Analysis of the Effect of Temperature and Volume Fraction on the Thermophysical Properties of MWCNT-Mineral Oil Nanofluid

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Abstract. Multiwalled carbon nanotubes (MWCNTs) are widely recognized for their exceptional thermal conductivity, high aspect ratio, and stability, making them ideal additives for enhancing the heat transfer performance of base fluids. Over recent decades, MWCNT-based nanofluids have demonstrated superior thermophysical properties; however, the combined influence of temperature and nanoparticle concentration remains insufficiently characterized, particularly for mineral oil applications in industrial thermal systems. This study investigates the effect of MWCNT volume fraction (0.025%, 0.050%, and 0.075%) and temperature on the density, viscosity, and thermal conductivity of mineral oil–based nanofluids. Samples were prepared using a two-step dispersion method, and measurements were conducted using a pycnometer, Brookfield Rheometer, and thermal conductivity unit. The results indicated that increasing the MWCNT concentration enhanced the density, viscosity, and thermal conductivity, whereas higher temperatures reduced the density and viscosity, but improved the thermal conductivity. Classical predictive models that neglect temperature dependence show significant deviations from the experimental observations. To address this, new empirical correlations were developed using linear and nonlinear regressions, providing substantially improved prediction accuracy. These findings advance the understanding of temperature–concentration interactions in MWCNT nanofluids and provide validated predictive tools for engineering applications where precise thermal-fluid performance estimation is critical.

Keywords: nanofluid, MWCNT, viscosity, density, thermal conductivity

1 Introduction

Indonesia possesses one of the largest geothermal energy potentials in the world, estimated at 28.91 GW across 312 identified locations including Sumatra, Java, Bali, Nusa Tenggara, Sulawesi, Maluku, and Papua. Despite this vast resource base, only about 1,533.5 MW—less than 5% of the total potential—has been harnessed to date. The relatively low efficiency of heat extraction from subsurface reservoirs is a primary challenge in geothermal development. To address this limitation, closed-loop geothermal systems (CLGS) have emerged as a promising alternative to conventional

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hydrothermal methods. The CLGS employs a sealed network of pipes through which a working fluid circulates, enabling enhanced heat recovery, operational flexibility, and minimal environmental impact, particularly for low- to medium-temperature geothermal resources.

The performance of CLGS can be further improved by the application of nanofluid-engineered working fluids containing nanoparticles (1–100 nm) uniformly dispersed in a base fluid such as water, mineral oil, ethylene glycol, ionic liquids, propylene glycol, or silicone oil [1]. Brownian motion contributes to the stability of these suspensions, and their thermophysical properties such as thermal conductivity, density, viscosity, and specific heat capacity play a critical role in determining the heat transfer performance in exchangers and geothermal loops. The incorporation of nanoparticles typically enhances the thermal conductivity, density, and viscosity while reducing the specific heat capacity without inducing significant sedimentation [2]. Among the various nanoparticles, multiwalled carbon nanotubes (MWCNTs) stand out because of their exceptional thermal conductivity, high aspect ratio, large surface area, and low density, making them particularly attractive for advanced thermal applications.

Nanofluids possess thermophysical properties that differ markedly from those of conventional fluids primarily because of the inclusion of nanoparticles with exceptionally high specific surface areas. The presence of these nanoparticles alters key parameters, including thermal conductivity, density, and viscosity. Among these, thermal conductivity is of particular importance, as it directly contributes to improving the heat transfer efficiency. Furthermore, variations in viscosity resulting from the addition of nanoparticles influence the flow characteristics of the fluid, which in turn affects the system performance. A comprehensive understanding of these property modifications is essential for optimizing nanofluid performance in thermal system applications.

The synthesis of nanofluids is a decisive step in ensuring optimal heat transfer performance, as it directly influences stability and homogeneity. The objective was to produce a suspension that was resistant to agglomeration, sedimentation, and chemical degradation. In this study, MWCNT-based mineral oil nanofluids were prepared by a two-step method. Initially, the nanoparticles were mixed with the base fluid using a magnetic stirrer, followed by ultrasonication in an ultrasonic bath to disrupt the agglomerates and promote uniform dispersion. Ultrasonication applies high-frequency vibrations to exploit the high diffusivity of nanoparticles [3], and agglomeration can be further mitigated through mechanical or chemical stabilization. If left uncontrolled, agglomeration can lead to sedimentation, clogging, and reduced thermal conductivity. Although more complex than single-step synthesis, the two-step approach provides better control over the particle size distribution and concentration, thus enhancing reproducibility and performance consistency [4].

Density plays a vital role in heat transfer systems. Increased density due to the addition of nanoparticles can lead to higher nanofluid viscosity, affecting buoyancy-driven convection in natural convective heat transfer processes [5]. In this study, the effective density of the nanofluid (nf) was calculated using the Pak and Cho model based on the mixture rule principle and particle volume fraction [6]. The equation is defined as (1):

$$\rho_{nf} = \phi\rho_{np} + (1-\phi)\rho_{bf} \quad (1)$$

The nanofluid viscosity is crucial in determining its stability because an increased viscosity can reduce the heat transfer efficiency. Einstein developed the first model used to calculate the viscosity of various heat transfer fluids in 1906 [7], as described in Equation (2).

$$\mu_{nf} = (1 + 2.5\phi)\mu_{bf} \quad (2)$$

However, this model does not account for the effect of particle volume concentration in the fluid. Therefore, the Brinkman model was used as an improvement, as shown in Equation (3). This approach offers a more accurate estimation than Einstein's model, particularly for higher particle volume fractions [8].

$$\mu_{nf} = \frac{\mu_{bf}}{(1-\phi)^{2,5}} \quad (3)$$

In 1977, Batchelor developed further corrections by incorporating the effects of the Brownian motion. This model offers a higher accuracy than Einstein's model, considering the more complex interparticle interactions caused by the random movement of small particles in the fluid. This motion increases the collision frequency between particles, eventually leading to an increase in total fluid viscosity [9]. Batchelor's theoretical model is given by (4):

$$\mu_{nf} = (1 + 2.5\phi + 2.5\phi^2)\mu_{bf} \quad (4)$$

Theoretical models based on Maxwell's equations were used to evaluate the thermal conductivity of the synthesized nanofluids [10]. This equation was subsequently modified by Hamilton to incorporate the nanoparticle shape factor [11]. Equations (5) and (6) represent the Maxwell and Hamilton theoretical models, respectively, for thermal conductivity. During the evaluation using the theoretical model, ideal conditions were assumed, in which the nanoparticles were uniformly distributed in the nanofluid and no agglomeration occurred. The values obtained from the theoretical models were then compared with the experimental results.

$$k_{nf} = \frac{k_p + 2k_{bf} + 2(k_p - k_{bf})\phi}{k_p + 2k_{bf} - 2(k_p - k_{bf})\phi} k_{bf} \quad (5)$$

$$k_{nf} = \frac{a + (n-1) - (n-1)(1-a)\phi}{a + (n-1) + (1-a)\phi} k_{bf} \quad (6)$$

2 Materials and Methods

2.1 Materials

The nanoparticles employed in this study were multiwalled carbon nanotubes (MWCNTs), a type of carbon nanotube composed of two or more concentric graphene cylinders. The interlayer spacing between graphene sheets is approximately 3.4 Å (0.34 nm). The outer diameters of the MWCNTs ranged from 1 to 50 nm, whereas the inner diameters varied according to the number of graphene layers. The thermophysical properties of the MWCNTs are summarized in Table 1.

Table 1. Characteristics of Multi-Walled Carbon Nanotubes

Characteristics	Values	
Purity	95	%
Outer diameter	8-15	nm
Inner diameter	3-5	nm
Length	3-12	μm
Actual density	2,1	g/cm^3
Specific surface area	233	m^2/g
Resistivity	1412	Ω·μm

The base fluid was a highly refined white mineral oil chosen for its excellent thermal stability and relatively low viscosity, which together promote efficient convective heat transfer in heat exchanger systems. The thermophysical properties of the white mineral oil were obtained from the manufacturer's specifications (Colombia Petro Chem PVT. LTD.) are presented in Table 2.

Table 2. Characteristics of Mineral Oil

Typical Characteristics		
Characteristics	**Test Method**	**Values**
Colour, Saybolt	ASTMD-156	+30
Specific Gravity @ 25°C/25°C	U.S.P	0,826
Kinematic Viscosity @ 40°C, mm^2/s	ASTMD-445	14,50
Viscosity @ 37,78°C, SUS	ASTMD-445	80,72
Density, g/cm^3	ASTMD-4052	0,82

2.2 Nanofluid Preparation

The MWCNT-based nanofluids were synthesized via a two-step dispersion method. The process involves the following stages:

1. Magnetic Stirring. The MWCNTs were mixed with mineral oil using a magnetic stirrer for 1 h to promote preliminary dispersion and minimize particle agglomeration.
2. Ultrasonication. The mixture was subjected to high-frequency vibrations using a Biosafer 1200-98 ultrasonic processor (1200 W, 20.5 kHz) for 1 h to break down the residual agglomerates and achieve a stable, homogeneous suspension.

Nanofluids were prepared at volume fractions of 0.025%, 0.050%, and 0.075% in 900 mL of mineral oil. These concentrations were selected to investigate the influence of particle loading on the thermophysical behavior. Photographs of the prepared samples showing visual differences corresponding to the nanoparticle concentrations are presented in Figure 1.

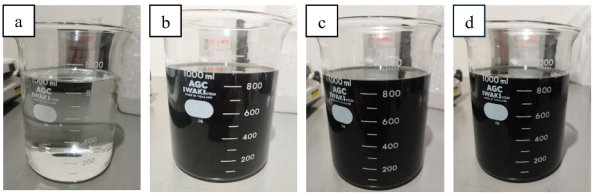

Fig. 1. Nanofluid samples: (a) base fluid mineral oil, (b) 0.025% fraction, (c) 0.050% fraction, and (d) 0.075% fraction.

2.3 Characterization of Thermophysical Properties

Density. Determined using a pycnometer. An empty pycnometer was weighed, filled with the sample, and weighed again. The density was calculated from the mass difference and known pycnometer volume.

Viscosity. Measured using a Brookfield DVNext Rheometer. The samples were placed in a beaker, and the spindle was immersed in the fluid. Measurements were taken at different spindle speeds to evaluate the rheological characteristics.

Thermal Conductivity. Evaluated using a Thermal Conductivity Unit for liquids and gases (Model H470). The sample was positioned between the heating and cooling elements, and the temperature gradients were recorded to calculate the rate of heat transfer through the fluid.

3 Results and Discussion

The experimental results for the density of MWCNT/mineral oil nanofluids demonstrated a significant dependence on both temperature and nanoparticle volume fraction. Density is a critical parameter for determining the flow characteristics and heat-transfer performance of nanofluid-based systems.

As shown in Fig. 2, the density decreased with increasing temperature for all tested volume fractions. The highest values were observed at 30 °C, whereas the lowest values occurred at 100 °C, indicating a consistent downward trend. This behavior is attributed to the thermal expansion effect, wherein increased heat energy causes greater

intermolecular spacing, reducing the number of particles per unit volume and thus lowering density [12].

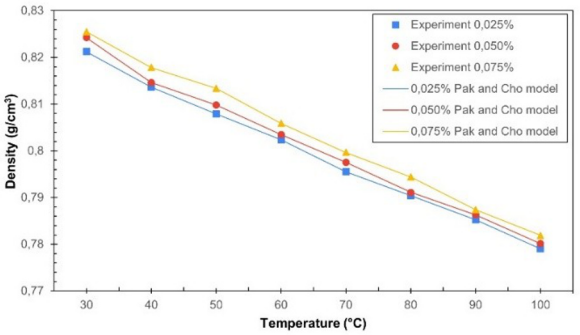

Fig. 2. Experimental and modeled density distributions as functions of temperature.

A comparison between the measured data and Pak–Cho model revealed similar overall trends. However, the Pak–Cho formulation accounts for the nanoparticle volume fraction, particle density, and base fluid density, but neglects the temperature dependence. To address this limitation, a new empirical model was developed using linear regression of the experimental data, expressed as

$$\rho_{nf} = a + b \cdot \rho_p + c \cdot \rho_{bf} + d \cdot \phi + e \cdot \frac{T}{T_0} \qquad (7)$$

This predictive correlation incorporates particle density, base fluid density, nanoparticle volume fraction (ϕ), and temperature (T). As shown in Fig. 3, the model accurately predicts nanofluid density with a maximum deviation of approximately ±1% across the tested range.

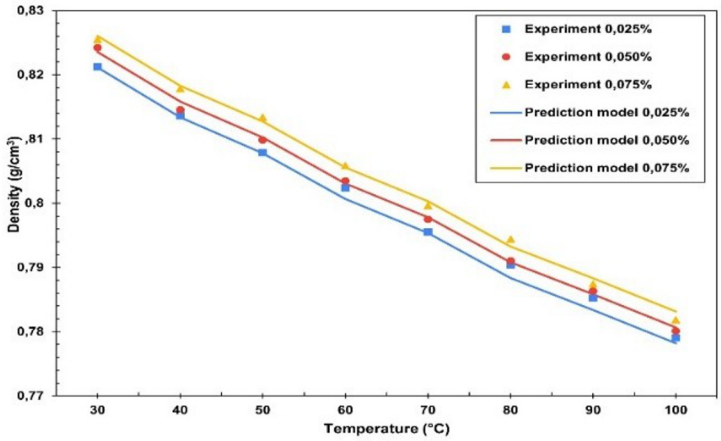

Fig. 3. Comparison of experimental results with predictive model for nanofluid density.

The dynamic viscosity was also found to vary with both the temperature and nanoparticle volume fraction. Viscosity is a governing factor in determining the pumping power requirements, flow regimes, and convective heat transfer efficiency.

As illustrated in Fig. 4, the viscosity decreased with increasing temperature for all tested volume fractions. This reduction was attributed to the decreased molecular cohesion at elevated temperatures, resulting in a lower resistance to flow.

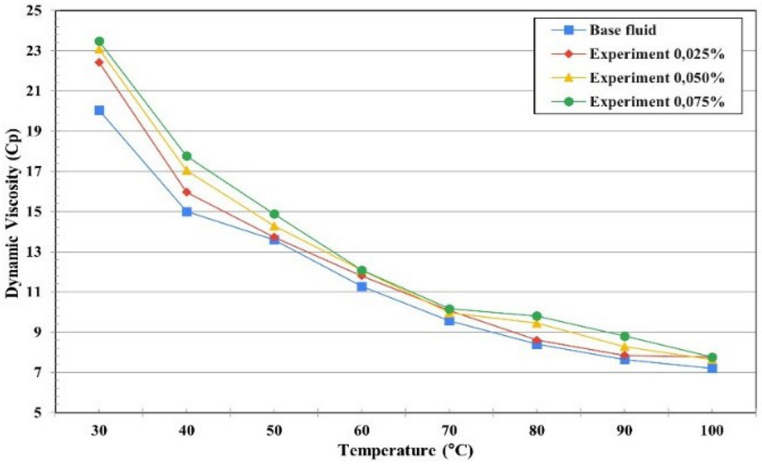

Fig. 4. Effect of temperature on dynamic viscosity.

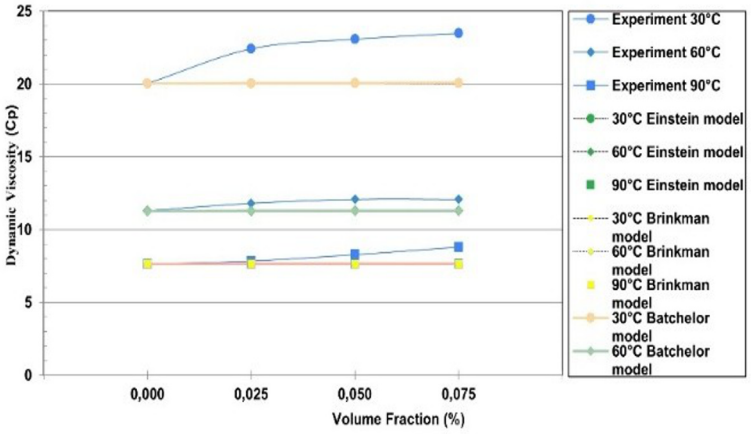

Fig. 5. Experimental and modeled viscosity distributions at 30, 60, and 90°C.

Owing to the nonlinear nature of the temperature–viscosity relationship, selected temperatures (30, 60, and 90 °C) were compared with the classical models by Einstein, Brinkman, and Batchelor (Fig. 5). These models consistently underestimated viscosity

primarily because they excluded temperature effects and complex interparticle interactions. In contrast, the nonlinear regression approach proposed by Khanafer provided closer agreement with the experimental results [13].

A new polynomial-based regression model was developed to further improve the predictive accuracy.

$$\mu_{nf} = a + \frac{b}{T} + c(1-\phi) + d(1-\phi)^2 + \frac{e}{T}(1-\phi)^3 + f(1-\phi)^3 + \frac{g}{T}(1-\phi) \quad (8)$$

This correlation incorporates particle viscosity, base fluid viscosity, nanoparticle volume fraction, and temperature, with additional terms to account for particle–fluid interactions. As shown in Fig. 6, the proposed model closely matched the experimental data, with a maximum error of ±4% for a volume fraction range of 0.025% < ϕ < 0.075% and a temperature range of 30 – 100°C. Minor deviations were likely due to particle agglomeration or experimental uncertainties.

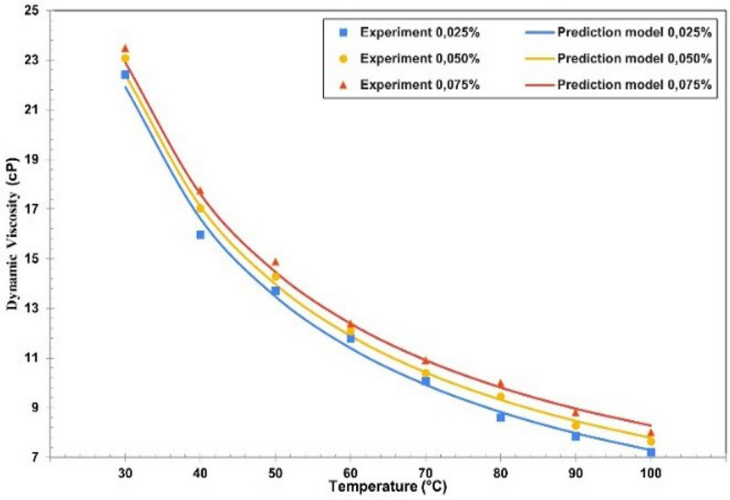

Fig. 6. Comparison of experimental results with the predictive model for nanofluid viscosity.

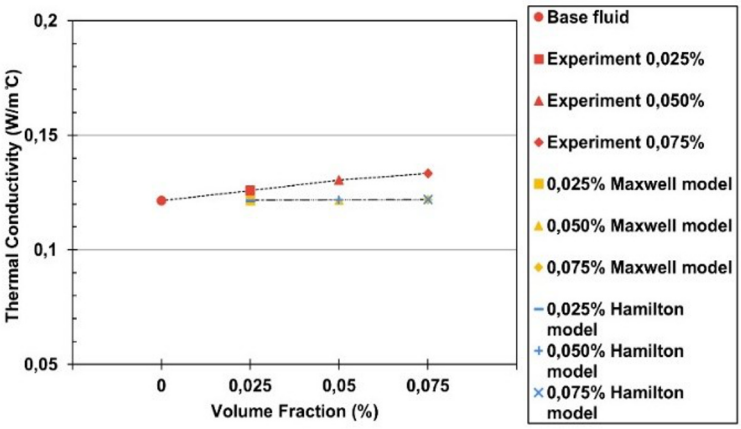

Fig. 7. Thermal conductivity distribution (experimental vs. modeled) as a function of volume fraction.

Thermal conductivity measurements of the MWCNT/mineral oil nanofluids revealed a positive correlation between nanoparticle concentration and effective thermal conductivity. As shown in Figure 7, the thermal conductivity increased nearly linearly with volume fraction, indicating that higher nanoparticle loadings enhanced the heat conduction capability. This enhancement can be attributed to three main factors: (1) Intrinsic conduction. MWCNTs possess significantly higher thermal conductivity than the base fluid, thus increasing the overall conductive pathways within the nanofluid. (2) Brownian motion. Random nanoparticle motion promotes additional micro-convection, facilitating energy transport. (3) Particle–fluid interactions. Nanoparticles may strengthen the intermolecular energy transfer mechanisms, further improving thermal performance.

The experimental results were compared to classical models, namely Maxwell [10] and Hamilton–Crosser [14]. The Maxwell model, developed for spherical particles, underestimated the enhancement owing to the cylindrical geometry of the MWCNTs. The Hamilton–Crosser model, which accounts for nonspherical particle shapes, provides closer predictions. However, the experimental values still exceeded both model predictions, likely owing to the absence of Brownian motion and interfacial interaction effects in these classical formulations.

4 Conclusion

The investigation into the thermophysical properties of MWCNT/mineral oil nanofluids demonstrates that both the nanoparticle volume fraction and temperature exert a significant influence on the behavior of the fluid. An increase in the volume fraction of MWCNTs leads to a higher density owing to the greater intrinsic density of the nanoparticles compared to that of the base fluid. This increase was accompanied by a corresponding increase in viscosity, indicating an enhanced flow resistance as the particle

concentration increased. At the same time, the thermal conductivity improved markedly with a higher MWCNT content, confirming the potential of these nanoparticles to enhance the heat transfer capabilities of mineral oil-based systems.

Temperature variations also play a critical role in determining the performance of the nanofluids. The density decreases with increasing temperature as a result of fluid expansion, while the viscosity likewise declines, suggesting reduced shear forces and improved flow characteristics at elevated temperatures. In contrast, the thermal conductivity increases with temperature, indicating that higher thermal energy accelerates the energy transport mechanisms within the fluid and enhances the overall heat transfer efficiency.

The results show that, while the Pak and Cho model [6] captures general density trends, it overlooks temperature effects, causing deviations. Classical viscosity models (Einstein, Brinkman, Batchelor) and thermal conductivity models (Maxwell, Hamilton–Crosser) also underestimate the measured values due to their inability to account for nanoparticle geometry, Brownian motion, and particle–fluid interactions. This highlights the need for advanced models that incorporate temperature dependence and nanoparticle–fluid interactions to predict the thermophysical behavior of MWCNT-based nanofluids more accurately.

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