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Original article

Experimental studies on thermal and physical characteristics of mono and hybrid nanofluids

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ABSTRACT This research paper aims to present experimental findings on important thermophysical properties such as thermal conductivity, viscosity, and density of selected nanofluids. Ethylene glycol is considered as the base fluid, and multi-walled carbon nanotubes, zinc oxide, aluminum oxide nanoparticles are used in the present study. The nanopartices are chosen due to their remarkable thermal and physical properties. The results indicate that the thermal conductivity of the ethylene glycol increases in a linear manner when Al_2O_3, MWCNT, and ZnO nanoparticles are dispersed in the base fluid. Particle concentration varied from 0.1 to 0.3 vol %. The highest increment noted is 39 % at the highest concentrations. The viscosity of the nanoparticles containing ethylene glycol improves with temperature, and Al_2O_3 and MWCNT have the highest improvement. Thus, the density analysis shows that the nanofluids with 0.1 and 0.2 vol % nanoparticles dispersed in ethylene glycol and having 0.2 vol % have less fluctuation compared to nanofluids with 0.3 vol %, which may affect various characteristics of the coolant considerably. This shows how nanofluids can help in managing the thermal conditions of automobiles and electronic gadgets.

KEYWORDS hybrid Nanofluids, thermal conductivity, viscosity, density, automobile

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1. Introduction

Nanofluids are suspended with small particles having high heat conductivity, and these particles may be metal oxides or carbon nanotubes. The concept of nanofluids is comparatively recent and originated in the last decade, mainly with the first research focused on the introduction of nanoparticles into basic fluids. Nanofluid as a term was first used in the 1990s by Dr. W. Yu and colleagues at the Argonne National Laboratory. During the beginning of the 2000s, the primary focus in the field of nanofluids was to determine potential applications of the nanofluids and to develop methods to control problems such as instability and sedimentation. Thermal conductivity is a significant parameter, especially in heat transfer applications of nanofluids. It improves heat exchange between hot cores and coolants, productivity, stability, and prevents hot spots in the cooling systems, prolonging the life span of the engine elements. This paper discussed the thermal efficiency of mono- and hybrid nanofluids using ethylene glycol as a base fluid with different concentrations. Nanofluids having metallic particles with dimensions less than 100 nm inspired considerable interest due to their enhancement of heat transfer. Some of the materials used due to their unique thermal conduction include aluminum oxide (Al_2O_3), zinc oxide (ZnO), and multi-walled carbon nanotubes (MWCNTs). Nanoadditives have been incorporated into the engine coolants to increase their thermal effectiveness, so smaller radiators can be employed; thus, there is less weight and less fuel consumption. The study was focused on the utilization of nanofluid in cool blends of the engine by applying an accurate proportion of nanofluid to the basic fluid with the help of an ultrasonic wave device. The analysis of the results revealed that these nanoparticles, which include Al_2O_3, ZnO, and MWCNTs, are capable to increase the rates of heat transfer. This effect is illustrated when the nanofluid, which consists of ethylene glycol, has a volumetric fraction of 0.1 to 0.5 vol %. For high-efficiency engines, it is vital to provide an adequate rate of cooling, as overstress can bring about problems such as excessive heat, which affects the viscosity of oils, and the failure of different engine parts, among others. Thus, the various parameters of the radiator have to be chosen adequately in order to achieve consistently high efficiency in the engine's operation, especially if a new type of radiator design is to be developed.

The advantages were demonstrated with the new use of hybrid nanofluids as prominent in heat transfer systems, implying their importance in enhancing the heat transfer industry. Ethylene glycol plays another role in heat transfer, as this fluid, when mixed with silicon carbide nanoparticles as the base fluid, has the effect of improving thermal conductivity, thus increasing the efficiency of heat dissipation [1]. The study [2] showed that the thermal conductivity of multi-walled carbon nanotubes-dispersed ethylene glycol increases significantly, which in turn considerably enhances the heat transfer coefficient in solar thermal applications. Ethylene glycol is very important for increasing the boiling point of water and thus improving the efficiency of heat transfer in radiators, as shown by nanofluid studies [3]. Hybrid nanofluids are valuable because they raise heat transfer efficiency, decrease entropy generation, and offer ecologically sound means of transferring heat; hence, they find application in various heat transport processes [4]. Both types of nanofluids also show enhanced thermal and viscous properties; therefore, they are optimal for the improvement of heat transfer in heat exchangers, reduction of weight fractions, and increase in system efficiency [5, 6].

MWCNTs, Al_2O_3, and ZnO are widely used materials in nanofluids that affect heat transfer efficiently in numerous applications. These nanoparticles, when incorporated in nanofluids, enhance the thermal attributes and thus are applicable for heat transfer fluids in the aerospace and automobile industries, as well as renewable energy [7]. A study on the convective heat transfer coefficient and thermo-physical properties of Al_2O_3 nanoparticles in ethylene glycol has been presented for the possibility of increasing the enhanced heat transfer rates. Also, the enhancement of heat transfer coefficient is observed when ZnO nanoparticles are suspended in ethylene glycol using the base fluid ratio as follows: therefore, it can be concluded that ZnO/Ethylene glycol can be a good solution to control overheating problems in different industries. Additionally, the adjustable heat transport rate in ethylene glycol with ZnO and MWCNT hybrid nanofluid has revealed the best improvement out of all feasible nanofluid pairs, which is consistently essential in modernized heat transfer technologies [8–10].

The term nanofluid refers to a liquid enhanced with nanoparticles; the thermal conductivity of a heat exchanger is enhanced with the application of hybrid nanofluids, besides improving the mixing ratio of the nanoparticles [11]. Nanofluids enhance the base fluid's thermo-physical characteristics and heat transfer coefficients, making them useful for applications like heat exchangers, heat sinks, heat pipes, solar panels, and air conditioning [12]. On the method of preparing hybrid nanofluids, one-step and two-step methods are common, and in terms of durability, they apply the use of surfactant addition, surface treatment, and pH modification [13]. The preparation of hybrid nanofluids includes the addition of surfactant to improve stability, and the main focus will be on the preparation technique, which is important for the enhancement of the thermophysical property and heat transfer performance of the nanofluids [14]. Ultrasonication is widely used in the preparation of nanofluids since it enhances dispersion and thus leads to higher stable fluids, reduced particle size, higher thermal conductivity, and lower viscosity values [15].

For the preparation of nanofluid, it has been established that the duration of ultrasonication increases with an increase in dispersion, thermal conductivity, and density, as well as decreases with an increase in viscosity. Thus, the enhancement of thermal conductivity by ultrasonication for alumina-water nanofluids is favorable for heat transfer since it enhances stability [16]. The flowing drag coefficients of the nanofluids and the heat transfer coefficients are the viscosity and the coefficient of thermal conductivity, which are imperative in the design of the nanofluid system [17]. The viscosity of nanofluid is useful in convective thermal transport, and through the functioning of the ANSYS-based model, very accurate results are obtained for heat transport systems [18]. Nanofluid density influences heat transfer characteristics such as Reynolds number, Nusselt number, pressure loss, and the Darcy friction factor in heat transfers [19]. The study of thermal conductivity of nanofluids also focuses on hybrid nanofluids since they possess special thermo-physical properties significant for heat transfer [20].

Al_2O_3 and MWCNT hybrid nanofluids enhance the thermal conductivity of radiator coolant in response to temperature and volume fraction changes. The maximum gain with 0.5 % vol % was 11 % at 60°C. These improved thermophysical properties of nanofluid are important in solar applications since heat transfer is improved [21]. Therefore, nanofluids, when focused on the radiator coolant, prove to have a lower total outlet temperature as opposed to conventional coolants. The thermal conductivity of the nanofluid is higher than that of other fluids and enhances with an increase in temperature, especially for high-rpm engines. This leads to small radiators, better configuration and design, and lower pumping energy for better engine performance [22]. Rahul Ghimire et al. investigated the thermal characteristics of Al_2O_3 and ethylene glycol/water nanofluids in a vehicle radiator's flat tube using single and multiphase simulations and revealed that the later technique was more accurate [23]. Kumar et al. investigated the thermal conductivity of concentrated polyester oil with nanoparticles prior to and during ball-milling. They applied the Taguchi methods for designing parameters and realized an enhancement of the thermal conductivity of 0.020 W/m-K and a reduction in the friction coefficient [24]. Srimanickam et al. have made a comparison of water and nanofluid thermal efficiency with the help of Al_2O_3 nanoparticles. They identified a maximum improvement of 79.4 %, which is similar to any volume flow rate of water. Nanoparticles of Al_2O_3 enhanced thermal conductivity by 1.988 %, which is enabled the diurnal average thermal efficiency [25].

Raviteja Surakasi et al. have identified the role of TiO_2 nanoparticles as vital in environmental purification and water treatment. The zeta potential of TiO_2 nanofluids with pure CNTs was lower at the start, but SM-CNTs were more stable in coolants. Oxidized CNTs also maintained a constant zeta potential for two months [26]. Similar to the Alniacar study, Karar Mahdi Al-Araji et al. noted that by employing a nanofluid that is affected by the conductivity coefficient and the viscous coefficient, it is possible to enhance the thermal improvement value by more than 50 percent. Being inexpensive and highly effective, Al_2O_3 nanoparticles are widely employed [27]. In the preparation of nanofluids, Sanjeev Kumar Gupta et al. proposed two ways of sonicating, magnetically stirring, and homogenizing the base fluids with nanoparticles effectively and at a relatively low cost. To address the problems of nanoparticle deposition and buildup, this method optimizes the flow through the solar collectors and enhances the heat transmission rate with an increase in the concentration of the nanoparticles [28]. Serdar Mart et al. indicated that there is a possibility of enhancing the engine coolant's cooling capacity by up to 17.46 % when Al_2O_3 nanoparticles are incorporated. In this aspect, the density of Jews also decreased to 46 % from the original design. The study provided a comparative analysis between the cooling power per unit area, velocity, and flow rate of the clearance fluid for the engine radiator and the nanofluid to show the prospect of nanofluids as coolants for automobile engines [29]. In their study, Reza Aghayari et al. found that the Timofeeva, Drew, and Passman theoretical models present the thermal conductivity and viscosity of nanofluid. They concluded that employing Fe_2O_3/water nanofluid raised the values of Nusselt number, heat rate, and friction factor to the highest expressional thermal efficiency factor of 3.25 [30].

A study carried out by Akshata Pattanshetti et al. revealed that the nanocomposite films, the garlic powder, and the garlic microparticles exhibited substantial antibacterial effects in Gram-positive and Gram-negative bacteria species. The 3 % MWCNT film exhibited the steepest increase in antibacterial activity, and the GMs presented the optimum antibacterial efficacy because of the high SV ratio [31]. Abu Raihan Ibna Ali et al. also discovered that appropriate stability is the primary issue with nanofluid, which is critical for heat transfer. However, for the synthesis of nanoparticles and the required stability, further research has to be conducted on identifying the optimal sonication and magnetic stirring times, the concentration of the surfactant, and the mixture of nanoparticles [32]. CuO nanofluid, as per the research done by N. Sadashiv Vele et al., has excellent heat transfer characteristics and lower pressure losses compared to Al_2O_3 nanofluids. The study therefore recommends studying the Brownian motion of nanoparticles to improve their heat transmissivity. Further studies are necessary in order to better understand the mechanism by which hybrid nanofluids enhance heat transfers in practical applications [33].

Zafar Said et al. found that Al_2O_3-DW/EG nanoparticles with a 1:1 nanoparticle to AG surfactant mass ratio were the most stable sample, while TiO_2-DW/EG nanofluids with a 0.3 % volume fraction and no surfactant added were the most stable. High volume concentrations negatively affected nanosuspension stability. Al_2O_3-based nanoparticles indicated reduced corrosion at acid electrolyte and an elevated Nusselt number at 1 L min^{-1}1 [34]. The ZnO water nanofluids have a bright future in the automotive industry as well as in heat exchanger systems due to their improved heat transfer characteristics, light-weight radiators, and lesser fuel consumption", said Muhammad Qasim et al. Muhammad Qasim et al. have found that ZnO water nanofluids are promising for use in the automobile industry and heat exchangers because of enhanced heat transfer properties, lightweight radiators, and reduced petrol consumption. This is because a 0.2 % by volume concentration of such particles has resulted in decreased pressure drop and friction factor [35].

2. Selection of nanomaterials and base fluid

Aluminum oxide (Al_2O_3) nanoparticles are smaller than 100 nm. It has a huge surface area-to-volume ratio, which makes it of great importance in uses such as catalytic agents, circuits, medicine, and the environment. Multi-walled carbon nanotubes (MWCNTs) are long and thin carbon cylinders that have high mechanical, electrical, thermal, and optical properties. They are very strong and have high mechanical strength, which makes them among the hardest-known compounds. However, MWCNTs present brilliant electric conductivity, so they are useful for electronic in addition to energy applications. Zinc oxide nanoparticles (ZnO NPs) may be described as structures comprising zinc oxides that are very small and typically have sizes within the nanometer spectrum, which is between 1 and 100 nanometers. They possess some special characteristics, for instance, high photocatalytic activity, in which a material can decompose organic molecules in a solution with UV light. Also, ZnO nanoparticles have bactericidal properties, which make them an effective factor in the inhibition of bacterial as well as fungal development. This has made it compulsory to incorporate them in quite many consumer goods, like textile antimicrobial coatings, packaging, and medical devices, among others. The nanomaterials Alumina, MWCNTs, and ZnO nanomaterials are purchased from Nano Research Lab, Jharkhand.

Ethylene glycol is a clear, colorless, tasteless liquid often used as a capability of polymers. This molecule consists of two hydroxyl groups; hence, it is a dihydric alcohol. One of the main uses of this substance is in motor vehicle cooling systems as antifreeze in car radiators. As for the freezing point, it is considerably low, due to which ethylene glycol can remain in the liquid state even at extremely low temperatures. The positioning of this property is useful in ensuring that the radiator does not freeze during the winter period. However, the potency of the poison that it has is something to be worried about. Ingestion of ethylene glycol causes deep poisoning because the compound gets metabolized in the body to produce toxic products, which leads to kidney damage, neurological complications, and death. Considering the fact that ethylene glycol is toxic, it is important to avoid contamination by handling and disposing of products that contain the substance. This is in essence necessary to prevent any form of pollution to the environment or harm to any living species. That is why ethylene glycol is considered dangerous but remains indispensable as an industrial material with critical uses that are not limited to automotive ones. Some of these applications include the production of polyester fibers, plastics, and as a solvent across various industries. Some thermo-physical properties of the nanomaterials and the base fluid are listed in Table 1.

TABLE 1. Thermo-physical properties of Nanoparticles and Base fluid

Name of the material	Molecular Mass (g/mol)	Thermal conductivity (W/m-K)	Specific Heat (J/Kg k)	Density g/cm^3)	Boiling Point (°C)	Melting Point (°C)
Al_2O_3	101.96	17.65	525	3.97	2977	2055
MWCNTs	120.1	2586	550	2.1	4027	3550
ZnO	81.38	49	494	6	2360	1975
Ethylene Glycol	62.08	0.253	2093	1.11	197.3	−12.9

2.1. Characterization of nanoparticles using XRD and UV

2.1.1. UV and XRD analysis of Al_2O_3 nanoparticles. UV-Vis spectroscopy is indispensable for the characterization of Al_2O_3 nanoparticles due to its importance for the understanding of the optical, electronic, and surface characteristics of nanoparticles. It can be used for finding absorption characteristics, transparency, band gap energy, size-dependent characteristics, defects and impurities, SPR, concentration and stability investigations, interaction with other materials, and surface functionalization. UV-Vis spectroscopy is especially helpful in determining UV protection, coatings, and transparent ceramics in electronic and optoelectronic devices, surface plasmon resonance, and composites. It is also used in defect sensing, impurity analysis, and surface plasmon resonance experiments. In conclusion, UV-Vis spectroscopy plays a key role in controlling and improving the Al_2O_3 nanoparticle properties essential for their application in modern high-tech applications in optics, electronics, catalysis, and material science.

The UV-Vis absorption spectrum of synthesized Al_2O_3 nanoparticles presented in Fig. 1 revealed considerably high light absorption capability, with a with a marked "band edge" peak at around 400 nm. It ranges from 400 nm to 600 nm, and the graph steadily drops as the wavelength increases. The spectrum also looks to extend down to the longer wavelengths, which is another way of saying that it is quite broad. The high value and the decrease rate demonstrate high purity as well as crystallinity on the basis of absorbance and crystallinity, whereas the same sample contains numerous different peaks that determine less impurity or secondary phase. Thus, a large absorption tail points to the existence of different sizes of nanoparticles or variations in the surface states, which is quite typical for nanoscale materials. From the UV-Vis absorption properties, there could be applications in ultra-violet protection coatings, sensors, and optical apparatus. Further characterization and comparison of these nanoparticles with doped or modified Al_2O_3 nanoparticles will help to elucidate their optical properties.

The X-ray diffraction pattern for Al_2O_3 nanoparticles illustrated in Fig. 2 has diffraction peaks. These peaks can be used for the comparison with the standard diffraction pattern proves that the sample is crystalline. The peaks width gives information about the crystallite size, while the broader peaks suggest a small crystallite size. The crystallite size of Al_2O_3 nanoparticles was calculated using the Scherrer formula, $D = \dfrac{K\lambda}{\beta\cos\theta}$ where, K is the shape factor (0.9), λ is the X-ray wavelength (1.5406 Å), β is the full width at half-maximum (FWHM), and θ is the Bragg angle. The estimated size was approximately 33 nm.

2.1.2. XRD analysis of MWCNTs. The X-ray diffraction (XRD) pattern of the Multi-Walled Carbon Nanotubes (MWCNTs), as shown in Fig. 3, has specific features that include a prominent (002) peak at 2θ = 26 °C, signifying the presence of graphical carbon. The other two peaks can be indexed to the (100) and (004) crystallography planes of graphite. The peak at $2\theta = 26^\circ$ represents the highest intensity, which demonstrates high graphitization. The broadening of the first peak indicates that the MWCNTs possess nanoscopic characteristics and structure the irregularity. Based on background noise and a broad shoulder at $2\theta \approx 25^\circ$, there is usually amorphous carbon and a wide peak at $2\theta = 20^\circ$ to 30°.

The XRD analysis of multi-walled carbon nanotubes showed a very prominent peak at $2\theta = 26^\circ$ and indicated a high degree of graphite formation as well as the presence of graphitic carbon. The crystallite size calculated through the Scherrer formula was approximately 10.2 nm, confirming the nanoscale features of MWCNTs.

2.1.3. UV analysis of ZnO nanoparticles. The optical properties of the ZnO nanoparticles have been characterized using UV-Vis spectroscopy. From Fig. 4 one can conclude that there is a strong absorption peak around 350–380 nm. This is because the semiconductor is showing the band-gap transition.

2.2. Characterization of nanoparticles using SEM and TEM

2.2.1. TEM analysis of Al_2O_3 nanoparticles. Further tests resulted for the presented Al_2O_3 nanoparticles from the Nano Research Lab in Jamshedpur. As shown in Fig. 5, the morphology of the synthesized Al_2O_3 nanoparticles was spherical, as revealed by TEM. In the case of the synthesized nanoparticles, the degree of purity can be marked as very high; their composition is 99.9 %. The synthesized nanoparticles have particle sizes below 50 nm, and most of them are in the

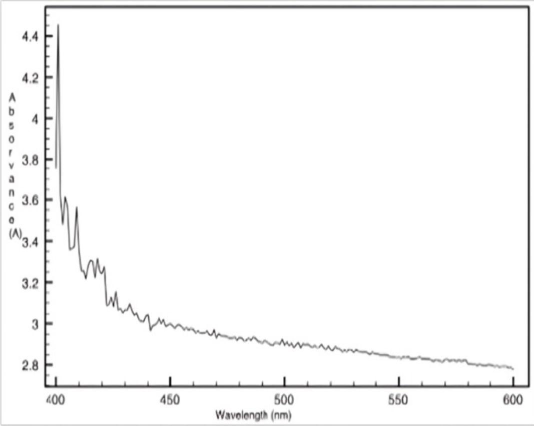

FIG. 1. UV Spectroscopy of Al_2O_3 nanoparticles

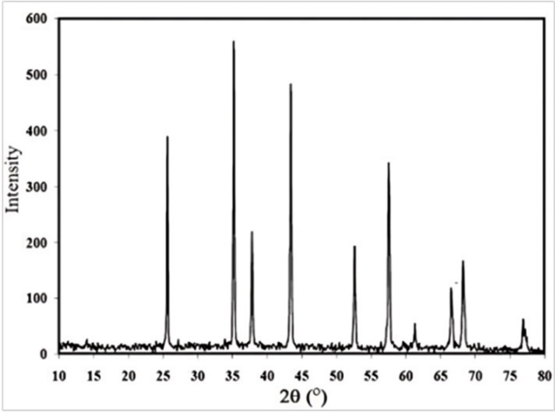

FIG. 2. XRD Analysis of Al_2O_3 nanoparticles

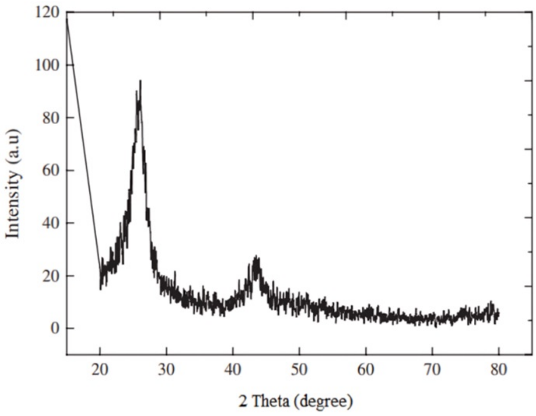

FIG. 3. XRD analysis of MWCNTs

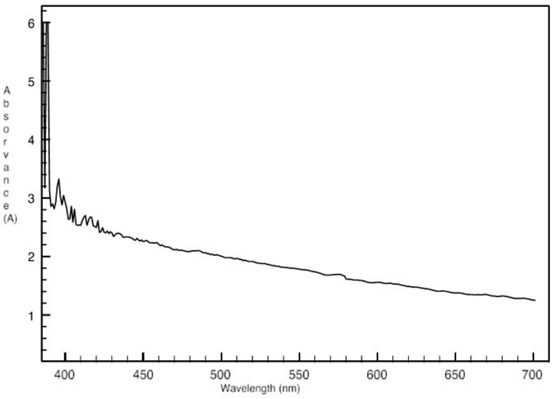

FIG. 4. UV Spectroscopy of ZnO nanoparticles

range of 30–50 nm. Aluminum oxide nanoparticles are also uniform in shape and size and have a fairly high purity level, according to the obtained results. Due to this, these nanoparticles are preferable for use in settings that require frequent supplies of high-quality nanomaterials.

2.2.2. SEM analysis of MWCNTs. In the SEM image of MWCNTs shown in Fig. 6, it can be observed that they have a very high entangled fibrous structure interconnected in various forms and different diameters. The image retains a sort of purity in that both it and its neighboring pixels are free from blemishes and contamination, therefore the higher purity value. The MWCNTs produced in this study have a good dispersion and no obvious agglomeration, and their size is generally in the range of a few nanometers to tens of nanometers, which meets the requirements of various applications.

SEM data showed that the outer diameter ranged from 10 to 20 nm. With an interlayer spacing of 0.34 nm, the average number of layers was estimated to be around 44. The internal channel diameter, calculated by subtracting the wall thickness from the outer diameter, ranged from 0 to 0.28 nm, emphasizing their nanoscale features.

2.2.3. TEM analysis of ZnO nanoparticles. The TEM analysis of ZnO nanoparticles synthesized and offered by the Nano Research Lab as mentioned in Fig. 7, declared an average particle size of 30–50 nm with a 99.9 % adsorption and hence a nearly spherical morphology, which makes them more useful in advanced applications.

3. Synthesis of Nanofluids

3.1. Estimation of Nanofluid volume concentration

In this experiment, Al_2O_3, MWCNTs, and ZnO nanofluids were prepared. The weight of the nanoparticles for a particular volume concentration can be expressed using the formula [12].

$$\Phi = \frac{[\frac{w_{np}}{\rho_{np}}]}{[\frac{w_{np}}{\rho_{np}} + \frac{w_{bf}}{\rho_{bf}}]} \cdot 100 \tag{1}$$

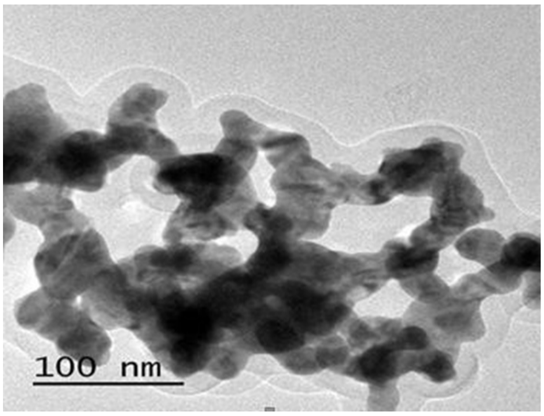

FIG. 5. TEM Photograph of Al_2O_3 nanoparticles

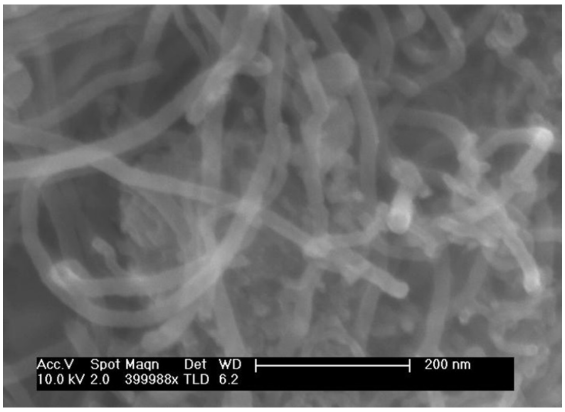

FIG. 6. SEM Analysis of MWCNTs

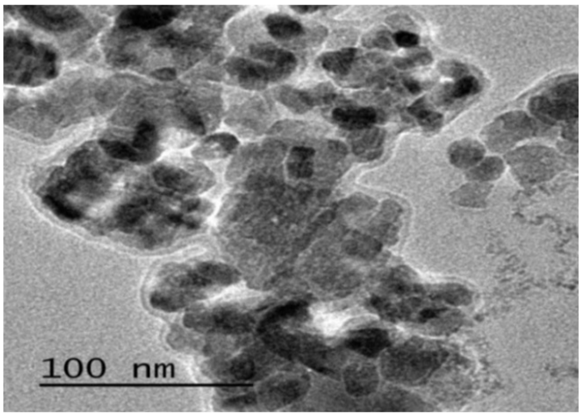

FIG. 7. TEM Analysis of ZnO Nanoparticles

Where, np represents nanoparticles and bf represents base fluid.

3.2. Estimation of Hybrid Nanofluid volume concentration

Hybrid nanofluids, which consist of a combination of different nanoparticles like aluminum oxide (Al_2O_3) and multi-walled carbon nanotubes (MWCNTs), are being extensively studied due to their improved thermal properties and possible use in numerous heat transfer systems. The procedure for synthesizing nanofluids will significantly determine the development of a stable hybrid nanofluid. Evidently, the ultrasonication process has been found to be most effective in forming nanofluids, as identified by R. M. Mostafizur [21]. The nanofluids were synthesized at room temperature following a two-phase dehydration-rehydration technique. The prediction of hybrid nanofluid volume concentration by the proposed quantity (50:50) of multi-walled carbon nanotubes (MNCNT) and aluminum oxide (Al_2O_3) nanoparticles was evaluated by the equation.

$$\Phi = \left[\frac{\left[\frac{W_{MWCNT}}{\rho_{MWCNT}}\right] + \left[\frac{W_{Al2O3}}{\rho_{Al2O3}}\right]}{\left[\frac{W_{MWCNT}}{\rho_{MWCNT}}\right] + \left[\frac{W_{Al2O3}}{\rho_{Al2O3}}\right] + \left[\frac{W_{bf}}{\rho_{bf}}\right]} \right] \cdot 100 \tag{2}$$

The focus and control of nanoparticle volume are important characteristics in the field of nanotechnology. Thus, it aids in the determination of the distribution, activity, and interconnection of the nanoparticles in a certain environment. The volume concentration of the nanoparticles with their respective weights is presented in Table 2.

3.3. Mixing of nano powder in the base fluid

The flowchart of the method used in the preparation of nanofluid is shown below in Fig. 8. The aim of the work is to obtain steady nanofluids of ZnO, MWCNTs, and Al_2O_3 nanoparticles suspended in ethylene glycol (EG) using ultrasonication and probe sonication, each process taking 2 hours for the nanoparticles to be well dispersed in the base fluid. This involves determining the mass of the nanoparticles, pouring the ethylene glycol into the beakers, and then adding the nanoparticles to the ethylene glycol. The ultrasonication technique also controls the temperature of the solutions, while probe sonication exposes the samples to more hours of sonication – 2 hours, to be precise. Subsequently, the resultant

TABLE 2. Volume concentration of the nanoparticles along with their associated weight

S.No.	Nanoparticles	Volume Concentration (%)	Weight Concentration(grams)
1	Aluminium Dioxide(Al_2O_3)	0.1	0.4
2		0.2	0.7
3		0.3	1
4	Multi-Wall Carbon Nanotubes (MWCNT)	0.1	0.2
5		0.2	0.4
6		0.3	0.6
7	Zinc Oxide (ZnO)	0.1	0.6
8		0.2	1
9		0.3	1.7
10	Al_2O_3 + MWCNT	0.25	0.6
11		0.35	0.84
12		0.45	1.08

samples will cool and be transferred to containers that are airtight to avoid the penetration of air after the process of sonication.

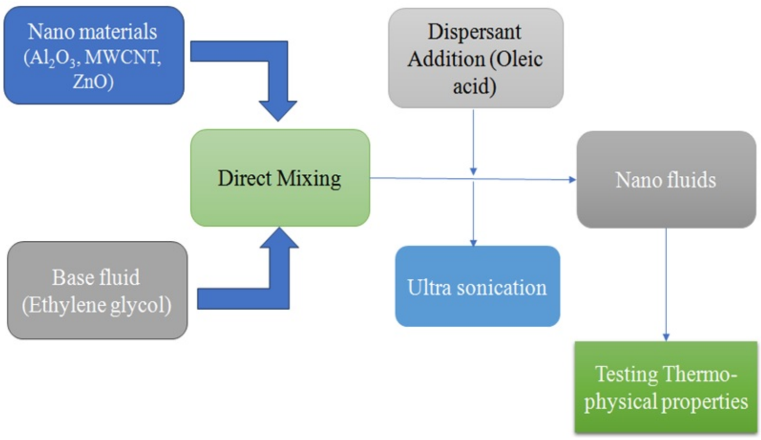

FIG. 8. Flow chart for the preparation of nanofluids

3.3.1. Dispersant for stability. Oleic acid ($C_{18}H_{34}O_2$) can be blended with various kinds of ethylene glycol, and thus the stability of the nanofluids containing ZnO, MWCNTs, and Al_2O_3 nanoparticles would greatly increase. Oleic acid works as an emulsifying agent and prevents the aggregation of the particles, thus allowing an even distribution of the nanoparticles.

The procedure entails measuring the necessary quantity of nanoparticles, transferring the ethylene glycol into beakers, introducing the nanoparticle suspensions, incorporating oleic acid, and agitating the mixes. The ultrasonication procedure entails immersing the suspensions in an ultrasonicator bath and subjecting them to sonication for duration of 1 hour. Following the sonication process, the prepared nanofluids with different concentrations (0.1, 0.2, and 0.3 wt %) samples are allowed to cool and then stored in containers.

4. Experimentation

4.1. Experimental measurement of viscosity

Viscosity, which is a measure of the fluid's resistance to change in shape and form, plays a significant role in the hydrodynamic and thermal characteristics of the nanofluids used in automobile heat transfer systems. It affects the Reynolds number, the coefficient of heat transfer, and the stability of the nanofluid; the nanoparticles should be uniformly distributed to obtain optimum results. Therefore, studies on the viscosity of nanofluids (ethylene glycol) with dispersed nanoparticles like Al_2O_3, MWCNT, and ZnO are of immense importance in materials science and fluent dynamics. The fluids of these nanocomposite materials express distinctly different rheological parameters that impact their viscous and flow characteristics.

One of the traditional viscometers, namely the Redwood viscometer, has been used to measure the viscosity of petroleum products, including nanofluids such as Al_2O_3, ZnO, and MWCNT dispersed in the base fluid, ethylene glycol. This method is easily understood, inexpensive, and ideal for obtaining viscosity values in the field or within industries.

4.1.1. Theoretical estimation of viscosity. The Einstein model is an effective method that can be used for the prediction of the viscosity of nanofluids. It is for suspensions only and offers a means by which the viscosity of a dilute suspension of spherical particles in a liquid can be approximated. The model hereby adopted accepts the premise that the viscosity of a fluid loaded with particles or droplets is presumed to have the ability to be determined with the aid of the volume fractions or concentrations of the particles and the base fluid viscosity. From the formula, one is in a position to estimate the volume fraction of nanoparticles contained in a nanofluid. It is presumed that the nanoparticles in the model have a low volume fraction, that they form a stable suspension, and that the particle size and shape do not change significantly. It is most accurate where the concentration is low and where the effects of interactions between particles and their packing are negligible. Application of nanoparticles to the base fluid can easily be explained by the Einstein model, depending on the concentration of the nanoparticles.

$$\mu_{nf} = \mu_{bf}(1 + 2.5\emptyset) \tag{3}$$

4.2. Experimental measurement of density

The investigation of density for these nanofluid systems in ethylene glycol is necessary to enhance their description. Nanofluids cover nanoparticles suspended in a base fluid such as ethylene glycol, and it is not unusual for the density of the new fluids to be significantly different than that of the base fluid solely due to the nanoparticles. Higher accuracy density values provide significant information about the dispersion quality, stability, and movement of nanofluids. The density of nanofluids in ethylene glycol is measured by an instrument known as a densitometer, as depicted in Fig. 9, since it is not uncommon for nanofluids to exhibit some rather strange density trends in terms of the nanoparticles they contain. The instruments, such as the densitometer, can correctly read the density of the liquid and, hence, the buoyancy or mass of the sample, depending on the volume or displacement formulas formulated. It involves the generation of the required nanoparticles, their dispersion in ethylene glycol, and putting the samples in the densitometer.

4.2.1. Theoretical estimation of density. The Pak and Cho model [37] is an empirical model to predict the density of nanofluids that confines the former output, which is a developer of densities and volume fractions of the base fluid and nanoparticles. The density of the nanofluid according to the given model can be expressed through the contributions of the base fluid and nanoparticles. The formula for calculating the density of a nanofluid is:

$$\rho_{nf} = (1 - \emptyset)\,\rho_{bf} + \emptyset\rho_{np} \tag{4}$$

When the volume fraction of nanoparticles is low, the Pak and Cho model becomes useful for estimating the density of nanofluids in practical applications. This is a viable and simple way of determining the density of these nanofluids; therefore, it can help in many applications of nanofluids in different areas.

4.3. Experimental measurement of thermal conductivity

The C-Therm Analyzer Setup (ASTM D7984) is a valuable equipment to determine the thermal conductivity of nanofluids, as it allows doing that quickly and accurately and provides pleasing versatility given the ability to work with rather various samples. So it is useful in deciding the heat transfer coefficient, materials to be used, and overall performance. The C-Therm analyzer works on the modified transient plane source (MTPS) method, which shows a high degree of accuracy and reliability. It is non-destructive; hence, the same sample can be tested over and over again, which gives more accurate results. The analyzer is also usable for different types of samples and gives immediate results at stable temperatures. It again necessitated a low sample volume, which can prove advantageous in cases where a large amount of money is invested or a small amount of nanomaterial is available. In this study, some of the processes that have been carried out are sample preparation, calibration, measurement, and obtaining the value of thermal conductivity. The advantages of having accurate thermal conductivity include better thermal control, improved nanofluid composition, and standardization.

4.3.1. Theoretical estimation of thermal conductivity. The current experimental data demonstrates that the thermal conductivity of nanofluids is influenced by the thermal conductivities of both the base fluids and particles. Many mathematical models have been derived by Maxwell et al. (1956), Hamilton and Crosser et al. (1962), Masuda et al. (1993), and H. S. Chen et al. (2007) to enable the comparison of experimental data with theoretical data.

This model considers the thermal conductivity of the base fluid and the dispersed nanoparticles, as well as their volume fractions, in order to compute the overall thermal conductivity of nanofluids. Maxwell's model demonstrates that the thermal conductivity of suspensions with spherical particles increases as the volume percentage of the solid particles

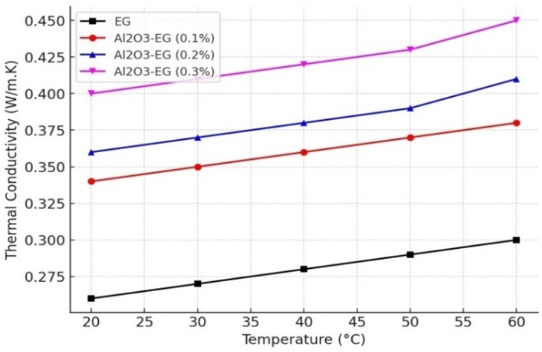

FIG. 9. Thermal conductivity Vs Temperature Al_2O_3/EG

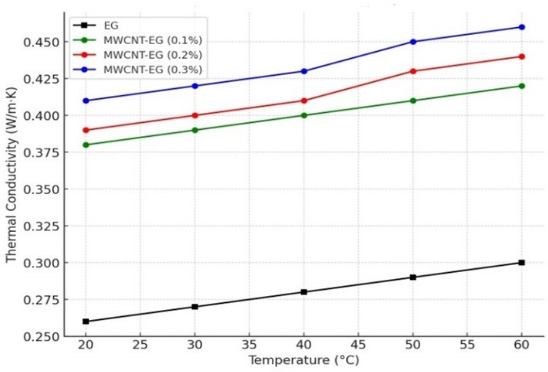

FIG. 10. Thermal conductivity Vs Temperature MWCNT/EG

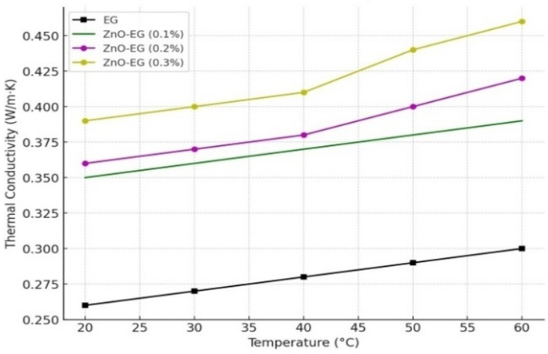

FIG. 11. Thermal conductivity Vs Temperature ZnO/EG

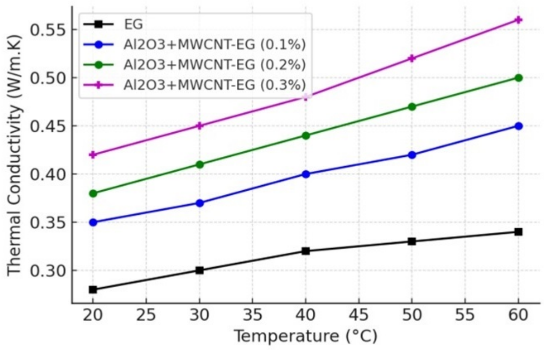

FIG. 12. Thermal conductivity Vs Temperature Al_2O_3 + MWCNT /EG

increases. The thermal conductivity of suspensions containing non-spherical particles is influenced by factors beyond only the volume fraction of the particles. The Maxwell model is the most appropriate mathematical model for determining the effective thermal conductivity of solid-liquid mixtures containing nanoparticles [36].

$$k_{nf} = \frac{k_p + 2k_f + 2\emptyset(k_p - k_f)}{k_p + 2k_f - \emptyset(k_p - k_f)} x k_f \tag{5}$$

5. Results and discussions

5.1. Thermal conductivity

Experiments on heat transfer using a C-thermal analyzer are comprised of ethylene glycol containing some nanoparticles. The C-thermal analyzer is used primarily in computing thermal conductivity values for nanofluids by means of the transient plane source (TPS) technique. A well-controlled heat pulse is produced during an electrical power supply, providing such sensors as those placed between two samples, termed a plane source. When producing heat within itself led to non-permanent thermal reactions, those were captured at that moment in the shape of sharp flats or rectangles made up of common materials; in reference to them, such materials would have high degrees of heat transfer. The speed at which those reactions spread out through these sample materials depends on the thermal conduction rate. While the heat pulse traverses the sample, the device monitors the temporal temperature variations on both sides of the sensor. By closely monitoring these temperature swings, it is feasible to determine the thermal conductivity of the material.

The findings of this study are shown in Figs. 9–12, along with a comprehensive report. The impact of temperature on the thermal conductivity of ethylene glycol with nanoparticles is demonstrated in the following study.

The thermal conductivity of ethylene glycol, when mixed with nanoparticles of Al_2O_3, MWCNT, and ZnO, rises as the quantities of the nanoparticles are raised while keeping the temperature constant. More precisely, when the volumetric concentrations increase from 0.1 to 0.2 vol % and 0.3 vol %, the thermal conductivity improvement reaches a maximum of 39.09 %.

The thermal conductivity increases linearly as the volumetric concentration percentage increases, while keeping the temperature constant. Furthermore, within the temperature range of 20 °C to 60 °C, the thermal conductivity of ethylene glycol with these nanoparticles increases in a nearly linear fashion. At lower temperatures, the rise in thermal conductivity is less significant compared to the rise observed at higher temperatures within the range of 20 °C to 60 °C.

While the experimental results show an increase in thermal conductivity within thestudied temperature range of 20 °C to 60 °C and nanoparticle concentrations from 0.1 vol % to 0.3 vol %, extrapolation to higher temperatures and concentrations requires caution. At highertemperatures, changes in the base fluid properties (e.g., viscosity reduction) and potentialnanoparticle agglomeration could lead to non-linear effects. Similarly, at concentrationsexceeding 0.3 vol %, increased inter-particle interactions and aggregation might diminish the thermal conductivity or even destabilize the nanofluid. These factors need to be accounted for in theoretical models or further experimental investigations.

TABLE 3. Comparison of theoretical and experimental thermal conductivity

(a) Comparison of theoretical and experimental thermal conductivity of Al_2O_3/EG

S. No.	Samples	Maxwell model (W/m·K)	Experimental value (W/m·K)	% Deviation
1	EG+Al_2O_3 0.1 vol%	0.3333	0.333	0.09
2	EG+Al_2O_3 0.2 vol%	0.372	0.367	1.36
3	EG+Al_2O_3 0.3 vol%	0.40	0.394	1.5

(b) Comparison of theoretical and experimental thermal conductivity of MWCNT/EG

S. No.	Samples	Maxwell model (W/m·K)	Experimental value (W/m·K)	% Deviation
1	EG+MWCNT0.1 vol%	0.384	0.382	0.52
2	EG+MWCNT0.2 vol%	0.403	0.391	2.91
3	EG+MWCNT0.3 vol%	0.412	0.399	3.15

(c) Comparison of theoretical and experimental thermal conductivity of ZnO/EG

S. No.	Samples	Maxwell model (W/m·K)	Experimental value (W/m·K)	% Deviation
1	EG+ZnO 0.1 vol%	0.342	0.343	0.2
2	EG+ZnO 0.2 vol%	0.375	0.361	3.70
3	EG+ZnO 0.3 vol%	0.41	0.379	7.38

(d) Comparison of theoretical and experimental thermal conductivity of Al_2O_3+ MWCNT/EG

S. No.	Samples	Maxwell model (W/m·K)	Experimental value (W/m·K)	% Deviation
1	EG+Al_2O_3/MWCNT 0.1 vol%	0.414	0.413	0.24
2	EG+Al_2O_3/MWCNT 0.2 vol%	0.458	0.436	4.80
3	EG+Al_2O_3/MWCNT 0.3 vol%	0.546	0.4972	8.65

From the obtained theoretical results of thermal conductivity at 20 °C represented in Tables 3(a-d), show that for all the volumetric concentrations, ethylene glycol shows a better result at 0.1 vol % and 0.2 vol % for all nanofluids, and ethylene glycol with ZnO and Al_2O_3+MWCNT at 0.3 vol % shows a higher percentage deviation due to the agglomerations formed with the increase in mass concentration of the compositions.

The findings of the experiments shown in Fig. 13 indicated that for all nanofluid concentrations at 20 °C, the thermal conductivity calculated exceeded the predicted values of the Maxwell model. In particular, the improvements varied between a low of 2 % and a high of 12 % across types and amounts of the nano injection. A small increase of 2–8 % was recorded for single-component nanofluids like EG + Al_2O_3 and EG + ZnO while double-phase nanofluids comprised of EG and Al_2O_3 and MWCNT recorded the largest increase of up to 12 %. This demonstrates the significance of nanoparticle concentration and synergism in tailoring thermal conductivity for advanced heat transfer applications.

5.2. Viscosity

Experimentation is carried out for the estimation of viscosity using a Redwood viscometer. Data on the variation of the viscosity of ethylene glycol with nanoparticles is presented in Tables 4(a–d) with regards to its correlation with temperature. The tables below provide the results of the dependency of the EG-nanoparticle solution's viscosity at different

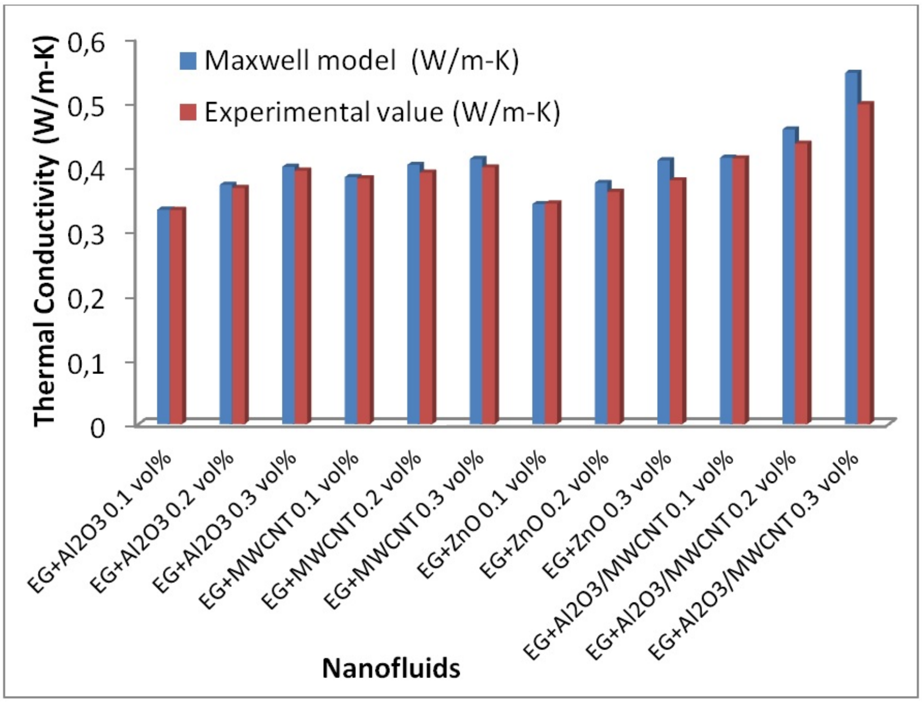

FIG. 13. Thermal conductivity of Nanofluids

concentrations on the nanoparticle type and temperature: 30 °C and 60 °C. Furthermore, this document also contains theoretical viscosities, and the percentage deviation from experimental values. The comparison of the experimental and calculated values of viscosity is represented in Fig. 14.

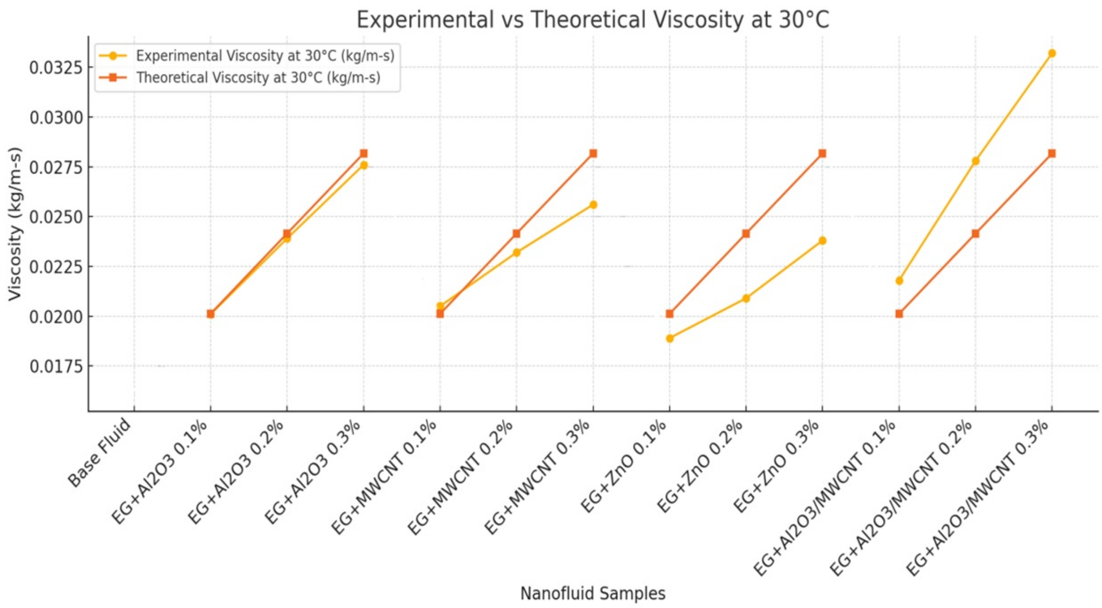

FIG. 14. Viscosity of Nanofluids

It is established that there was a significant and rapid rise in viscosity based on the results obtained. When increasing the temperature, the intermolecular bond interaction diminishes, and subsequently, the viscosity of ethylene glycol-containing nanoparticles decreases. Thus, it is seen that the viscosity has a very significant change or a steep fall with the increase in temperature. In the case of ethylene glycol, the viscosity increases with an increase in nanoparticles, and the maximum viscosity enhancement is 39.24 %. The above observations were all made at a constant temperature. Due to the higher inter-particle interaction, there is a direct relationship between the viscosity of the substance and the concentration of nanoparticles. The results imply that nanoparticle concentration affects the degree of viscous behavior, and a sharp increase can be seen when transitioning from a volume concentration of 0.1 % to 0.2 %.

TABLE 4. Viscosity of EG

(a) Viscosity of EG with Al_2O_3 nanoparticles

S. No.	Nanofluid Samples	Viscosity at 30 °C μ (kg/m-s)	Viscosity at 60 °C μ (kg/m-s)	Theoretical Viscosity at 30 °C μ (kg/m-s)	% deviation
1	Base fluid	1.61×10^{-2}	1.15×10^{-2}	1.61×10^{-2}	0
2	EG+Al_2O_3 0.1 vol%	2.01×10^{-2}	1.45×10^{-2}	2.012×10^{-2}	−0.09
3	EG+Al_2O_3 0.2 vol%	2.39×10^{-2}	1.58×10^{-2}	2.415×10^{-2}	−1.03
4	EG+Al_2O_3 0.3 vol%	2.76×10^{-2}	1.96×10^{-2}	2.817×10^{-2}	−2.02

(b) Viscosity of EG with MWCNT nanoparticles

S. No.	Nanofluid Samples	Viscosity at 30 °C μ (kg/m-s)	Viscosity at 60 °C μ (kg/m-s)	Theoretical Viscosity at 30 °C μ (kg/m-s)	% deviation
1	Base fluid	1.61×10^{-2}	1.15×10^{-2}	1.61×10^{-2}	0
2	EG+MWCNT 0.1 vol%	2.05×10^{-2}	1.52×10^{-2}	2.012×10^{-2}	1.88
3	EG+MWCNT 0.2 vol%	2.32×10^{-2}	1.76×10^{-2}	2.415×10^{-2}	−3.93
4	EG+MWCNT 0.3 vol%	2.56×10^{-2}	1.92×10^{-2}	2.817×10^{-2}	−9.12

(c) Viscosity of EG with ZnO nanoparticles

S. No.	Nanofluid Samples	Viscosity at 30 °C μ (kg/m-s)	Viscosity at 60 °C μ (kg/m-s)	Theoretical Viscosity at 30 °C μ (kg/m-s)	% deviation
1	Base fluid	1.61×10^{-2}	1.15×10^{-2}	1.61×10^{-2}	0
2	EG+ZnO 0.1 vol%	1.89×10^{-2}	1.42×10^{-2}	2.012×10^{-2}	−6.06
3	EG+ZnO 0.2 vol%	2.09×10^{-2}	1.65×10^{-2}	2.415×10^{-2}	−13.45
4	EG+ZnO 0.3 vol%	2.38×10^{-2}	1.75×10^{-2}	2.817×10^{-2}	−15.51

(d) Viscosity of EG with Al_2O_3 + MWCNT nanoparticles

S. No.	Nanofluid Samples	Viscosity at 30 °C μ (kg/m-s)	Viscosity at 60 °C μ (kg/m-s)	Theoretical Viscosity at 30 °C μ (kg/m-s)	% deviation
1	Base fluid	1.61×10^{-2}	1.15×10^{-2}	1.61×10^{-2}	0
2	EG+Al_2O_3/ MWCNT 0.1 vol%	2.18×10^{-2}	1.92×10^{-2}	2.012×10^{-2}	8.34
3	EG+Al_2O_3/ MWCNT 0.2 vol%	2.78×10^{-2}	2.58×10^{-2}	2.415×10^{-2}	15.11
4	EG+Al_2O_3/ MWCNT 0.3 vol%	3.32×10^{-2}	4.15×10^{-2}	2.817×10^{-2}	17.85

Fluids based on ethylene glycol (EG) appear to be thickening with the addition of nanoparticles such as Al_2O_3, MWCNTs, and ZnO, where stronger increases are seen with higher concentrations and Al_2O_3/MWCNT mixtures because of the synergetic effect. Remembering also that high shear viscosity has an apparent relation with fluid temperature: As the temperature rises, viscosity decreases; however, that would be an oversimplification, as higher concentrations bring forth agglomeration, and that makes the results deviate away from the prediction. This emphasizes the significance of the status of the particles and the interplay between them in determining the nature of the fluid.

5.3. Density

A densitometer is one of the most effective tools to determine the density of liquids, especially nanofluids with ethylene glycol as the base fluid. The functioning of this device is based on Archimedes' principle, which states that the upward thrust that is exerted by fluid in which an object is fully or partly immersed is equal to the weight of the fluid displaced by the body. Density is experimented with by carrying out trials using the densitometer at room temperature.

TABLE 5. Comparison of Theoretical and Experimental Density results

(a) Comparison of Theoretical and Experimental Density results of Al_2O_3/EG

S. No.	Samples	Theoretical value (kg/m^3)	Experimental value (kg/m^3)	% Deviation
1	EG+Al_2O_3 0.1 vol%	1396	1391.2	0.34
2	EG+Al_2O_3 0.2 vol%	1482	1462.5	1.31
3	EG+Al_2O_3 0.3 vol%	1596	1565.3	1.92

(b) Comparison of Theoretical and Experimental Density results of MWCNT/EG

S. No.	Samples	Theoretical value (kg/m^3)	Experimental value (kg/m^3)	% Deviation
1	EG+MWCNT 0.1 vol%	1199	1189.3	0.80
2	EG+MWCNT 0.2 vol%	1288	1273.1	1.15
3	EG+MWCNT 0.3 vol%	1377	1351.8	1.83

(c) Comparison of Theoretical and Experimental Density results of ZnO and ethylene glycol

S. No.	Samples	Theoretical value (kg/m^3)	Experimental value (kg/m^3)	% Deviation
1	EG+ZnO 0.1 vol%	1599	1592.9	0.38
2	EG+ZnO 0.2 vol%	1765	1752.1	0.73
3	EG+ZnO 0.3 vol%	1862	1821.9	2.19

(d) Comparison of Theoretical and Experimental Density results of Al_2O_3 + MWCNT and ethylene glycol

S. No.	Samples	Theoretical value (kg/m^3)	Experimental value (kg/m^3)	% Deviation
1	EG+Al_2O_3/ MWCNT 0.1 vol%	1132	1125.2	0.60
2	EG+Al_2O_3/ MWCNT 0.2 vol%	1186	1169.9	1.35
3	EG+Al_2O_3/ MWCNT 0.3 vol%	1286	1237.1	3.80

The test for the density of a solution of ethylene glycol at increasing volumetric proportions of aluminum dioxide, multi-wall carbon nanotubes, and zinc oxide is conducted with the help of a densitometer. It also has Ethylene Glycol impact density, Aluminium Dioxide, Multi-Wall Carbon Nanotubes, and Zinc Oxide presented in tabular forms 5 (a-d) compared with the theoretical model.

By comparing all the theoretical values and experimental values of density, the results shown in Fig. 15 indicated that with 0.1 vol % and 0.2 vol % nanoparticles in ethylene glycol, the percentage deviation is less when compared to 0.3 vol % nanofluids. This percentage deviation is caused by the fact that with the increase in volume concentration, there is a chance to form agglomerated particles, which may cause a reduction in some coolant properties.

5.4. Correlation between thermal conductivity, viscosity, and density

Thermal conductivity increases nearly in linear fashion with nanoparticle concentration and temperature, achieving a maximum enhancement of 39 % at 0.3 vol % concentration and 60 °C. Viscosity exhibits a significant rise with increased nanoparticle concentration but decreases with temperature due to weakened intermolecular forces. The maximum observed increase in viscosity is 39.24 %. Finally, density shows minor deviations from theoretical predictions, with higher concentrations leading to marginal increases in density due to nanoparticle agglomeration. These properties collectively demonstrate the potential of the studied nanofluids in applications requiring efficient thermal management. High thermal conductivity and controllable viscosity ensure enhanced heat transfer, while density stability supports consistent performance.

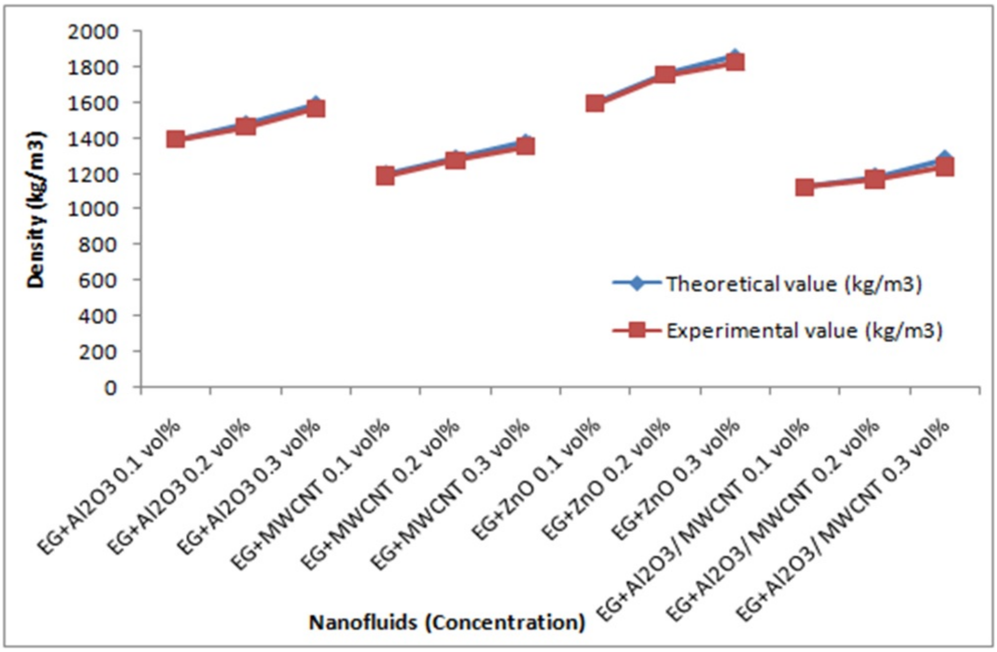

FIG. 15. Density of Nanofluids

The remarkable thermophysical properties of the studied nanofluids make them optimal. The improved thermal conduction in the core industry results in the use of small and lightweight radiators that have high efficiency in cooling, thus improving fuel economy and reducing emissions. With stable viscosity and density over temperature ranges, effective and reliable engine cooling systems would be assured. In cars and in electronics industries, a high rate of heat dissipation avoids overheating of miniaturized electronic devices. Better thermal management increases the lifetime and good efficiency of high-end devices like CPUs or GPUs.

6. Conclusions

The thermal conductivity of ethylene glycol increases linearly with the addition of Al_2O_3, MWCNT, and ZnO nanoparticles, reaching a maximum of 39.09 % when volumetric concentrations increase from 0.1 to 0.3 vol % and linearly within the temperature range of 20 °C to 60 °C.

This linear increase in thermal conductivity as temperature increases, especially at 60 °C, shows the great possibility of nanofluids for thermal management in automobiles as well as in electronic appliances.

The study shows that as temperature increases, the viscosity of ethylene glycol-containing nanoparticles increases because of a weak interaction between the particles. It does this at lower temperatures, though at higher temperatures the viscosity decreases up to a maximum of 39.24 %.

It was observed that high concentrations of nanoparticles raised the viscosity of the solution, for instance, when going from 0.1 % to 0.2 %. EG+ZnO nanofluid and EG+MWCNT/ Al_2O_3at 0.2 and 0.3 vol % show the maximum deviation in viscosity. It is expected to have this deviation due to experimental errors and the agglomeration of hybrid nanofluids.

The incorporation of Al_2O_3 and MWCNT nanoparticles into the base fluid EG raises the fluid's viscosity, with a minor effect on Al_2O_3 and a greater effect on MWCNT nanoparticles. It is observed that the mix of Al_2O_3 and MWCNT has the highest increment in viscosity of the composites.

The density study shows that nanoparticles in EG (ethylene glycol) with 0.1 and 0.2 vol % exhibit a lower percentage deviation than nanofluids with 0.3 vol %, which may reduce the coolant's physical properties.

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