid, the electrical conductivity improves [54].

Electrical impedance spectroscopy (EIS) is a very sensitive technique for the investigation of the dielectric properties of nanofluids [55]. To conduct an EIS test on the nanofluids, 2.0 mL of a 0.1 M phosphate buffer solution containing 1 mM of K_3 [Fe $(CN)_6$] electrolyte at pH 5.0 was added to an electrochemical cell containing 5.0 mL of a nanofluid prepared with 44 : 56 Ethylene Glycol/Water, 0.41 % wt SWCNT and 1.15 % wt CuONPs. Then, the corresponding Nyquist diagrams were plotted. This experiment was performed for nanofluids containing mono nanoparticles, DI water, Ethylene Glycol, and Ethylene Glycol/DI water. The results are presented in Fig. 3. Generally, Nyquist plots consist of two parts, a semicircle and a linear part [56]. The size of the semicircle in a Nyquist plot represents the Charge Transfer Resistance (R_{CT}) of the fluid or the electrode. Therefore, the smaller the R_{CT} is, the higher the conductivity would be [57].

It is noticed from Fig. 3 that the DI Water used in the experiments had a lower charge transfer resistance (R_{ct}) than Ethylene Glycol (930 kΩ) and EG/Water (780 kΩ). This means that the rate of the electron transfers in Ethylene Glycol is decreased due to the addition of DI water to the base fluid. Also, the half-circle radius (*i.e.* R_{ct}) of the Nyquist plot was reduced upon the addition of nanoparticles to the Ethylene Glycol/Water fluid, which was due to the excellent conductivity of SWCNT (6 kΩ) and CuONPs (22 kΩ). As the Nyquist plot corresponding to the nanofluid containing both SWCNT and CuONPs shows, the R_{CT} of the hybrid nanofluid (1.5 kΩ) was less than that of the mono nanofluids. This is in agreement with the results of Table 4 and confirms the mutual role

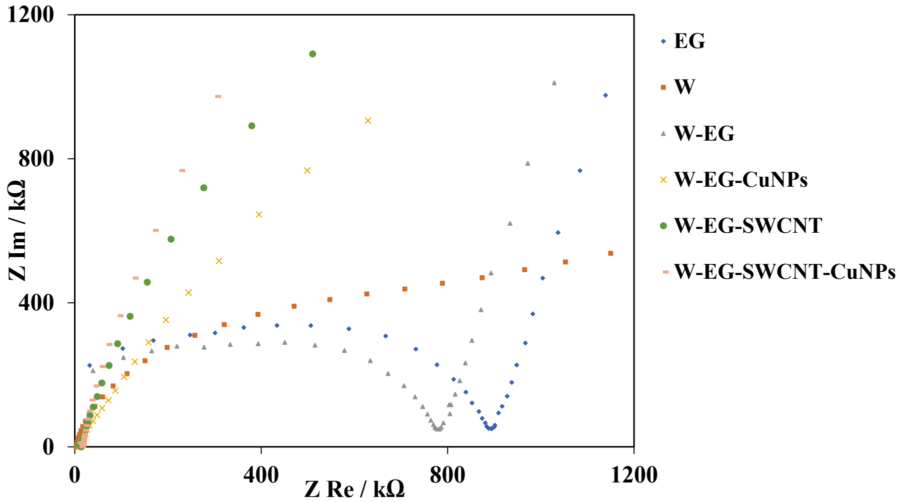

Fig. 3. EIS graphs of the base, mono and hybrid nanofluids. (Fluid solution contains 1.0 mM $[Fe (CN)_6]^{3-/4-}$).

of both nanoparticles in improving the electrical conductivity of the fluid.

Evaluation of the viscosity and density of the nanofluids

Nanofluids as a new class of energy carriers have attracted particular attention with special and unique features in recent decades. The first step in studying a nanofluid and describing its behavior is to know the nanofluid characteristics. Viscosity and density are the most important parameters in the dynamic behavior of the nanofluids [58]. Here, a comparison is made between the physical properties of the base fluid and the studied hybrid and mono nanofluids, given in Table 4.

Generally, the addition of very fine particles significantly improves the transient properties and heat transfer behavior of the base fluid. The results of the table show that viscosity and density of the fluids increase when nanoparticles are added to the base fluid.

Adding nanoparticles to the base fluid increases the viscosity of the nanofluids. As a result of this increment, the pressure drop is increased in the cooling systems containing nanofluids. Also, pumping energy must be augmented to compensate for this pressure drop in the system. This may have economic and environmental consequences. Therefore, a desirable nanofluid must have a higher Thermal conductivity with appropriate viscosity and density.

To confirm the results of this study, the viscosity and density of prepared nanofluids were compared with similar fluids. The viscosity of the proposed nanofluid with the optimum values of the constituents is far less than similar fluids. Other authors have also acknowledged that the increase in viscosity reduces Thermal conductivity as well as fluid flow properties. This limits the use of nanofluids in engineering design and industrial applications. Also, it is noticeable that by adding solid particles to the fluid, the fluid total mass, and density increase [59].

As it has been observed, a decrease in the apparent volume of nanofluids occurs, because a part of those liquids is trapped in nanomaterial clusters. It has also been reported that, when SWCNT is dispersed in a base fluid, surface interactions increase due to the entangled structure of SWCNT; therefore, the nanofluid viscosity increases too.

CONCLUSION

In this study, hybrid nanofluids were prepared by adding CuO nanoparticles and SWCNT to an Ethylene Glycol/Water base fluid. The Thermal conductivity of the nanofluids was optimized by changing the amounts of CuO nanoparticles and SWCNT, the volume ratio of Ethylene Glycol, and the solution pH using Response Surface Methodology. In this way, the electrical conductivity, viscosity, density, and dielectric nature of the nanofluids were studied. FESEM/EDS, TEM, and EIS were applied to characterize the prepared nanofluids. The experiments indicated that the Thermal conductivity of nanofluids would be enhanced when the solid volume fraction of CuONPs and SWCNT was increased up to some maximum values. Moreover, the Thermal conductivity was proved to be the highest, in the pH range of 4.5-5.0. Under these conditions, the surface charge of the nanoparticles changed in the solution, and the electrostatic repulsion force among the particles led to the reduction of agglomeration rate, enhancement of mobility, and ultimately, improvement of heat transport. The Thermal conductivity measurements showed that the maximum enhancement in the thermal and electrical conductivity rates of the nanofluids was 157 % and 18000 %, which occurred in 44:56 Ethylene Glycol/Water containing 1.15 % wt CuONPs and 0.41 %wt SWCNT at the pH value of 5.0. The enhancement in the thermal and electrical conductivities of the water/EG-based hybrid nanofluids was found to be somewhat higher than that in mono nanofluids. Also, the EIS results confirmed the synergetic effect of the addition of nanoparticles and carbon nanotubes on the electrical conductivity of the base fluids.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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