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Preparation and measurement of thermophysical and electrical properties of ZnO-MWCNT/DIW hybrid nanofluid

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Abstract

Recent research has focused on improving the performance of thermal management systems. Dispersing composite nanoparticles in the traditional heat transfer fluid known as hybrid nanofluids (HNF) has been an idea engaged for the augmentation of their thermophysical properties and thus their thermal performance. This work focused on the consequence of mass percentage ratio and temperature on the thermophysical properties of ZnO-MWCNT/deionized water (DIW) HNF. ZnO (20 nm) nanoparticles hybridized with MWCNT (30–50 nm) nanotube have been dispersed in DIW to synthesize composite nanoliquids at 0.1 vol.% and by various mass% ratio of (ZnO: MWCNT) 20:80, 40:60, 60:40, and 80:20. The morphology of the prepared composite nanoliquids (NF) samples was monitored via standard instruments to assess their stability condition. The composite nanoliquids were detected to be stable. Then viscosity (μ), thermal conductivity (κ), and electrical conductivity (EC) (σ) of this HNF have been measured in temperatures ranging from 20 to 55 °C. With the cumulative ratio of MWCNT and the temperature, while μ of this nanoliquid was noticed to decrease, an increase in κ was detected. The σ was slightly enhanced as the temperature and the ratio of ZnO nanoparticles increased with a decrease in the ratio of MWCNT. The minimum and maximum enhancements obtained are, respectively, 12.27% and 33.33% at 80:20 for the viscosity, 10.17% and 23.11% at 20:80 for the thermal conductivity, and 325.93% and 386.10% at 80:20 for the EC of ZnO-MWCNT/DIW hybrid nanoliquids in comparison with the based fluid. New correlations have been established to approximate the thermal conductivity of these composite nanoliquids as a function of temperature for all percentage ratios. The proposed correlations have been compared with existing correlations from literature. The HNF was found to have a lower viscosity than that of the single NF and is suitable for thermal management applications.

Keywords Hybrid nanofluids · ZnO nanoparticles · MWCNT · Viscosity · Thermal conductivity · Electrical conductivity

Abbreviations

AR	Aspect ratio
BNFs	Briny nanofluids
DIW	Deionized water
DW	Distilled water
DWCNT	Double-walled carbon nanotube
EG	Ethylene glycol
W/EG	Water ethylene glycol
EO	Engine oil
G	Graphene
GA	Gum arabic
GL	Glycerol
GNF	Green nanofluid
GO	Graphene oxide
GON	Graphene oxide nanosheet
GNP	Graphene nanoplatelet
HNF	Hybrid nanofluid
HNP	Hybrid nanoparticle
MO	Mineral oil
MOD	Margin of deviation
MWCNT	Multiwalled carbon nanotube
ND	Nanodiamond
NF	Nanofluid
NP	Nanoparticle
PG	Propylene glycol
PWR	Particle mass ratio
SDBS	Sodium dodecyl benzene sulfonate
SDS	Sodium dodecyl sulfate
SWCNT	Single-walled carbon nanotube
T	Temperature
TO	Transformer oil
V	Volume m^3

Extended author information available on the last page of the article

W	Width m
X	The ratio of hybrid nanoparticles mass

Greek symbols

ΔT	Temperature gradient
φ	The mass concentration of nanoparticles %
μ	Viscosity, kg m^{-2} s^{-1}
β	Thermal coefficient of expansion k^{-1}
ρ	Density, kg m^{-3}
κ	Thermal conductivity, W m^{-1} K^{-1}
δ	Uncertainty
σ	Electrical conductivity, μS cm^{-1}
∂	Partial differential

Subscripts

b	Bias
E	Enhancement
Eff	Effective
Exp	Experimental
Av	Average
Pred	Predicted

Introduction

The current advancement in technological development has brought about a huge challenge of thermal management in the application and existing heat transfer techniques in thermal management are presently reaching their limits. The working heat transfer fluids such as water, ethylene glycol, propylene glycol, engine oil, and palm oil are commonly used in numerous thermal applications. The main weaknesses of the specific limitations in their capability and thermal properties are low thermal conductivity and low heat transfer performance of media. The enhancement of heat transfer performance of the thermal systems and devices required to have increased thermal properties of the media reduced total cost and energy. Generally, the traditional convectional heat transfer fluid has a very small thermal conductivity value compared to solid material. Therefore, one possible way to augment the thermal conductivity of conventional fluids is by dispersing metallic or nonmetallic particles in those fluids or media. Such dispersion of nanoparticles is known as nanofluids which were coined by [1, 2] and found to have higher thermal conductivity compared to their base fluid (conventional heat transfer fluid). Masuda et al. [3] prepared suspensions of nanoparticles and measured their thermophysical properties which was found to be higher compared to their base fluids.

The efforts of researchers have recently been motivated to augment the properties of the mean heat transfer liquid by enhancing the thermophysical properties of different based fluids. These properties of nanofluids were enhanced by using different kinds of nanoparticles such as MgO, ZnO, Al_2O_3, Fe_2O_3, TiO_2, SiO_2, CNT have been consequently experimented at several volume concentrations for changed temperature ranges [4–9].

The idea of developing a novel kind of nanofluids to augment the thermophysical properties of conventional liquids is not new. The thought of hybridization of nanoparticles suspended different kinds of nanomaterial into the based fluid, known as hybrid nanofluid. Many investigations have been conducted on this new type of nanoliquids. Jana et al. [10] examined thermal conductivity by synthesized Cu-CNT and Au-CNT. Their result showed a higher value of the thermal conductivity of the single nanofluid compared to a hybrid nanofluid. Sundar et al. [11] synthesized MWCNT-Fe_3O_4/distilled water hybrid nanoliquids. They found a 29.39% enhancement in thermal conductivity, viscosity enhanced by 23.24% (1.2324 times) with 0.3% particle concentration. Batmunkh et al. [12] synthesized TiO_2–Ag/W composite nanofluids and demonstrated enhancement in thermal conductivity. Moradi et al. [13] performed an empirical study on the influence of (20–60 °C) temperature and (0.0625–1%) volume concentration (TiO_2-MWCNTs/(EG-water)) hybrid nanoliquid. The results displayed that the temperature and volume concentration influenced at 60 °C and 1.0vil.% volume concentration. Nasajpour et al. [14] suspended (ZnO–Ag) nanocomposite in water and experimented on the effect of the temperature range (25–60 °C) and volume fraction of (0.125–2%) on the thermal conductivity. They detected that the increase in temperature and volume fraction leads to enhanced thermal conductivity. Hemmat et al. [15] examined the influence of concentration ranging from 0.02 to 1.0 vol% and temperatures (303–332 K) of CNT-Al_2O_3/water HNFs on the κ. Esfe et al. [16] have measured the thermal conductivity of EG-based liquids of (70:30%) SiO2/MWCNT hybrid nanofluid at volume fractions ranging from 0.025 to 0.86% and temperatures of (30–50 °C). They mentioned the thermal conductivity increased by 20.1% more than the based fluid EG at 50 °C and 0.86% volume fraction. Esfe et al. [17] experimentally observed 45% thermal conductivity enhancement with (70:30%) SWCNT-ZnO/(60:40)(EG-water)-based HNFs at $\varphi = 1.6\%$ and at temperatures 50 °C. Hemmat et al. [18] measured the rheological behavior of nano-lubricant ((30:70%) MWCNT: ZrO_2 /(10w-40)) hybrid nanofluid affected with temperature range (5–55 °C) and volume concentration (0.05–1%). The result shows 31% viscosity enhancement at 55 °C and $\varphi = 1.0$ vol.%. Murshed et al. [19] they conducted experimental and theoretical on the effective thermal conductivity (κ) and viscosity (μ) of nanofluids. Their result indicated that both the thermal conductivity and viscosity of nanofluids rise through the nanoparticle volume fraction. The thermal conductivity of nanofluids was also detected to be powerfully reliant on the temperature rise. Giwa et al. [20] prepared composite nanofluid by dispersal (MWCNT)-Fe_2O_3 nanoparticle into DIW and studied the μ and σ at temperatures variety from 15 to 55 °C and volume concentrations ranging from 0.10 to 1.50 vol%. They establish that all the considered measured thermophysical properties are enhanced with the rise of volume concentration. Viscosity was seen to moderately diminish with temperature increase. Eshgarf and Afrand [21] examined the rheological behavior of hybrid nanofluids prepared from 50%SiO_2 -50%MWCNT /W-EG for φ = of 0.0625–2%, temperature of 27.5–50 °C and shear rate of 0.612–122.3 s^{-1}. The result demonstrates shear-thinning behavior through a power-law index of less than unity.

Ajeeb and Murshed [22] experimentally investigated the thermophysical properties of SiC-BN/ (EG: DW) nanoliquids for volume concentration of 0.01–0.05 vol.%, temperature of 22–41 °C and shear rate of 200–800 s^{-1}. Their results showed a decent rise in thermal conductivity and thermal diffusivity of nanoliquids through growing volume concentration also Newtonian rheological nature was detected. Harandi et al.[23] studied the effect of temperature (25–50 °C) and solid volume fraction range of 0% to 2.30% on κ of F-MWCNT-Fe_3O_4 (at equal amounts)/EG composite nanoliquids. Their results showed that at 2.3vol. % and 50 °C, the maximum augmentation (30%) in the κ was measured. Nadooshan et al. [24] premeditated the rheological behavior of MWCNT-Fe_3O_4 (at equal amounts) for a shear rate of 12.24–73.44 s^{-1}. The result showed Newtonian behavior for the hybrid nanofluids through φ of 0.10–0.80 vol.% and non-Newtonian flow for the HNFs at volume fractions of 1.25 and 1.8%. Esfe and Sarlak [25] studied the rheological behavior of based engine oil composite nanofluids MWCNT-CuO (15%-85%) for temperature, solid volume fraction, and shear rate ranges of and 5–55 °C, 0–1 vol.% and 2666.6–11,999.7 s^{-1}, respectively. Their result revealed non-Newtonian flow Bingham pseudoplastic at temperature > 45 °C and plastic non-Newtonian above 45 °C by maximum viscosity rise of 43.52% at 1% solid volume fraction. Viscosity was observed to advance through rises in temperature and φ owing to the flow behavior of the nanoliquid.

Sundar et al. [26] have studied the electrical conductivity of EG- and DW-based (84:16) (ND-Ni) NFs at a φ of (0.02 vol.%, 0.05 vol.%, and 0.10 vol.%) and of the temperature range (24–65 °C). The outcomes indicate the enhancement value in EC of ND (nanodiamond)-Ni/W-based HNFs are 1339.81% at 65 °C and 853.15% at 24 °C and 0.1vol% in comparison with water. For (0.1%) ND-Ni/EG hybrid nanofluid, the property was improved by 199.52% at 24 °C and 200.23% at 65 °C compared to based fluid (EG). Hemmat et al. [27] conducted an investigational study on κ of (50%:50%) mixture of EG:W-based ZnO-MWCNT binary nanofluid at φ range of 0.02–1.0 vol.% and temperatures from 30 to 50 °C. The maximum thermal conductivity increase is 13.3% achieved at φ of 1.0 vol.% and 50 °C temperature. Sundar et al. [28] experimentally investigated κ and μ of (85:15)ND-Ni/DW binary nanofluid for φ variation of 0.10–0.30 vol% and temperature variety of 30 to 60 °C. Rendering to results from their study, the κ was enhanced by 10.23% at 0.10 vol. % and 30 °C, and 29.39% at 0.30 vol. % and 30 °C and the viscosity was enhanced by 16.65% and 23.24% for φ = of 0.10 vol. %, 0.30 vol. % and at 30 °C, 60 °C, respectively, in comparison with DW. Dardan et al. [29] studied the rheological behavior of EO Al_2O_3-MWCNTs/SAE40 HNFs at φ variety from (0% to 1.0%) and temperature range from (25 °C to 50°) at the shear rate variety of (1333–13,333 s^{-1}). The HNFs exhibited Newtonian behaviors at all volume fractions and measured temperatures. Results of relative μ of the binary nanoliquid were augmented by 46% Also their results presented that the μ augmented by increasing φ and decreasing temperature. Giwa et al. [30] have studied the thermo-convection performance of $Al_2O_3 - MWCNT/W$ NFs, at φ = 0.10 vol.% volume concentration, temperature range from (20 to 50 °C) and at various percent masses of (Al_2O_3/MWCNT; 80:20, 60:40, 40:60, and 20:80). The μ of binary nanofluid was improved by 24.56% for the sample (80:20) NFs at 0.1 vol% and 55 °C. The electrical conductivity was enhanced by 134.12%–255.34% at 0.1 vol% and 55 °C, in comparison with water. Hamid et al. [31] experimentally investigated the κ and μ of (SiO_2-TiO_2)/(W-EG) binary nanofluids at φ of 1.0 vol% with five mixture ratios (W-EG 80:20,60:40; 50:50,40:60 and 20:80) and temperatures range from (30 to 80 °C). Their consequences showed that the mixture ratio of 20:80 (TiO_2: SiO_2) nanofluids had the highest thermal conductivity enhancement of 16% in comparison with the mixture ratio of 20:80. The mixture ratio of 80:20-based hybrid nanofluid exhibited the lowest viscosity. For the κ and μ, the HNFs by the mixture ratios 80:20 and 40:60 were observed to exhibit good performance and thus can be suitable for engineering applications. Also, they concluded that the HNFs W: EG (50:50)-based mixture was not applicable as it has the lowest and highest values of κ and μ, respectively, in compression to the based fluid. Kakavandi and Akbari. [32] found the effects of φ = (0 to 0.75%) and (25–50 °C) on the κ of (50–50%) masses of (SiC-MWCNT) W-EG (50–50%) mixture composite nanoliquid. The maximum thermal conductivity enhancement of 33% was achieved at volume concentration 0.75 vol% and at 50 °C temperature in comparison with W-EG (50–50%) mixture. The increase in the temperature from 25 to 50 °C and φ from 0 to 0.75% showed a considerable enhancement of the thermal conductivity.

Qing et al. [33] synthesized SiO_2-GNP/TO and studied the stability, thermal conductivity, viscosity, and electrical conductivity of composite nanofluid (SiO_2-GNP/TO) at diverse nanoparticle concentrations (0.01 mass%, 0.04 mass%, and 0.80 mass%) and temperature (20 to 100 °C). They observed the highest thermal conductivity enhancements of 80% for (0.04 mass% pH9 at 100 °C), 29.7% for (0.08 mass% at 100 °C), and viscosity 29.7%, 12.87% for hybrid SiO_2-GNP/NO and GNP/NO (naphthenic oil) nanofluids, respectively, relative to based fluids. The reduction of electrical conductivity of hybrid SiO_2-GNP/TO nanofluid from 557 to 97% was found in their study. Results from literature studies on the thermophysical and electrical properties of various HNFs are summarised in Table 1.

The present study focuses on the thermophysical properties of ZnO-MWCNTs/DIW hybrid nanofluid at a percent mass ratio (ZnO: MWCNT) 20:80, 40:60, 60:40, and 80:20. The DIW-based ZnO-MWCNTs hybrid nanoparticles and nanotubes are scarce in the literature. In recent years, researchers have been focusing on using carbon nanotubes (CNT) for the preparation of composite materials to enhance the thermal properties of the composite material. This is due to the high κ of CNT owing to their role in enhancing the properties of heat transfer and there is a lack of information on the σ of binary nanoliquids, particularly ZnO-MWCNT/ DIW-based hybrid nanofluid. In the current work, the viscosity, thermal conductivity, and electrical conductivity of ZnO-MWCNT/DIW hybrid nanofluid at different percentages mass ratio dispersed into deionized water (DIW) at φ = 0.10 vol.% and temperature ranging from 20 to 55 °C were experimentally determined. New correlations were developed to calculate thermophysical properties correlated as dependent on the temperature.

Preparation of hybrid nanofluids

Material

The hybrid nanoparticles of ZnO–MWCNT were acquired where multiwalled carbon nanotubes (MWCNTs) were obtained from Nanomaterials Inc, USA, and ZnO nanoparticles (with 20 nm) were purchased from Nanostructured and Amorphous Materials Inc. (USA). Surfactant (SDS) of purity of $\geq$ 98.5% was bought from Sigma-Aldrich, Germany, for better stability of hybrid nanoliquids. Deionized water (DIW) was used as the base fluid. Parameter and characterisitics of these nanoparticles are provided in Tables 2 and 3.

Method of preparation

Hybrid nanofluids in the present study were prepared by directly suspending powder of nanocomposite of ZnO-MWCNTs in the based fluid, using a two-step technique. HNF has been prepared with four mass percentages ratio of 20:80, 40:60, 60:40, and 80:20 (ZnO-MWCNTs) at 0.1vol% for good dispersion of nanoparticles in the based fluids, and the volume fraction (%) can be determined by using Eq. (1):

$$\varphi = \frac{\left(\left(\frac{w}{\rho}\right)_{\mathrm{MWCNTs}} + \left(\frac{w}{\rho}\right)_{\mathrm{ZnO}}\right)}{\left(\frac{w}{\rho}\right)_{\mathrm{MWCNTs}} + \left(\frac{w}{\rho}\right)_{\mathrm{ZnO}} + \left(\frac{w}{\rho}\right)_{\mathrm{basefluid}}} \times 100 \quad (1)$$

where φ is volume concentration(%), ρ the density, and w is the mass. Weighing balance (AS 220.R2—Poland) with precision of $\pm$ 0.01 g was used to weigh the determined masses of the hybrid nanocomposite and surfactant. To find a homogeneous mixture from a nanocomposite magnetic stirrer (Ha400 HSB, Indonesia) for 45 min with a magnetic agitator and a sonicator (Qsonica, Q-700; USA) was continuously employed to break down agglomerations the mixture sonicated for 90 min during the sonication time the temperature of the mixture kept constant by using thermal bath (LAUDA ECO RE1225). Figure 1 shows the formulation step.

Measurement of viscosity

The viscosity was measured using the sine wave Vibro-viscometer (SV-10, A&D, Japan) with an accuracy of $\pm$ 3%. At first, the viscometer was calibrated by measuring the viscosity of the base fluid for the temperature range of 20 to 55 °C at 5 °C intervals. Figure 2 shows the viscosity measuring apparatus.

Thermal conductivity of binary nanoliquid

Figure 3 shows the device for thermal conductivity measurement. The thermal conductivity in the present study is measured using a KD2 device (METER Group Inc.USA; KS-1-05038 sensor). This apparatus scheme is based on the transient hot-wire process. The thermal conductivity of DIW, single-nanofluid, and HNFs was measured at 20–55 °C at 5 °C intervals. Before measurement the device was self-calibrated by the producer fluid for the adjustment at 25 °C and measurement was conducted after reaching the sensor to be stable. The KD2 pro calculates thermal conductivity using Eq. (2):

Table 1 Summary of studies on the thermophysical and electrical properties of HNFs

Authors	HNPs/ratio	φ/vol. %	Base fluid	Properties	Temperature	Enhancement/%
Jha et al. [34]	Cu/MWCNT & MWCNT	0.6–4.0	EG & DIW	κ	26.5–48.9	14.8–210 (DIW) 3.6–20.2 (EG)
Sundar et al. [35]	ND-Fe_3O_4 (72%:28%)	0.05–0.2	DW & DW-EG mixtures	κ, μ, & σ	20–60	13.4–17.8 (κ) 1.5X–2.19X (μ)
Kannaiyan et al. [36]	Al_2O_3-CuO	0.05–0.2	DIW-EG (80:20)	ρ, μ, & ρ	20–60	45
Mousavi et al. [37]	CuO-MgO-TiO_2 (5 diff. ratios)	0.1–0.5	DW	κ, μ, ρ, C_p & surface tension	15–60	–
Abbasi et al. [38]	MWCNT-Al_2O_3 (1:1)	0.1	DIW	κ	Room temp	20.68
Sundar et al. [39]	CNT-Fe_3O_4 (26:74)	0.1 & 0.3	DW	κ & μ	20–60	28.46 (κ); 1.5X (μ)
Zadkhast et al. [40]	MWCNT-CuO (50:50)	0.05–0.6	DIW	κ	25–50	30.38
Akilu et al. [41]	SiO_2-CuO/C (80:20 mass%)	0.5–2.0	GL-EG (60:40 mass%)	C_p, κ, & μ	30–80	1.15X (μ); 21.1 (C_p); 26.9 (κ)
Hamid et al. [42]	TiO_2-SiO_2 (40:60 vol.%)	0.5–3.0	EG	κ	30–70	21
Suresh et al. [43]	Al_2O_3-Cu (90:10 mass%)	0.1–2.0	DIW	κ & μ	Room temp	1.47–12.11 (κ); 8–115 (μ)
Marcos et al. [44]	BN-SiO_2 (1:9 mass%)	0.01–0.1	EG-W (15:80 vol.%)	κ	10–50	2.3
Esfe et al. [45]	DWCNT-ZnO (10:90)	0.045–1.90	EG	κ	30–50	24.9
Rostamian et al. [46]	CuO-SWCNT (50:50 vol.%)	0.02–0.75	EG-W (40:60)	κ	20–50	36.2
Kumar et al. [47]	Cu–Zn (50:50)	0.1–0.5	EO, VO, paraffin	μ, κ, & FP	30	Cu–Zn/VO (best)
Esfe and Sarlak [48]	CuO-MWCNT (85:15)	0.05–1.0	EO	μ	5–55	43.52

Table 2 Characteristics of MWCNT nanoparticle

Parameter	Value
Purity	> 97%
Out. diameter	10–20 nm
In. diameter	3–5 nm
Thermal conductivity	2000 W m^{-1} K^{-1}
Density	~ 2100 kg m^{-3}

$$\kappa = \frac{q}{4\pi(T_2 - T_1)} \ln\left(\frac{t_2}{t_1}\right) \quad (2)$$

where κ is the thermal conductivity, q is the heart rate(W/m), T_1, T_2 are the temperatures at time t_1, t_2, respectively. The sample host was placed inside a water bath to keep the temperature constant during the measurement.

The pH and EC measurement

pH values of the nanoliquid are obtained by measuring it using a pH meter (Jenway 3510; –2 -19.999 range and precision ± 0. 3%), and it was calibrated with the standard solution at room temperature with 2-points 4, 7 calibrations. The EC meter was first calibrated by using a standard solution (glycerin) delivered by the producer. The device measured 1414 μS cm^{-1} at room temperature (25 °C). This value was close to the glycerine (1413 μScm^{-1}) measured by the producer. Then, the EC of deionized water, single, and binary nanoliquids were measured at a temperature of (20–55 °C) at 5 °C intervals. The relative and the enrichment of the EC of the NFs were estimated by Eqs. (3) and (4), respectively. Figure 4 shows the experimental setup for pH and EC.

$$\sigma_{rel} = \frac{\sigma_{hnf}}{\sigma_{bf}} \quad (3)$$

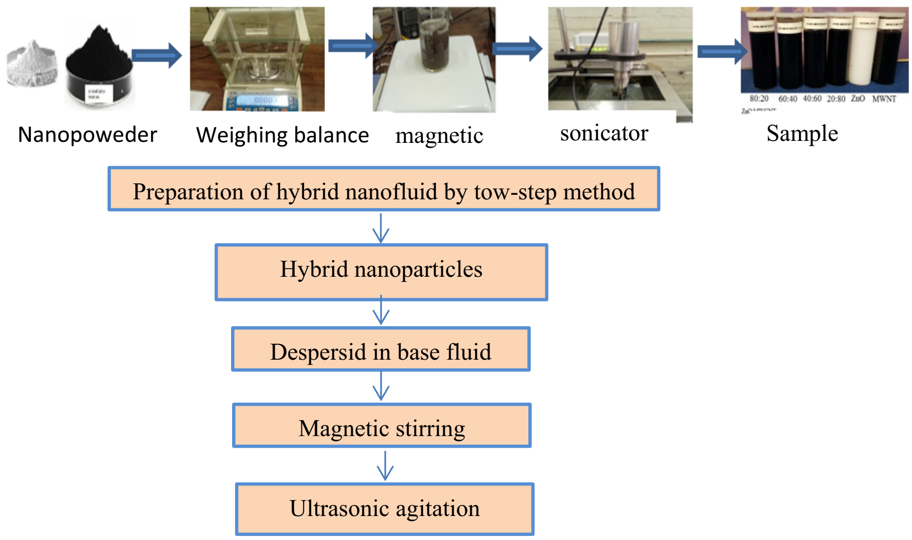


Fig. 1 Preperation step of hybrid nanofluid

Fig. 2 The apparatus of viscosity measurement

Fig. 3 Experimental setup for thermal conductivity measurement

$$\sigma_{\text{enhan}}(\%) = \left(\frac{\sigma_{\text{hnf}} - \sigma_{\text{bf}}}{\sigma_{\text{bf}}}\right) \times 100 \quad (4)$$

where σ_{rel} is the relative electrical conductivity.

σ_{hnf} EC of composite nanofluids.

σ_{bf} EC of water.

σ_{enhan} enhancement of the electrical conductivity.

Development of correlations

In the present study, by the means of curve fitting technique on the obtained data, new correlations to estimate the thermophysical properties (viscosity, thermal and electrical conductivity) on behalf of the ZnO-MWCNTs/ DW hybrid nanofluids were introduced. This resulted in the relative viscosity, and thermal and electrical conductivity that was fitted into correlations. The established correlations were dependent on the considered and the determination coefficient R^2 (R-squared).

Results and discussion

Stability assessment of nanoliquids

The stability of suspended nanoparticles in a based fluid to formulate HNFs is an important issue for heat transfer application media. The effective variables used such as the sonication parameters (e.g., power setting, duration, and amplitude), and the amount of surfactant required adjusted to attain the good dispersion of the nanoparticles in based fluids, to control the best sonication parameters adjustment, and the amount of surfactant required (dispersion fraction).

Fig. 4 Experimental facilities for pH and EC measurements

The EC and pH of the formulated hybrid nanoliquid at the mass-% ratio of 20:80 (ZnO: MWCNT) and φ = of 0.05 vol.% have been measured to achieve the optimum point of the stability of the effective variables. This optimum point is called CMC (critical micelle concentration) and indicates the best of the adjustable optimized. Figures 5 and 6 present the optimum (period and amplitude) of sonication, and surfactant fraction required for the binary nanofluids. An incline in the EC and pH values was noticed while later augmented with an increase in the amount of surfactant required. This drop in significance point of variation meant the critical micelle concentration and so the optimum amount of surfactant required. The CMC point was noticed at sonication parameters (80%, 90 min) and 1.0 the amount of SDS required [49, 50].

Alternative ways to validate the stability of the HNFs the spectrophotometers scheme (JENWAY; MODEl 7315, UK) was used to quantify the absorbance of light passing through the sample. Figure 7 shows the absorbance featured measured for the mano-fluid and hybrid nanofluid with percentage ration(ZnO-MWCNT 80:20, 60:40, 40:60, and 20:80) at 0.1vol% volume concentration for 2000 min. The absorbance peak is between 1.247 and 3.182 through wavelengths of (200–368 nm). Table 3 presents the absorbances and wavelengths of the single nanoparticle and composite NFs. Furthermore, the photographic images of the samples of single and hybrid nanofluids showed no sedimentation and confirmed better stability. So, the samples were found to be stable even after 5 months from the preparation day (Fig. 8).

Characterization of ZnO-coated MWCNTs

The characteristic morphology of the zinc oxide-coated MWCNTs nanosizes powders are presented in Fig. 9(a, b) of hybrid nanofluids as identified by a transmission electron microscope (TEM) and FESEM devices. The NPs at the nanometer scale can be realized from images in Fig. 9(a) on the TEM images. From Fig. 9(b), it can be observed in the FESEM image that the uniform distribution of ZnO wrapper by the MWCNT. It can be noticed that excellent dispersion of the nanoparticles and nanotubes into the aqueous base liquids was attained in the basic to stable HNFs (Table 4).

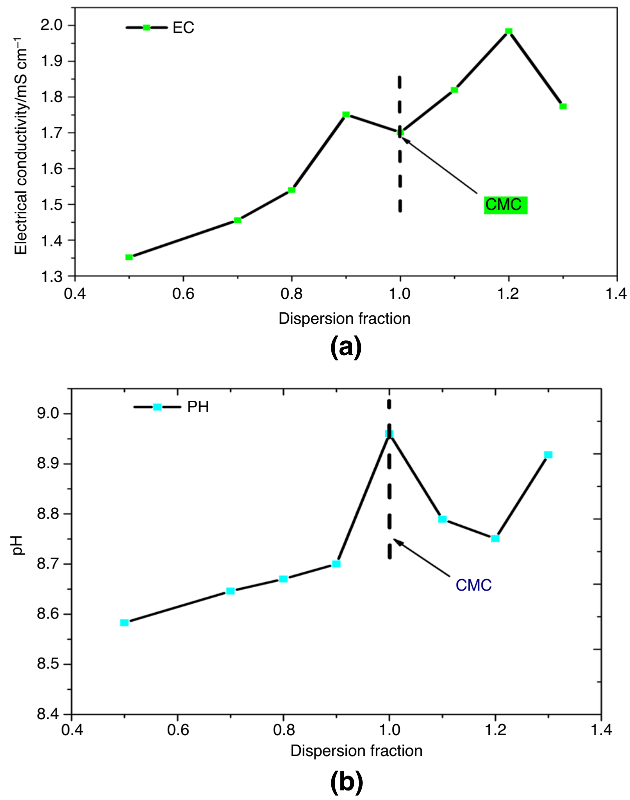


Fig. 5 Optimization of surfactant amount using **a** electrical conductivity and **b** pH value

Validation of thermal conductivity and viscosity devices

The reliability of the meter was achieved through the standard measured viscosity available in the literature [51]. A deviation of 8.67% was estimated between the device reading viscosity of the DIW and the standard values as shown in Fig. 10. After that, the hybrid nanofluid and single-particle nanofluid μ were measured at (20–55 °C). Both the relative μ and augmentation of the considered fluids were estimated by Eqs. (5) and (6), respectively.

$$\mu_{\text{rel}} = \frac{\mu_{\text{hnf}}}{\mu_{\text{bf}}} \tag{5}$$

$$\mu_{\text{enhan}}(\%) = \left(\frac{\mu_{\text{hnf}} - \mu_{\text{bf}}}{\mu_{\text{bf}}}\right) \times 100 \tag{6}$$

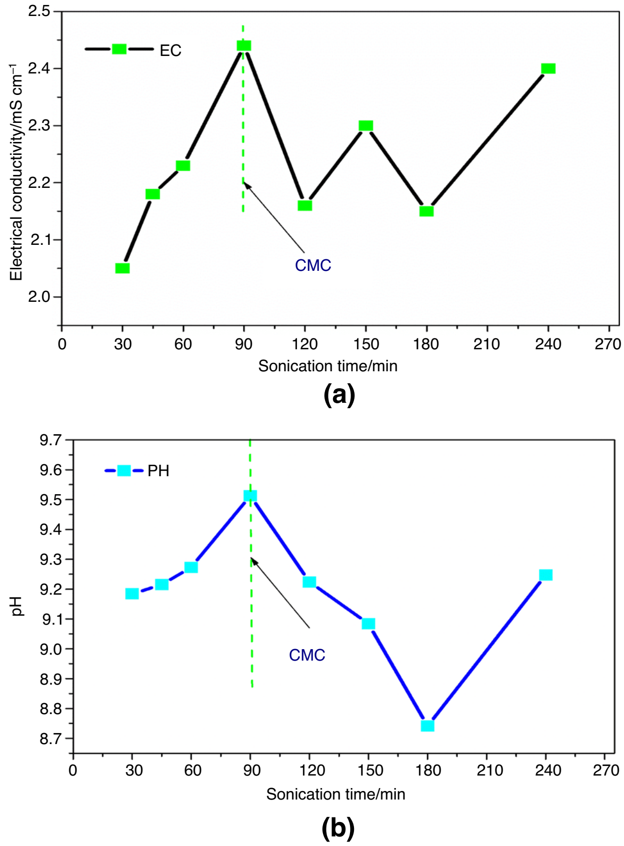


Fig. 6 Optimization of sonication time using **a** electrical conductivity and **b** pH value

where $\mu_{rel}\mu_{hnf}$,μ_{bf} , μ_{enhan} the relative, HNFs, base fluids, and the enhancement viscosity, respectively.

The validation of the verified thermal conductivity of base fluid was related to that of value in the literature [51]

Table 3 Characteristics of ZnO nanoparticle

Parameter	Value
Purity	> 99%
color	white
Morphology	Nearly spherical
diameter	20 nm
Thermal conductivity	29 W m^{-1} K^{-1}
Density	~ 5606 kg m^{-3}

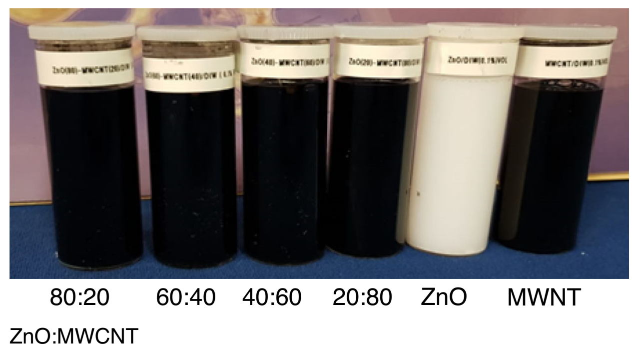
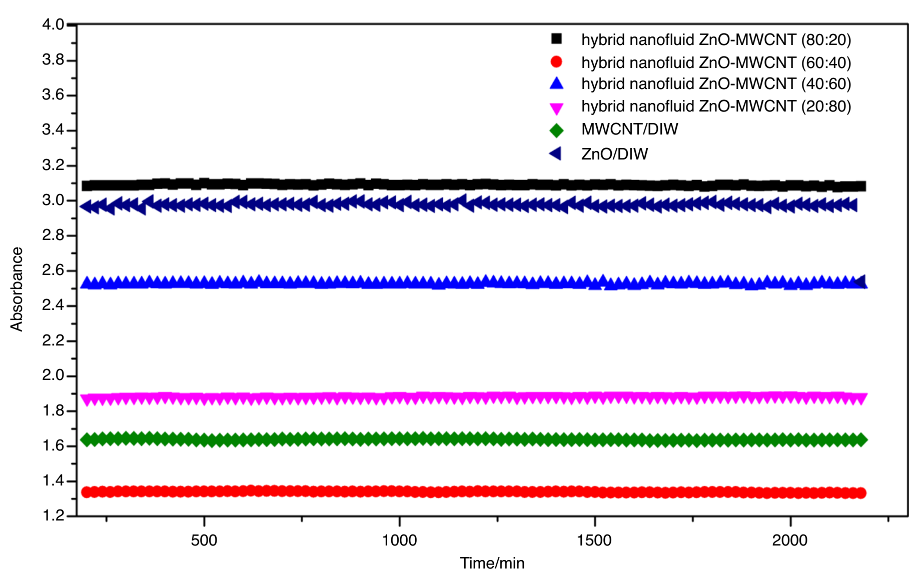


Fig. 8 Samples of prepared (mono and hybrid) nanofluids

at the considered temperature and the reliability was checked off as shown in Fig. 11. Based on experimental data, the relative and enrichment of the thermal conductivity of the HNFs were determined by Eqs. (7) and (8), respectively.

$$\kappa_{rel} = \frac{\kappa_{hnf}}{\kappa_{bf}} \tag{7}$$

Fig. 7 Stability evaluation of mono and hybrid nanofluids



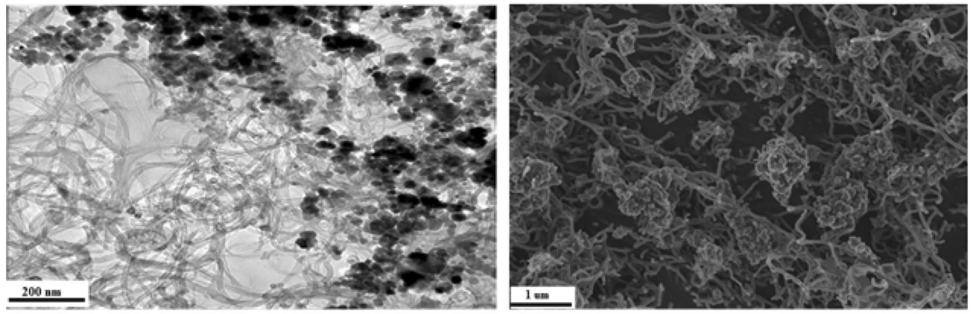


Fig. 9 **a** TEM image and **b** FESEM image of the HNFs

$$\kappa_{\text{enhan}}(\%) = \left(\frac{\kappa_{\text{hnf}} - \kappa_{\text{bf}}}{\kappa_{\text{bf}}}\right) \times 100 \quad (8)$$

where κ_{rel} κ_{hnf} κ_{bf} and κ_{enhan} are the relative, HNFs, base fluids, and the enhancement of the thermal conductivity, respectively.

Viscosity of hybrid nanofluids

The viscosity of nanofluid is an important feature for flow and heat transfer applications. It significantly impacts the required pumping power of the system. The μ of the fluid in laminar flow and the pressure drop are directly related to it, and also the coefficient of convection heat transfer is affected by viscosity. The μ of single nanofluid and hybrid of (ZnO-MWCNT/DW for different percentage ratios of 20:80, 40:60, 60:40, and 80:20) NFs at φ of 0.10 vol.% and temperatures of (20–55 °C) has been carried out. Figure 10 illustrates the effects of the percentage ratio of (20:80, 40:60, 60:40, and 80:20) (ZnO-MWCNT) and temperature range (20–55 °C) on the μ of the HNFs at 0.1 vol.%. From Fig. 12, it can be noticed that the temperature increase principles reduce the μ for all samples of HNFs. Thus, showing a decrease in viscosity as temperature increases which is expected and found in previous studies [52–54]. Also, it was noticed that as the MWCNT increases through a corresponding reduction of ZnO nanoparticles, the hybrid nanofluids viscosity reduces. This can be attributed to the weightier and larger density of ZnO (5.606 g m^{-3}) compared to that of MWCNT (2.1 g m^{-3}) nanotubes. A related trend is detected in Fig. 13 for the hybrid nanofluids with the percentage ratios 80:20 and 40:60 having the maximum and minimum viscosity, respectively.

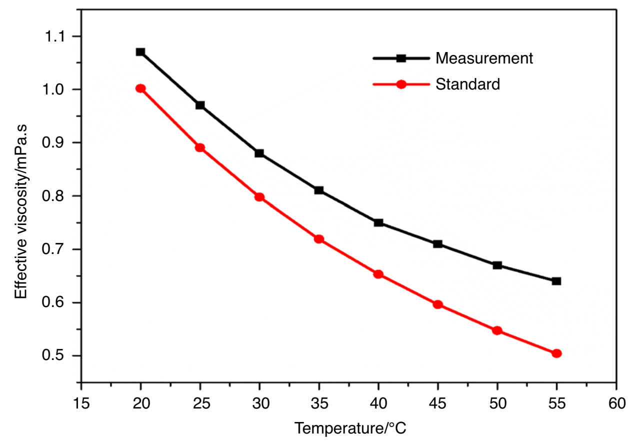


Fig. 10 Comparison of measured viscosity of based fluid (DIW) and standard data [52] with temperature rise

The viscosity of the single nanofluids (ZnO/DIW and MWCNT/DIW) is dependent on the temperature. As illustrated in Fig. 14, an increase in temperature reduces the viscosity of the NFs. The (Zinc- Oxide/DIW) was noticed to have a greater μ than the (MWCNT/DIW). The μ of ZnO nanoparticles is higher than MWCNTs nanotubes. Thus, the measured μ of the NFs was an effect of the densities of ZnO and (DIW). The achieved results are aligned with the published results [6, 56–59]. It can be seen from Figs. 12 and 13 that the μ of the HNFs is lower compared with the single NFs. Thus, showing a decrease in viscosity as temperature increases which is also in line with with previous studies.

Furthermore, the enhancement in the effective viscosity is presented in Fig. 15. The viscosity was enhanced by 12.27% –33.33%, 10.38%-31.58%, 6.6%-27.72%, and 9.43%-30.81% for percent mass ratio (20:80, 40:60, 60:40

Table 4 Wavelength and absorbance of mono and hybrid nanofluids

Variable	MWCNT	ZnO (20 nm)	ZnO-MWCNT (80:20)	ZnO-MWCNT (60:40)	ZnO-MWCNT (40:60)	ZnO-MWCNT (20:80)
Absorbance	1.673	2.565	3.182	1.347	2.587	1.895
Wavelength	291	368	296	290	291	287

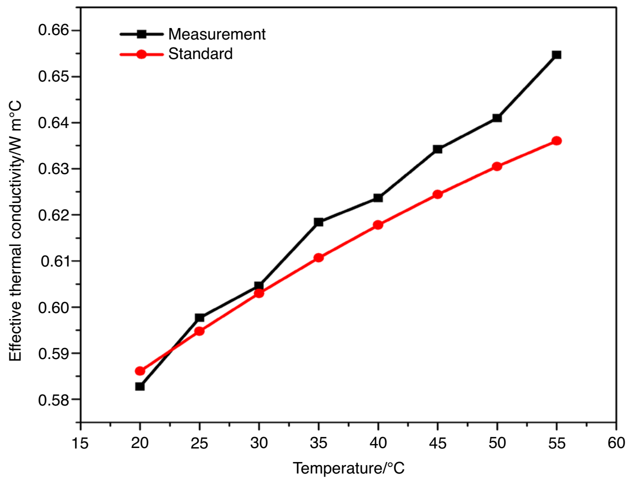


Fig. 11 Comparison of measured thermal conductivity of based fluid (DIW) and standard data [52] with temperature rise

and 80:20) (ZnO-MWCNT) of hybrid nanofluids compared to based fluid (DW) at measured temperature. The results of works of literature [11, 26, 30, 59] also showed enhancements of 23.24%, 24.56%, 33.3 and 4.55–20.43% for based (DW) ND-Ni (84:16), (DW) Al_2O_3-MWCNT (80:20), (SAE40) MWCNT/ZnO(90:10), (DW) CNT-Fe_3O_4 (26:74) and (DW) (25%:75%) Al_2O_3-Fe_2O_3 HNFs, respectively.

Thermal conductivity of HNFs

Figure 15 presents the thermal conductivity of HNFs at different percent mass ratios of hybrid nanoparticles with increasing temperature. From Fig. 15. A clearer demonstration of the effect of dispersion composite nano-size material into the base fluids, the κ increased significantly with increasing temperature the κ was also found to enhance which is similar to reported results from the

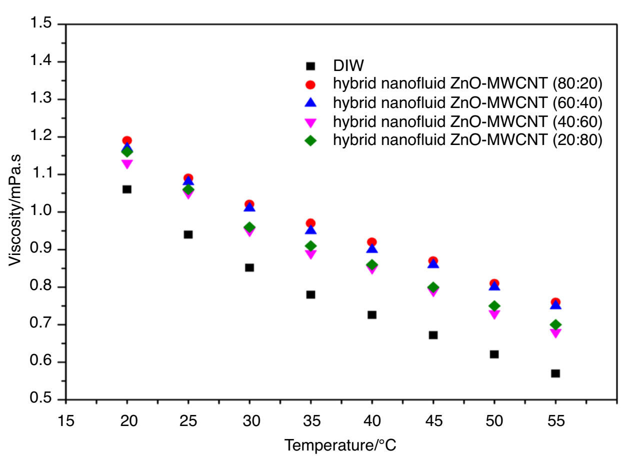


Fig. 12 Viscosity of HNFs with temperature rise

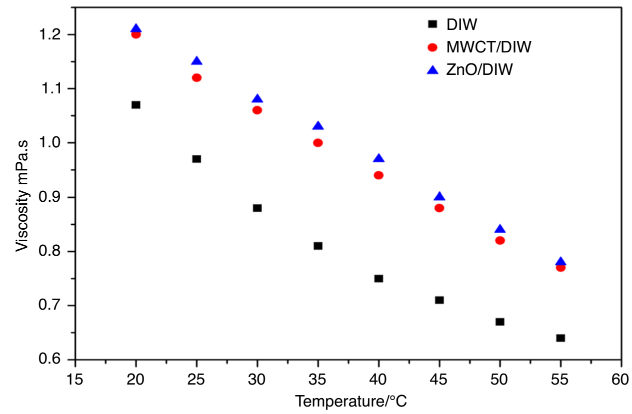


Fig. 13 Viscosity of conventional (mono) nanofluids with temperature

literature [11, 16, 60]. With the use of ZnO-MWCNTs (Fig. 15), the thermal conductivity of 20:80 composite nanofluid was the highest followed by 40:60, 60:40, and 80:20 samples. The higher thermal conductivity contributed to the κ of MWCNTs nanotubes (2000 W m^{-1} K^{-1}), the interaction between the thermal conductivity of ZnO nanoparticles (29 W m^{-1} K^{-1}) and based fluid [61] assumed to be accountable for the observed outcomes. This was similarly agreed with the consequences obtainable in Fig. 16 which exhibited that the thermal conductivity of (MWCNT/DIW) NFs is higher than (ZnO/DIW) nanofluid.

Figure 17 represents the κ enhancements of HNFs samples which are 10.17–23.11%, 8.10–17.25%, 6.20–14.36% and 6.10–12.71% for temperature range (20–55 °C) and the percentages mass ratio of (20:80, 40:60, 60:40 and 20:80) ZnO-MWCNT hybrid nanofluids, respectively, in comparison with based fluids DW. Form Fig. 16 it can be understood that the higher enhancement of

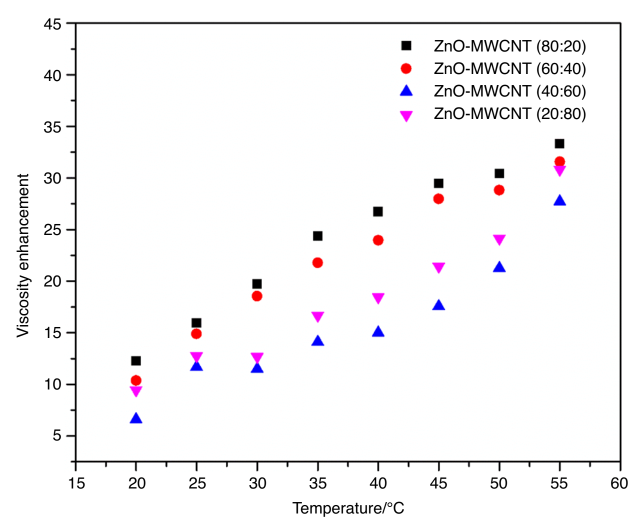


Fig. 14 Enhancement of viscosity of hybrid nanofluid with temperature rise

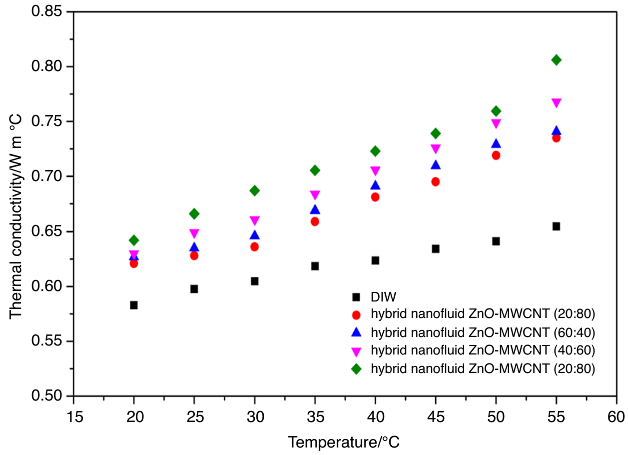


Fig. 15 Thermal conductivity of hybrid nanofluids with temperature rise

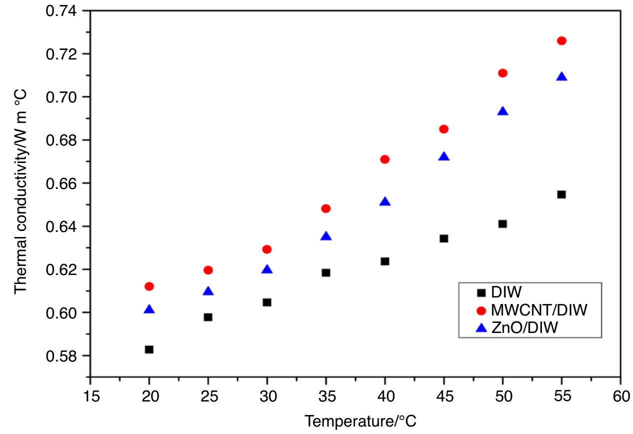


Fig. 16 Thermal conductivity of mono nanofluids with temperature rise

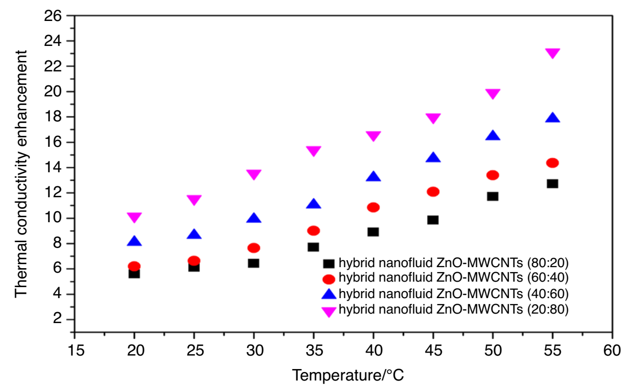


Fig. 17 Enhancement (%) of κ of hybrid nanofluids with temperature rise

κ is 10.15% (at 20 °C)–23.11% (at 55 °C) recorded for the 20:80 (ZnO: MWCNTs) sample. The reason for thermal conductivity enhancement is understood to be due to the temperature increase that led to Brownian Motion augments collision between the nanoparticle and nanotubes. A further factor for the thermal conductivity enhancement is, while the nanoparticles and nanotubes are suspended in the base fluid, the heat transfer in nanoparticle and nanotubes suspended takings place at the particles and nanotubes surface area, the growth in the heat transfer area can lead to further growth the effective heat transfer properties through collision caused by Brownian motion.

The works in the literature [41, 58, 62] examined the percent mass ratios of hybrid nanofluids with the maximum thermal conductivity enhancement and reported 22.8%, (60:40)(TiO_2-SiO_2/W-EG), 26.9%, (80:20)(SiO_2-CuO/C), 32% (20:80)(SWCNT-MgO/EG), respectively, which were outside the mass% ratio (20:80 (ZnO: MWCNTs)) of this study that resulted the maximum thermal conductivity augmentation. Earlier researchers have reported the κ augmentations of 28.1% (ZnO-MWCNT/EG-W (50%:50%) at 1.0 vol.% and at 50 °C [63], 17.8% (ND/Fe_3O_4 (20:80)/(EG-water) at 0.2 vol.% and 60 °C [64], 37% (CNT–AuNP)/water at 0.5 vol.% and at 30 °C [10], 29% (MWCNT–Fe_3O_4/water at 0.3 vol% and at 60 °C [11], 14.7% (Al_2O_3/Fe_2O_3 (25:75)/DIW at 0.3 vol.% and at 40 °C [65], 30.38% (MWCNT-CuO/DIW) at 50 °C and 0.6 vol.% [40]. The present results are well within the range of values stated in these works.

Electrical conductivity of nanofluids

The performance of the nanoliquid to conducted currents can be defined as the ability of an aqueous solution to conduct electric current it is named electrical conductivity. The EC of hybrid nanofluids is not adequately studied compared to their μ and κ. Figure 18 shows the electrical conductivity of ZnO-MWCNTs/DW-based HNFs at various percent mass ratios with a temperature increase. Adding the nanocomposites to DIW leads to a significant rise in the EC of the DIW. The 80:20 percent mass ratio hybrid nanofluid was found to yield the maximum values of electrical conductivity, whereas the 20:80 sample had the minimum values of electrical conductivity. Rising the temperature from 20 to 55 °C showed a slight augmentation of the EC for DIW and HNFs. These results are consistent with earlier works in which the EC of NFs improved with increasing temperature and nanoparticle loading at other hybrid and single nanofluids [65–67]. This was also agreed with the results presented in Fig. 19 which confirms that the EC of (ZnO/DW) was greater than (MWCNT/DW) nanofluid is also noted that the metallic oxide nanoparticles (ZnO) have superior electrical conductivity compared to nonmetallic nanotubes (MWCNT).

The enhancement of the EC of the binary nanofluids related to the DIW at different temperatures is presented in

Fig. 20. It can be detected that the EC of (80:20, 60:40,40:60 and 20:80) ZnO-MWCNTs hybrid nanofluids was enhanced by 325.93–368.10%, 303.71–334.40%, 255.56–273.94% and 214.82–236.00% with the rising temperature. [20, 26, 33] reported increases in electrical conductivity of 1339.81–853.15%, 97–557%, and 163.37–1676.4%, for DW (85:15)/ND-Ni- at 0.1 vol% and 24–65 °C, and 20–50 °C), (0.01–0.08 mass%) SiO_2/G (naphthenic mineral oil) and (MWCNT)-Fe_2O_3 (20:80) at 55 °C and 1.5 vol% hybrid nanofluids, respectively. From the present results, the EC of composite nanoliquids was greater than that of single nanoliquids.

Correlation development

The theoretical models and classical models for predicting the thermophysical properties of NFs have been developed by numerous researchers to be insufficient for their approximation [65, 68], and they also overestimate or underestimate the experimental thermophysical properties data of a single (mono) nanofluids or hybrid nanofluids. There is a need to develop correlations to expect the thermophysical properties of the NFs. According to the experimental results of μ, κ, and σ, they were estimated. The experimental data were fitted to advance correlations for the studied properties' estimation. Table 5 presents the correlations for the thermal properties as a function of temperature for hybrid nanofluid. The correlations established for the relative viscosity have the coefficient of determination (R-squared) R^2 in the range of 97.20–99.06%. The established correlations of relative thermal conductivity with R^2 of 99.58–99.32% have been obtained. Last the developed correlations of relative electrical conductivity as a function of temperature. The prediction accuracy for the correlations is between 94.87 and 98.26%.

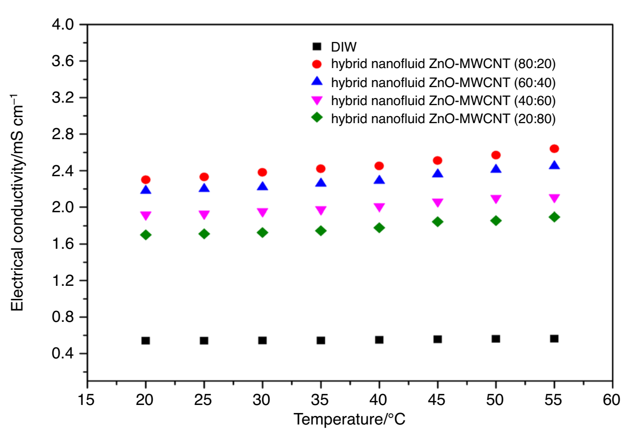


Fig. 18 The hybrid nanofluid's electrical conductivity with temperature rise

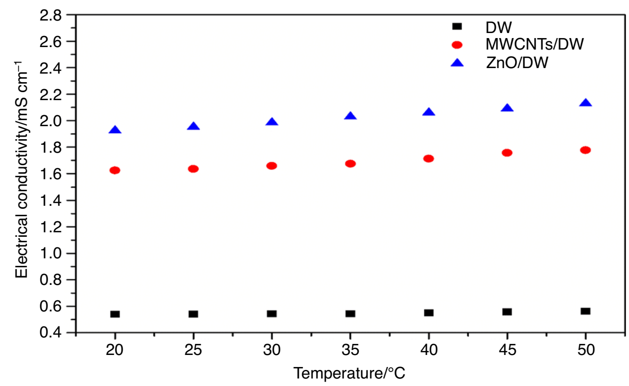


Fig. 19 Electrical conductivity of mono nanofluids at 0.10 vol% with temperature rise

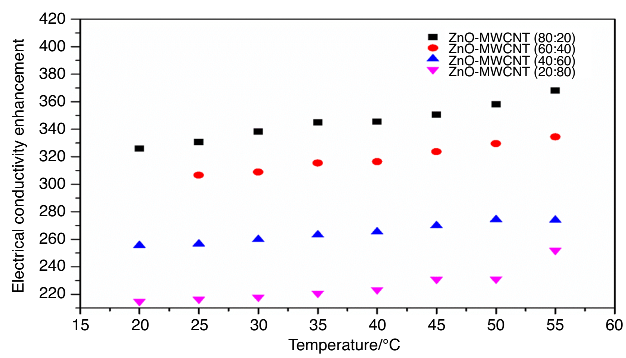


Fig. 20 Hybrid nanofluid's electrical conductivity enhancement with temperature rise

Comparisons of the predictions of results from present and common correlations

A comparison of the estimated relative viscosity, and thermal and electrical conductivity (fitted into correlations) with existing correlations from the literature for hybrid nanofluids was carried out as presented in Figs. 21 and 22.

The curve fittings of the viscosity result used for this study and the data found in the earlier studies for evaluation are demonstrated in Fig. 21. The correlations proposed by Esfe et al. [62, 69], Taherialekouhi et al. [70], Zadkhast et al. [40] and Akhgar et al. [71] are compared. It was observed that the curves fitted as of the correlations suggested by Taherialekouhi et al. [70], Zadkhast et al. [40], Akhgar et al. [71] nanofluids could not fit the obtained relative effective thermal conductivity data. Only the Esfe et al. [62] correlation fits data for ZnO-MWCNT/DW hybrid nanofluid with a 20:80 ratio between 45 and 55 °C.

Figure 22 shows the comparison of the correlations proposed from this study and the correlation previously published such as in Nabil et al. [58], Giwa et al. [65], Esfe et al. [72], and Hamid et al. [31] that have been fitted and related to the fitted result for this work (from Fig. 19).

Table 5 Developed correlations for this investigation

Parameter	ZnO-MWCNTs (80:20)	ZnO-MWCNTs (60:40)	ZnO-MWCNTs (40:60)	MgO-ZnO (20:80)
Relative viscosity				
$\frac{\mu_h}{\mu_b} =$	$1.0794 + 2.83 \times 10^{-3}T$	$1.0625 + 2.99 \times 10^{-3}T$	$1.0061 + 2.61 \times 10^{-3}T$	$1.0217 + 3.01 \times 10^{-3}T$
Relative electrical conductivity				
$\frac{\sigma_h}{\sigma_b} =$	$4.0323 + 1.145 \times 10^{-2}T$	$3.8391 + 0.904 \times 10^{-2}T$	$3.3858 + 0.728 \times 10^{-2}T$	$2.964 + 0.937 \times 10^{-2}T$
Relative thermal conductivity				
$\frac{k_h}{k_b} =$	$1.0364 + 3.36 \times 10^{-3}T$	$0.9802 + 2.80 \times 10^{-3}T$	$0.9931 + 2.77 \times 10^{-3}T$	$0.998 + 3.45 \times \times 10^{-3}T$

h = hybrid nanofluid; b = base fluid (DIW)

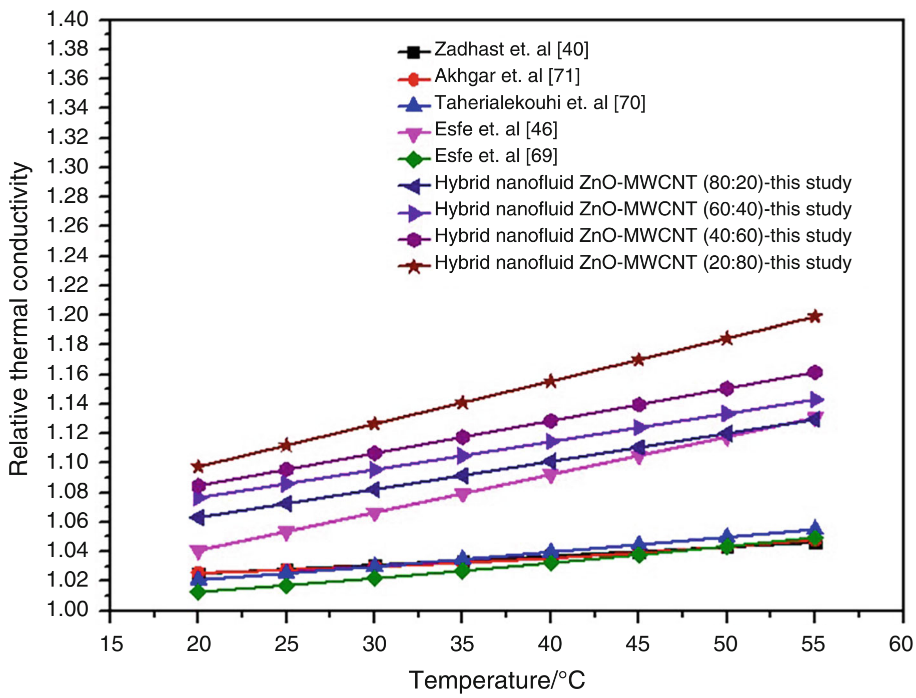


Fig. 21 Comparisons of the relative κ of ZnO-MWCNT/DW hybrid nanoliquids at 0.10 vol% from existing and present correlations

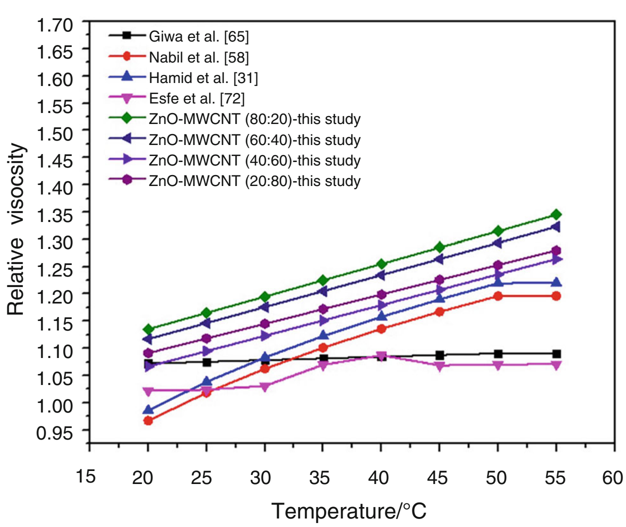


Fig. 22 Comparisons of the relative μ of ZnO-MWCNTs/DW hybrid nanofluids at 0.10 vol% from existing and present correlations

It can be detected that correlations such as those reported by Nabil et al. [58] overestimated the relative viscosity of 80:20, 60:40,40:60, and 20:80 hybrid nanofluids. There is a need to advance relationships to predict the comparative μ, σ, and κ for all percentages mass ratios of ZnO/MWCNT/DW HNFs.

Conclusions

Stable ZnO-MWCNT/DIW hybrid nanofluids (HNFs) have been prepared after optimizing the sonication parameters as well as the amount of surfactant (SDS). Thermophysical and electrical properties including viscosity, thermal conductivity, and electrical conductivity of the HNFs have been experimentally investigated at $\varphi = 0.1$ vol%, and percentage mass ratios of (ZnO-MWCNT) 80:20, 60:40, 40:60, and 20:80, and at temperature range from 20 to

55 °C. The hybrid nanofluids were found to be stable using a UV–Vis spectrophotometer and optical check. Also, the morphology of the HNFs has been characterized by TEM and SEM images and confirmed to be well dispersed. With increasing temperature, the κ and σ of the HNFs increased significantly while the viscosity as usual showed a decreasing trend with the temperature. In comparison with the DIW, maximum augmentations of 23.11%, 368.1%, and 33.33% are attained for κ, σ, and μ of the HNFs, respectively, at 0.10 vol.%. The obtained results are found to be reliable by comparing them with those of earlier works in the literature. The hybridization of nanoparticles for preparing hybrid nanofluid has shown to have a lower viscosity than that of the mono nanofluids and to be beneficial in engineering particularly thermal applications compared to single type of nanoparticles. Also, the 40:60 hybrid nanofluid was found to be the best with the lowest viscosity which was advantageous to reducing the pumping power required for engineering applications. New correlations which have been proposed for the predictions of μ, κ, and σ of the studied hybrid nanofluids found to yield better predictions compared to existing correlations from literature.

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