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Experimental Study of Cu Nanoparticles Loading and Temperature Effects on the Thermophysical Properties of SAE10W oil: Developing a New Mathematical Correlation

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Abstract

Nanofluids can enhance the thermophysical properties of base fluids to increase the efficiency of thermal systems. This study is to develop a new mathematical correlation to predict the thermophysical properties of the copper/damper oil (SAE10W oil) nanofluids. Also, experiments were conducted with varying concentrations of Cu nanoparticles and different temperatures. High-Resolution Scanning Electron Microscopy (HRSEM), Energy-Dispersive X-ray spectroscopy (EDX), and X-Ray Diffractometry (XRD) are done to characterize the Cu nanoparticles. After determining the structure of Cu nanoparticles, the Cu/damper oil nanofluid is prepared through a two-step method. The density and viscosity of the nanofluids are measured according to IS 1448-32 (1992) and ASTM D445-15 standards. The specific heat of nanofluids and thermal conductivity were measured using a thermal constant analyzer. The results demonstrate that Cu nanoparticles significantly improve the thermophysical properties of pure automotive damper oil, enhancing its thermal conductivity from 15.48% to 33.28%. Furthermore, the viscosity of automotive damper oil increases by 79% and 222% with 0.050% and 0.150% volume concentrations, respectively. The density and specific heat changes are also measured and reported. Based on the experimental findings, an empirical correlation is developed through a fitting method to predict the thermophysical properties of these nanofluids. This mathematical correlation accurately calculates the properties of Cu/damper oil nanofluid, with a margin of deviation ranging from −3.7% to 7%.

Keywords

copper nanoparticles, automotive damper oil, thermal constants analyzer, dynamic viscosity, thermal conductivity

1 Introduction

Vibrations induced in the vehicle structure must be dampened in order to ensure comfortable driving and safe vehicle handling. In the automotive suspension system, the active or semi-active suspension system is not commonly used in all vehicles due to the complications arising from the controller. Passive suspension systems are available in a vast majority of vehicles today. During the passive suspension process, energy dissipates into the damper oil. The damper will continue to absorb and dissipate heat, which causes its temperature to rise [1–3]. The reduction in the damper performance can be attributed to the gradual dissipation of heat in the damper oil. If damper performance decreases, the comfort level of the passengers in the vehicle and ride control will be adversely affected. Nanofluid, a novel heat transfer fluid, enhances thermophysical properties and heat transfer performance with the addition of solid particles with size in the range of nanoscale (1–100 nm) into conventional heat transfer fluids [4–10].

As a result, nanofluids have been deployed across various industrial applications, including automotive, aerospace, electronics, and energy sectors. Choi and other pioneers [11, 12] invented nanofluids in 1995 at the Argonne National Laboratory in the United States. Since the invention of the nanofluid, a significant amount of research has been done to improve the thermophysical properties of water, ethylene glycol (EG), the blend of water/EG, and oil as base fluids.

Researchers found that nano-sized solid particles distributed within a base fluid with increasing volume concentration exhibit greater thermophysical properties [13–17]. Ettefaghi et al. [18] conducted an experimental study by adding multi-walled carbon nanotubes (MWCNTs) to

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automotive engine oil with a concentration of 0.5 wt%, and thermal conductivity was enhanced by 22.7%. Although nanoparticles agglomerate and precipitate in oil when used as an additive, the lubricating properties are improved due to the increased concentration of nanoparticles. The rheological properties and thermal conductivity of copper (Cu) and gear oil-based nanofluids were investigated by Kole and Dey [19]. They reported that at 2% volume concentration, viscosity increased by 71%, and thermal conductivity improved by 24%.

Saeedinia et al. [20] investigated the oil-based nanofluids containing copper(II) oxide nanoparticles at weight fractions ranging from 0.2% and 2%. For 2% weight fraction, there was a significant increase in thermal conductivity of up to 6.2% in this study. They also proved that the viscosity of nanofluids is dependent on temperature. Wang et al. [21] prepared graphite/oil nanofluids and investigated the influence of nanoparticles on enhancing thermal conductivity properties. they observed that a 1.36% volume concentration of graphite nanoparticles enhanced thermal conductivity by up to 36%. Aberoumand et al. [22] conducted a study investigating the thermal conductivity and viscosity properties of silver/oil nanofluids for heat transfer applications. The findings revealed a notable enhancement in thermal conductivity, with an increase of approximately 40%. Additionally, the viscosity of the nanofluids showed an increase up to 27%. Fazlali et al. [23] studied engine oil-based nanofluids containing CuO and graphene nano additives prepared at 1% weight concentration. Compared to pure engine oil, the nanofluids exhibited an increase in thermal conductivity by 5.19% and 14.91%, respectively. In addition, the viscosity of the CuO and graphene nanofluids increased by 13.85% and 29.23%, respectively, at 25 °C.

As particle size decreases, nanofluids exhibit a gradual enhancement in thermal conductivity ratio. This phenomenon becomes particularly pronounced at higher volume concentrations [24]. Furthermore, heat transfer is more efficient at lower volume concentrations, while it is less effective at higher volume concentrations [25]. The enhancement in thermal conductivity, however, is not as apparent at lower volume concentrations. In the study conducted by Jaiswal et al. [26] and Jaiswal and Pandey [27, 28], a model was developed to predict the thermophysical properties of nanometals, taking into account shape effects and nano-scale material structure. Furthermore, their research explored the influence of shape and size on the thermal conductivity of metallic nanoparticles. Numerous research studies have been conducted in the past few years to investigate various nanosized particle suspensions, which consisted of a variety of nanomaterials with variations in shapes, sizes, and concentrations; most tests utilized polar base fluids consisting of water, ethylene glycol, and their blends [29–31].

The literature shows that very few studies have been conducted on oil-based nanofluids to improve thermophysical properties for heat transfer applications. In light of the identified research gap, further investigation into an oil-based nanofluid could lead to significant advancements that will be useful for various industrial applications. This study aims to develop a mathematical correlation to predict thermophysical properties based on experiments analyzing automotive damper oil properties and examining the effects of adding Cu nanoparticles.

2 Materials and methods

2.1 Characterization of nanoparticles and preparation of nanofluid

This study uses SAE 10W grade automotive damper oil (Castrol) as a base fluid. Spherical-shaped solid particles of Cu are used as the nanoparticle additive. The nanoparticles with an average size of 30–50 nm, and 99.9% purity are procured from Ultra Nanotech Private Limited, Bangalore, India. The Cu nanoparticles surface morphology and elemental analysis were investigated using High-Resolution Scanning Electron Microscopy (HRSEM) (Thermoscientific Apreo S) and Energy-Dispersive X-ray spectroscopy (EDX). The structural characteristics of Cu nanoparticles were examined by an X-Ray Diffractometer (XRD) (BRUKER USA D8 Advance, Davinci). The properties and characteristics of these Cu nanoparticles are comprehensively summarized in Table 1, and the thermophysical properties of the SAE10W oil are summarized in Table 2.

To determine the thermophysical properties of nanofluids, it is essential to prepare nanofluid samples. The thermophysical properties can vary depending on the method used [32–36]. Several approaches are available for preparing nanofluid samples, namely the one-step and two-step

Table 1 Properties and characteristics of the Cu nanoparticles

Properties	Units	Cu nanoparticle
Color	–	Black brown
Purity	–	99.9%
Density	kg/cm^3	8960
Average size	nm	30–50
Bulk density	g/cm^3	0.2
Specific surface area	m^2/g	16

Table 2 Properties and characteristics of SAE10W oil

SAE10W oil properties	Unit	Method	Value
Density at 15 °C	g/cm^3	ASTM D 4052	0.880
Viscosity at 100 °C	mm^2/s	ASTM D 445	6.1
Viscosity at 40 °C	mm^2/s	ASTM D 445	36
Viscosity index	-	ASTM D 2270	150
Flash point	°C	ASTM D 92	210
Pour point	°C	ASTM D 97	−40

methods. In the one-step method, nanoparticles are synthesized first and subsequently dispersed directly into the base fluid. On the other hand, the two-step method involves the formation of nanoparticles through physical or chemical synthesis techniques, followed by their dispersion into the base fluid. For this study, the two-step method shown in Fig. 1 (a) is utilized to prepare Cu/damper oil nanofluids with volume concentrations of the Cu nanoparticles in the nanofluids ranging from 0.050% to 0.150%.

The mass of Cu nanoparticles calculated using Eq. (1):

$$W_{\mathrm{Cu}} = \left[\frac{\Phi}{100-\Phi}\right]\left[\frac{\rho_{\mathrm{Cu}}}{\rho_{\mathrm{oil}}}\right] W_{\mathrm{oil}} \, . \tag{1}$$

Where, Φ represents the volume concentration of Cu nanoparticles in %, ρ_{Cu} denotes the density of Cu nanoparticles in kg/m^3, ρ_{oil} represents the density of damper oil in kg/m^3, W_{Cu} denotes the mass of the Cu nanoparticles in g, and W_{oil} represents the mass of the dampers oil in g.

Cu nanoparticles are added to the damper oil and stirred for 30 min for a homogeneous mixture. The mixture is then subjected to 60 min of ultrasonication in an ultrasonication bath, ensuring proper dispersion of the nanoparticles throughout the fluid. Visual observation confirms the stable distribution of the black-colored nanofluids over 20 days.

Stability refers to the ability of the nanoparticles to remain uniformly dispersed within the fluid without any visible signs of sedimentation or agglomeration. The observations made during the stability evaluation, as depicted in Fig. 1, demonstrate that the nanofluids remain stable throughout the observation period. No visible sedimentation or settling of the Cu nanoparticles is noted, indicating that the dispersion achieved through the stirring and ultrasonication processes effectively maintains the nanoparticles distribution within the damper oil.

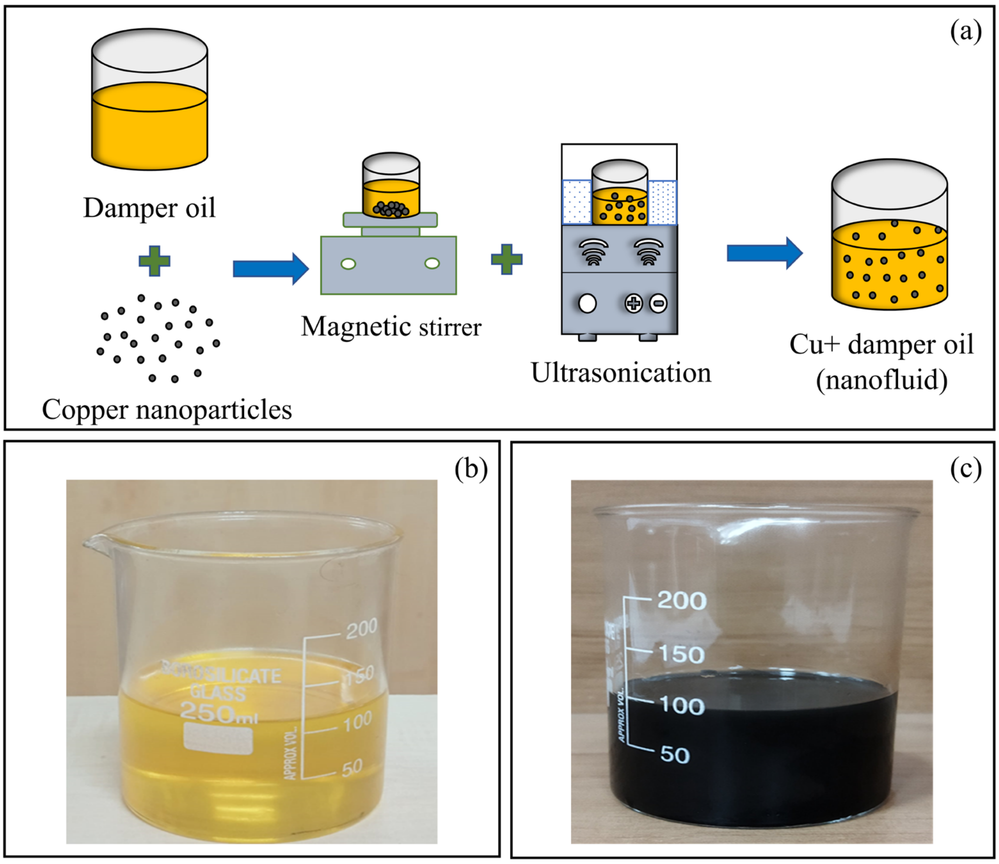


Fig. 1 (a) Two-step method for nanofluid preparation; (b) Automotive damper oil; (c) Cu/damper oil nanofluid

2.2 Experimental measurements

2.2.1 Density measurements

The density of pure damper oil and damper oil loaded with various concentrations of Cu nanoparticles are measured using a pycnometer, according to IS 1448-32 (1992) [37]. Pycnometers are laboratory devices that are used to measure density precisely [34, 38–40]. In order to determine the density of damper fluids, the pycnometer is calibrated with pure water at various temperatures. Density measurements are repeated three times to minimize measurement errors. Density is calculated based on the relationship between mass and volume. The pycnometer is also used to study the impact of different nanoparticle volume concentrations on Cu/damper oil nanofluids and the effects of varying temperatures ranging from 20 °C to 80 °C.

2.2.2 Viscosity measurement

The nanofluid viscosity is determined using a Cannon-Fenske opaque viscometer, following the ASTM D445-15 [41] measurement standard. The viscosity measurement is performed with an uncertainty of ±0.2%, as depicted in Fig. 2. The above methodology has been followed by many researchers [42–46]. Following this method, the nanofluid carefully flows through predetermined start and finish lines that the viscometer manufacturer marks. Before assessing the viscosity of the nanofluid, the viscometer is calibrated using pure water to establish a reference viscosity [47]. Viscosities are measured from 20 °C to 80 °C at temperature intervals of 10 °C. For the temperature control of the nanofluid samples, water baths are placed within a temperature range.

The measurement of efflux time involves allowing the sample to flow freely from the starting line to the finishing line. This process is repeated three times to obtain multiple measurements of efflux time, and the average of these values is calculated. The kinematic viscosity is then calculated by multiplying the efflux time by the viscometer constant. The volume of nanofluid taken for the viscosity measurement is 30 mL–50 mL. The dynamic viscosity of the nanofluid is obtained by multiplying the density of the fluid with its kinematic viscosity.

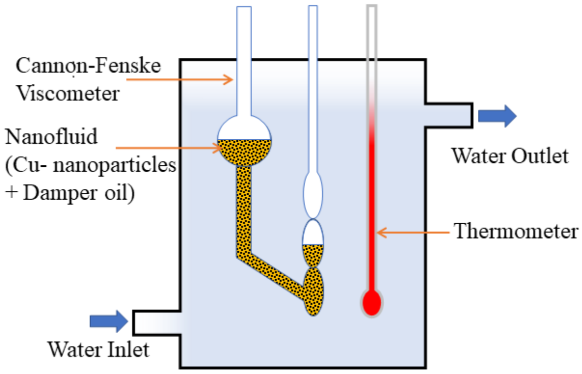


Fig. 2 Schematic layout of the viscosity measuring setup

2.2.3 Thermal conductivity and specific heat capacity measurements

Heat transfer effectiveness in nanofluids is assessed by considering their thermal properties, including specific heat capacity and thermal conductivity. These properties are crucial factors in evaluating the ability of nanofluids to heat transfer efficiently. In order to analyze the thermal properties of the prepared nanofluids, a hot disk thermal constant analyzer (TPS2500S) is used. Fig. 3 shows the schematic representation of the thermal constants analyzer. It is specifically designed to measure the thermal conductivity, thermal diffusivity, and specific heat of a wide range of solid and liquid samples in a single measurement. The Transient Plane Source (TPS) technique is used for this instrument, that involves applying a heat pulse to the sample, which generates a transient response. The TPS element acts both as a temperature sensor as well as a source of heat. The procedure involves placing a heating element directly in contact with the sample and monitoring its temperature response over time [48, 49]. Within this analyzer, the TPS element comprises a thin nickel foil sheet, measuring 10 µm in thickness, containing a dual spiral electrically conductive pattern. This pattern closely resembles that of a hot disk, enveloped within an insulating layer made of 7 µm thick Kapton.

The sensor is sandwiched between two flat surfaces, which serve as support for the sample fluid. During the measurement process, a high electric current is applied to the TPS element. Subsequently, the dual spiral nickel strip is energized, causing its temperature to rise rapidly, and the heat spreads to the thin hot disk films. After a certain period, the thermal properties of the sample fluid can be obtained by analyzing the real-time recorded temperature versus time curves.

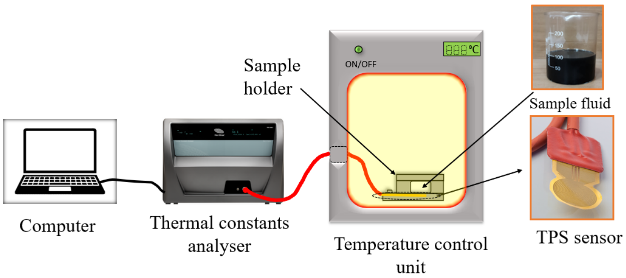


Fig. 3 Schematic layout of the thermal constants analyzer

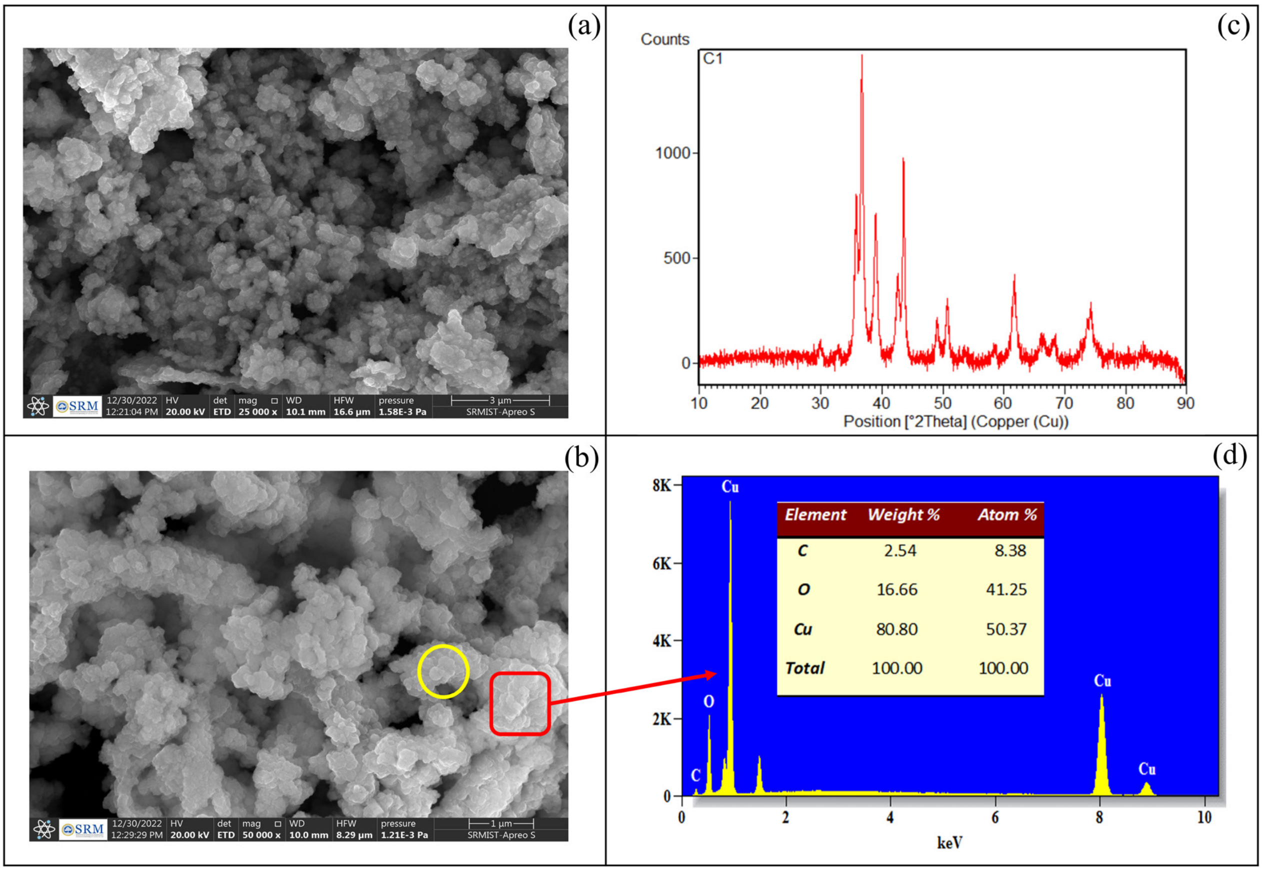
By analyzing the recorded temperature-time response from the sensor, accurate calculations can be performed to ascertain the nanofluid sample's thermal conductivity and specific heat. It can measure thermal conductivity between 0.005 and 1800 W/m·K and has a measurement accuracy of better than 5%. The specific heat capacity can be measured up to 5 MJ/m^3·K, and thermal diffusivity can be measured between 0.01 to 1200 mm/s^2 in the temperature range between −60 °C and 300 °C. The measuring instrument has a reproducibility of less than 1%. A sample holder having a capacity of 40 cm^3 volume is used. For this study, a temperature control unit is utilized to oversee and sustain the temperature of the sample nanofluids within the specified range of 20 °C to 80 °C. Prior to measuring the thermal properties of the nanofluid, tests were performed on this instrument to determine the thermal conductivity and specific heat of pure water. The obtained data was then compared with the Refprop 9.0 database [47].

3 Results and discussion

3.1 Characterization of Cu nanoparticles morphology and structure

The morphology of Cu nanoparticles is examined using the HRSEM test to analyze their surface structure. Fig. 4 (a) and Fig. 4 (b) display the HRSEM micrograph at 25000× and 50000× magnification, to observe the morphology of the Cu nanoparticles. The results indicate that the nanoparticles exhibit a predominantly spherical shape. Incorporating spherical nanoparticles into damper fluids has a beneficial effect on minimizing friction and enhancing the resistance to abrasion between surfaces. This leads to improved performance and durability in the damping system. Using XRD analysis with the range of 10° to 90°, Fig. 4 (c), presents the results of investigating the atomic structure of Cu nanoparticles.

The XRD results shows that the identified diffraction peaks at (2θ) angles of 38.02°, 44.56°, 50.78°, 62.51°, and 73.54° indicate the lattice plane orientations of (110), (111), (200), (220), and (311). It is evident from the reflections of the peaks that metallic Cu has a crystalline structure with a face-centered cubic structure [50, 51]. It can be demonstrated that the atoms of the Cu nanoparticle have specific angles based on the created peaks. The obtained results agree with the Inorganic Crystal Structure Database (ICSD) and the findings of previous studies [52, 53]. Fig. 4 (d) shows the elemental analysis of Cu nanoparticles, and the EDS results confirm the presence of the following elements carbon 2.54 wt.%, oxygen 16.66 wt.% and Cu 80.80 wt.%



Element	Weight %	Atom %
C	2.54	8.38
O	16.66	41.25
Cu	80.80	50.37
Total	100.00	100.00

Fig. 4 (a) HRSEM micrograph for 25000×, (b) HRSEM micrograph for 50000×, (c) X-ray diffraction pattern, (d) EDS spectra of a Cu nanoparticles

3.2 Effect of nanoparticle concentration and temperature on the density of the nanofluid

The density of the damper oil and the various concentrations of Cu/damper oil nanofluids exhibit a nearly linear decrease as the temperature increases within the range of 20 °C to 80 °C. This phenomenon can be attributed to the incorporation of Cu nanoparticles into the base fluid, as demonstrated in Fig. 5 (a). Comparatively, Cu/damper oil nanofluids display a substantial increase in density compared to the base fluid. This density enhancement is particularly evident in the volume concentrations ranging from 0.050% to 0.150% of Cu nanoparticles loaded into the base fluid.

The maximum density enhancement is around 149% at 80 °C for a base fluid containing 0.150% volume concentration of Cu nanoparticles. In Fig. 5 (b), the density ratio of Cu/damper oil nanofluids at various volume concentrations is illustrated in relation to the temperature range. The density ratio of Cu/damper oil nanofluids exhibits a significant enhancement as the concentration of Cu nanoparticles increases. Specifically, for nanofluids containing 0.050 volume% of Cu nanoparticles, from 1.462 to 1.495, the density ratio has increased when the temperature is varied between 20 °C and 80 °C. Similarly, for nanofluids with 0.150 volume% of Cu nanoparticles, the density ratio increases from 2.385 to 2.492 within the aforementioned temperature range. This phenomenon occurs mainly because Cu nanoparticles have a greater density than the base fluid.

3.3 Effect of nanoparticle concentration and temperature on the viscosity of the nanofluid

Fig. 6 (a), shows that the dynamic viscosity of base fluids is enhanced when Cu nanoparticles are loaded in the base

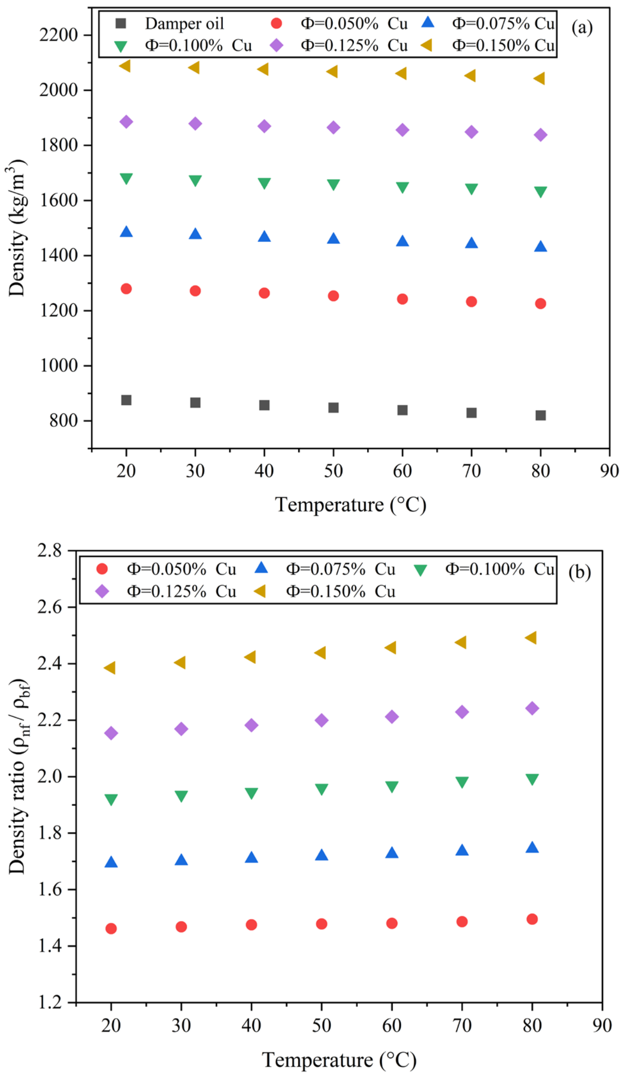


Fig. 5 (a) Density and (b) Density ratios for various volume concentrations of nanofluids with respect to temperature (ρ_{nf} denotes the density of nanofluid in kg/m^3, ρ_{bf} denotes the density of base fluid in kg/m^3)

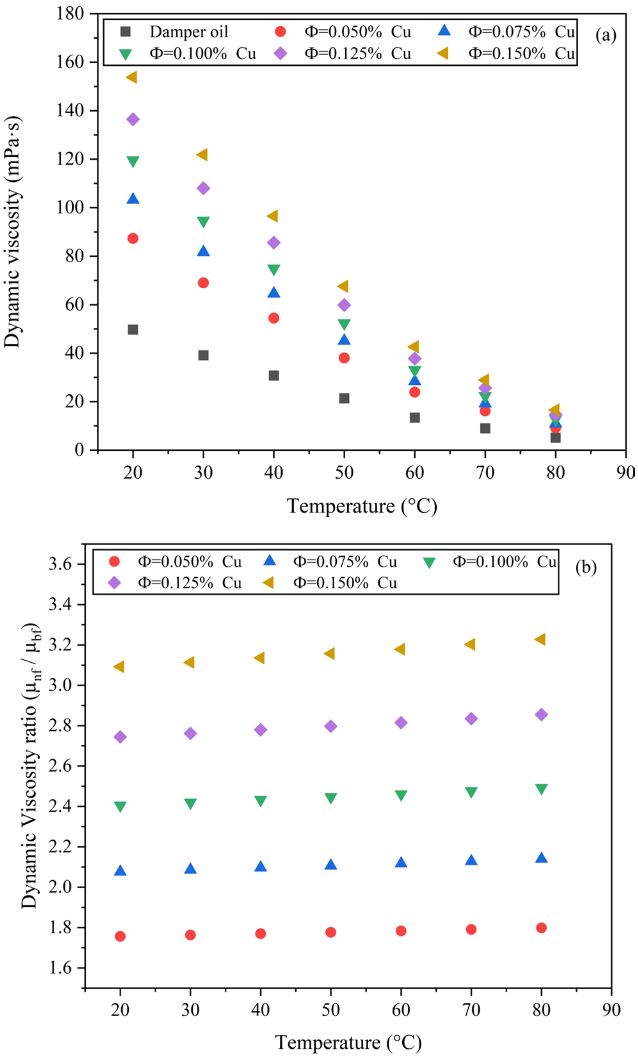


Fig. 6 (a) Viscosity and (b) Viscosity ratio for various volume concentration of nanofluids with respect to temperature (μ_{nf} denotes the dynamic viscosity of nanofluid in mPa·s, μ_{bf} denotes the dynamic viscosity of base fluid in mPa·s)

fluid at different volume concentrations at temperatures ranging between 20 °C and 80 °C. The quantum of collisions between the liquid molecules and the solid nanoparticles increases as the concentration of Cu nanoparticles increases in damper oil. As a result, internal shear stresses increased, resulting in an increase in dynamic viscosity [54, 55]. In the temperature range of 20 °C to 80 °C, there is an increase in the dynamic viscosity of the nanofluids with respect to the base fluid. The dynamic viscosity of damper oil at 20 °C was 49.7 mPa·s, which increased to 153.7 mPa·s, when Cu nanoparticles were loaded at 0.150%. The minimum and maximum viscosity enhancements at 80 °C were 79% and 222% for loadings of 0.050% and of 0.150% Cu nanoparticles, respectively.

The viscosity of both the base fluid and nanofluids decreased with an increase in temperature from 20 °C to 80 °C. This may be due the intermolecular forces within particles and the adhesion forces between them weaken in response to an increase in temperature [56]. Fig. 6 (b) shows that a significant increase in the viscosity ratio of Cu nanoparticles is detected when the temperature is raised from 20 °C to 80 °C. When 0.050% volume concentrations of Cu nanoparticles are present, the viscosity ratio increases from 1.75 to 1.79, and when 0.150% volume concentrations are present, it increases from 3.09 to 3.23.

3.4 Effect of nanoparticle concentration and temperature on the thermal conductivity of the nanofluid

The measurements are conducted between 20 °C and 80 °C. The thermal conductivity of the base fluid decreases as its temperature rises in Fig. 7 (a). As demonstrated by the experimental results in this study, the physical properties of oil cause these variations. In addition, the thermal conductivity of Cu/damper oil nanofluids is observed to increase as the temperature rises. This behavior can be attributed to the inherent properties of the Cu nanoparticles, which contribute to the enhanced thermal conductivity of the nanofluids at higher temperatures.

Due to molecular motion, nanoparticles in the base fluid move more rapidly at high temperatures. These changes increase the thermal conductivity of nanofluids by transferring energy between the interfacial layers. With the inclusion of Cu nanoparticles in various volume concentrations, there is an increase in thermal conductivity from 0.050% to 0.150%. With Cu nanoparticle loadings of 0.050% and 0.150%, respectively, the minimum and maximum thermal conductivity enhancements were 15.48% and 33.28%. The thermal conductivity ratio of Cu/damper oil nanofluids is depicted in Fig. 7 (b). As demonstrated, the ratio of variations in thermal conductivity increases with temperature. From 20 °C to 80 °C, the thermal conductivity ratio of nanofluids with a volume concentration of 0.050% increases from 1.06 to 1.25. Within the same temperature range, the ratio for nanofluids with a volume concentration of 0.150% increases from 1.154 to 1.33. This increase in the ratio is predominantly a result of the Brownian motion demonstrated by nanoparticles in nanofluids. The intensified Brownian motion leads to a greater influence of micro-convection on heat transport, resulting in a more pronounced enhancement of the thermal conductivity in nanofluids [56].

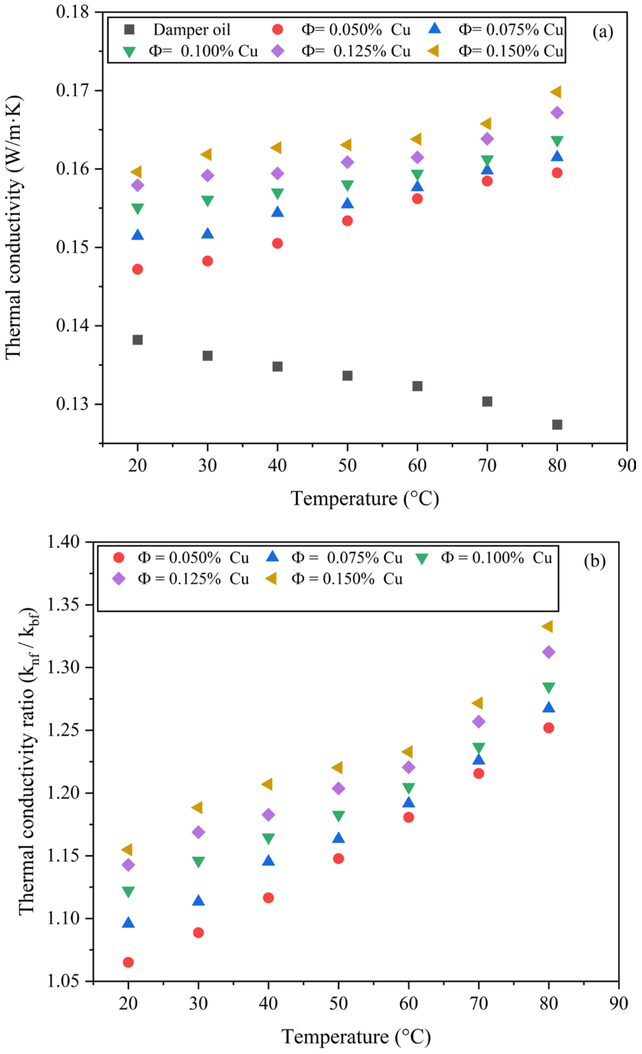


Fig. 7 (a) Thermal conductivity and (b) Thermal conductivity ratio for various volume concentration of nanofluids with respect to temperature (k_{nf} denotes the thermal condutivity of nanofluid in W/m·K, k_{bf} denotes the thermal condutivity of base fluid in W/m·K)

3.5 Effect of nanoparticle concentration and temperature on the specific heat of the nanofluid

Fig. 8 (a) illustrates the variation in specific heat capacities of Cu/damper oil nanofluids with respect to both volume

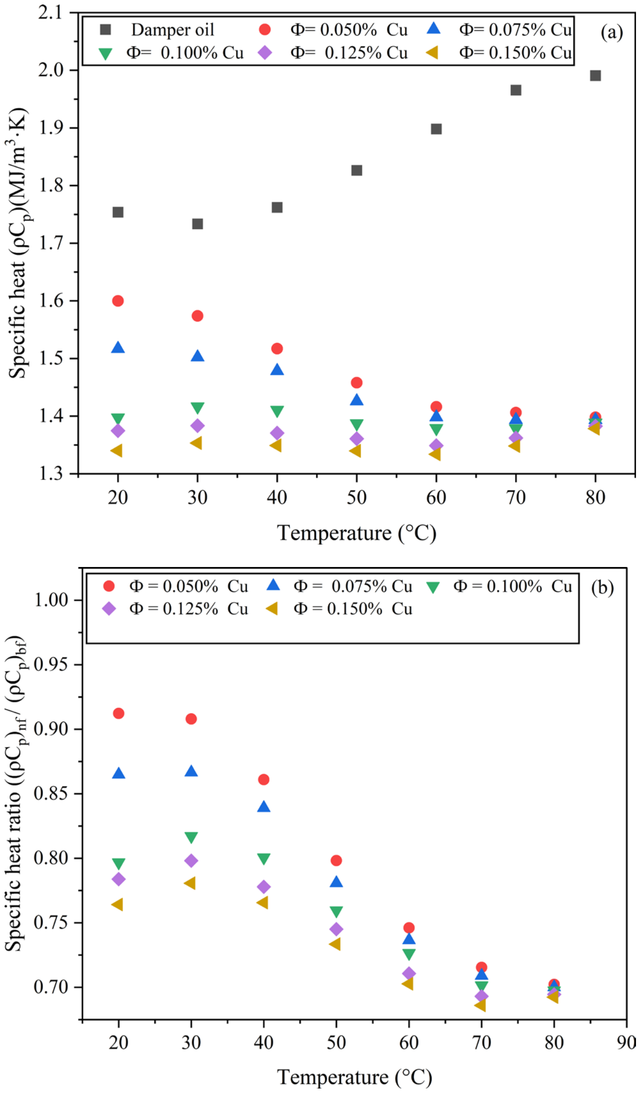


Fig. 8 (a) Specific heat and (b) Specific heat ratio for various volume concentration of nanofluids with respect to temperature ($(\rho C_p)_{nf}$ denotes the specific heat of nanofluid in $\mathrm{MJ/m^3 \cdot K}$, $(\rho C_p)_{bf}$ denotes the specific heat of base fluid in $\mathrm{MJ/m^3 \cdot K}$)

concentration and temperature. As the temperature of the fluid increases, the specific heat capacity of the base fluid exhibits an increase. Additionally, the base fluid's specific heat capacity is observed to be higher than that of Cu/damper oil nanofluids. Within specific temperature ranges, decreasing specific heat capacities are observed as Cu volume concentration is increased. At a nanoparticle concentration of 0.150% in the Cu/damper oil nanofluid, a decrease in the specific heat of 23.4% is observed at a temperature of 20 °C. Furthermore, at a temperature of 80 °C and the same nanoparticle concentration, the maximum reduction in specific heat reaches 30.15%.

Fig. 8 (b), illustrates the specific heat capacity ratio for the Cu volume concentration in automotive damper oil. As the temperature increases from 20 °C to 80 °C, the specific heat ratio of the base fluid, containing a volume concentration of 0.050% Cu nanoparticles, decreases from 0.91 to 0.70. Similarly, for a volume concentration of 0.150%, the specific heat ratio decreases from 0.76 to 0.69. This reduction in specific heat is directly proportional to the volume concentration of Cu nanoparticles in the base fluid. It is important to note that the base fluid has a higher specific heat than Cu nanoparticles. Thus, adding Cu nanoparticles leads to a decrease in specific heat.

3.6 Presenting a new correlation for predicting thermophysical properties

When designing thermal systems that utilize nanofluids for cooling and heating, it is essential to know its thermophysical properties, particularly its thermal conductivity and viscosity. This information is vital for minimizing potential harm or negative impacts on the system. Researchers have developed correlations in the existing literature that can be used to predict the thermophysical properties of various nanofluids containing distinct nanoparticles.

However, it is crucial to note that most of these correlations have predominantly focused on polar-based fluids, leaving limited correlations available for non-polar fluids. There is no existing theoretical correlation found in the literature to describe the relationship between Cu nanoparticles concentration and temperature for the prediction of the thermophysical properties of Cu/damper oil nanofluids. This study uses curve fitter tool in MATLAB software to develop a new mathematical correlation based on experimental data to predict Cu/damper oil nanofluid properties. As shown in Fig. 9. The experimentally measured thermophysical properties of Cu/damper oil nanofluids are well fitted by the 3D surface fitting. From the curve fitting method, the mathematical correlation was developed.

Table 3 provides mathematical correlations for predicting the thermophysical properties of Cu/damper oil nanofluids. The column labeled "Mathematical Correlations" in Table 3, lists the mathematical expressions for nanofluid properties, including density ratio in row 1., viscosity ratio in row 2., thermal conductivity ratio in row 3. and specific heat ratio in row 4. as functions of volume concentrations and temperature. The column labeled "RMSE" represents the Root Mean Square Error values for these mathematical expressions. RMSE serves to quantify the degree of alignment between predicted values and the actual experimental values. Lower RMSE values indicate higher predictive accuracy. The column labeled "R^2" displays the R-squared value, which is a statistical metric representing the goodness of fit of the correlation. R^2 values range from 0 to 1,

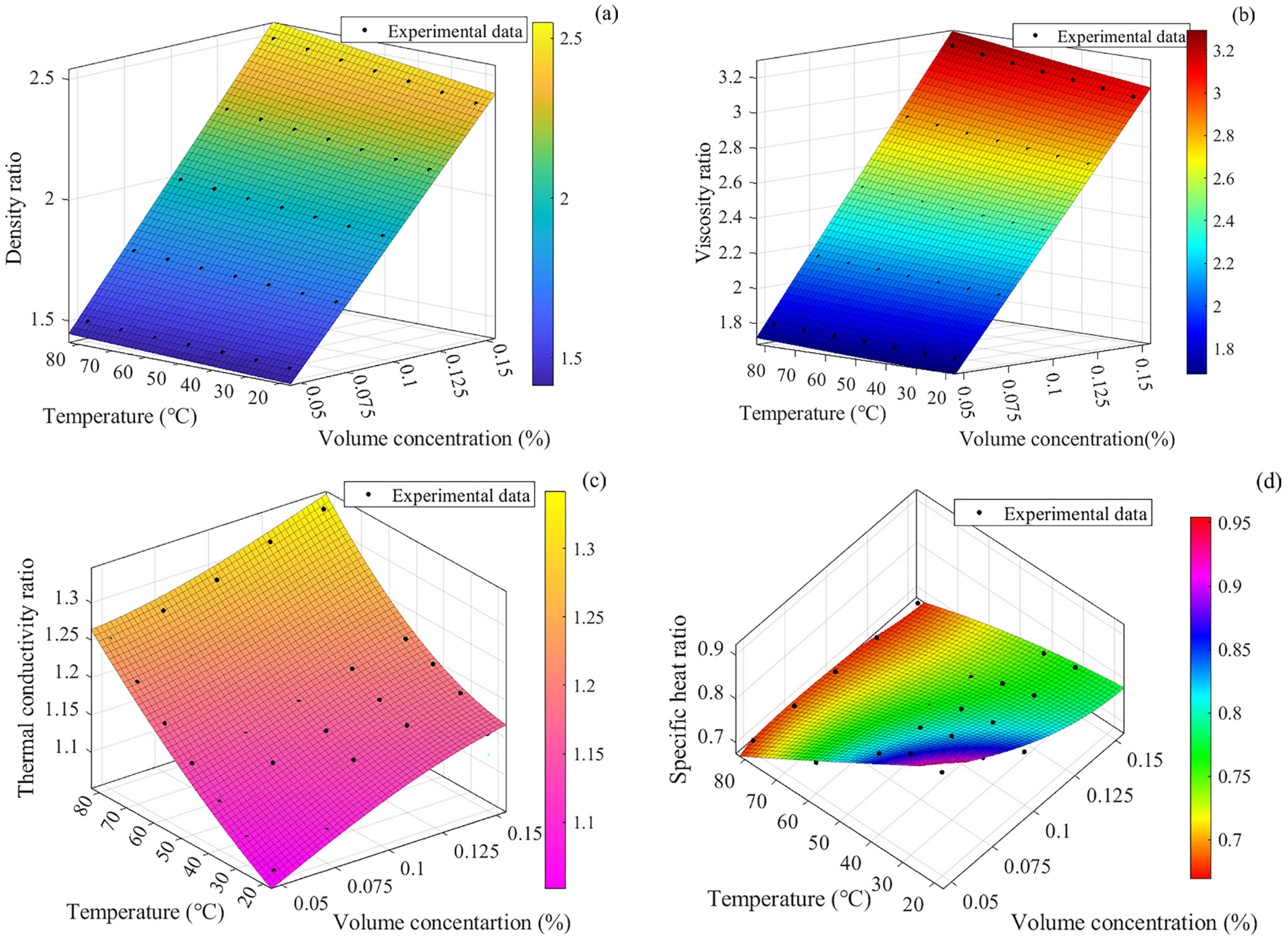


Fig. 9 The 3D surface fit of thermophysical properties of nanofluid (a) density ratio, (b) dynamic viscosity ratio, (c) thermal conductivity ratio, (d) specific heat ratio

Table 3 Mathematical correlation for predicting nanofluid thermophysical properties

No.	Mathematical correlations	RMSE	R^2
1.	$\frac{\rho_{nf}}{\rho_{bf}} = 1.0028 + 8.9831\Phi - 0.0001T + 0.0126\Phi T$	0.0014	1
2.	$\frac{\mu_{nf}}{\mu_{bf}} = 1.0843 + 13.0470\Phi - 0.0003T + 0.0154\Phi T$	0.0090	0.9997
3.	$\frac{k_{nf}}{k_{bf}} = 0.9238 + 2.0434\Phi + 0.0038T + 0.3533\Phi^2 - 0.0458\Phi T - 21.8057\Phi^3 + 0.1148\Phi^2 T + 0.0002\Phi T^2$	0.0074	0.9895
4.	$\frac{\left(C_p\right)_{nf}}{\left(C_p\right)_{bf}} = 1.1943 - 3.7017\Phi - 0.0076T - 1.1186\Phi^2 + 0.0799\Phi T + 52.8152\Phi^3 - 0.2169\Phi^2 T - 0.0001\Phi T^2$	0.0171	0.9459

with a value closer to 1 indicating a stronger fit between the predicted and actual data. The goodness fit of the equation in row 1 shows an R^2 of 1 and an RMSE of 0.0014. For the equation in row 2, the RMSE is 0.0090 and the R^2 is 0.9997. The equation in row 3 has a RMSE of 0.0074 and an R^2 of 0.9895. RMSE and R^2 for the equation in row 4 are 0.0171 and 0.9459, respectively. The RMSE values are all below 0.0171, and the R^2 values are all above 0.9459, which indicates that the correlations represent a very stronger fit.

The experimental data and the predictions derived from the correlations are well concordant, as illustrated in Fig. 10. There is a strong alignment and coherence

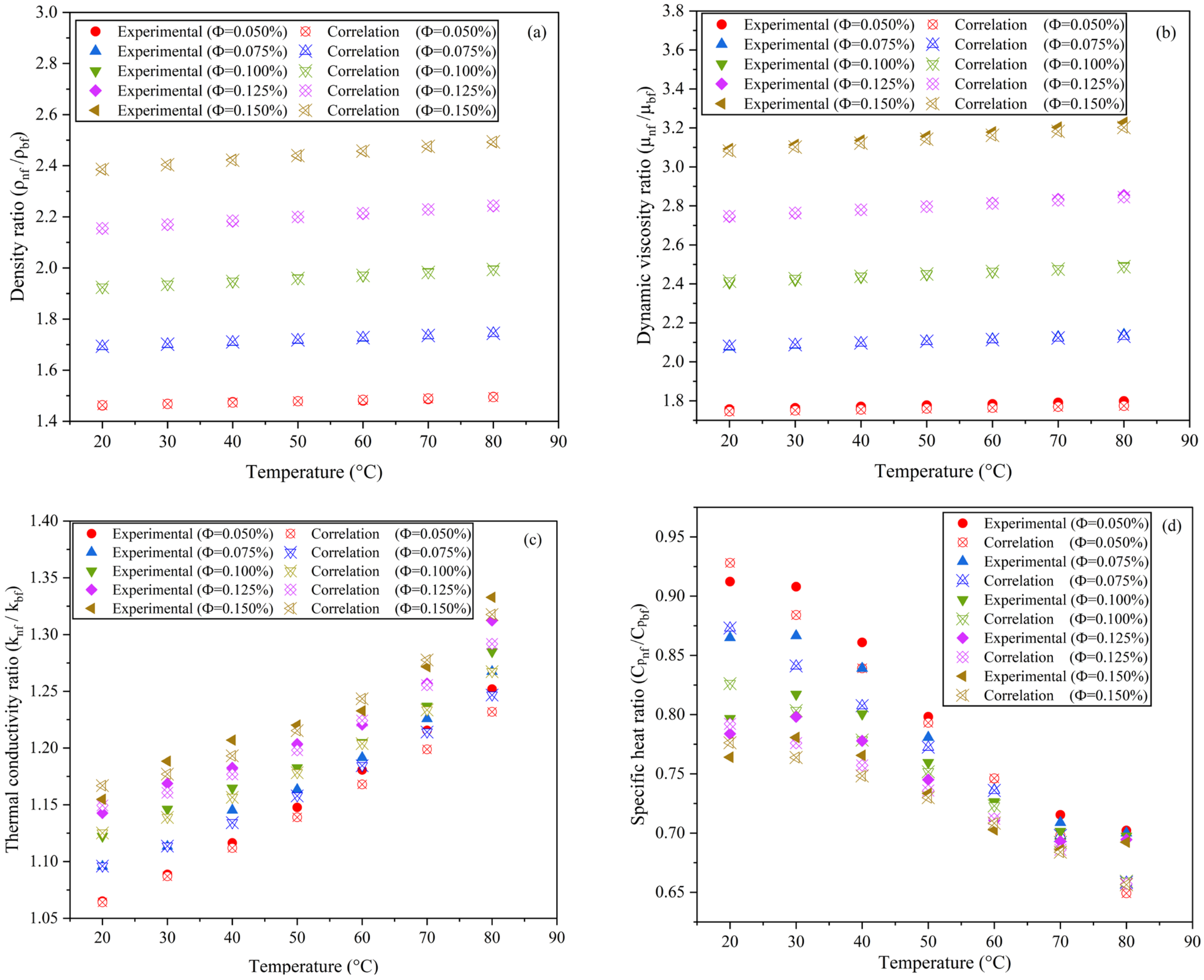


Fig. 10 Comparison of thermophysical properties of nanofluids between the experimental data and proposed correlation output at different temperatures and volume concentrations (a) density ratio, (b) dynamic viscosity ratio, (c) thermal conductivity ratio, (d) specific heat ratio.

between the two sets of data, as evidenced by the close grouping of the majority of data points. It is evident from this graph that the experimental data and correlation outcomes are high.

3.7 Margin of deviation

This study compared experimentally measured thermophysical properties of Cu/damper oil nanofluid with the results obtained from newly developed mathematical correlations. The comparisons were conducted over a temperature range from 20 °C to 80 °C. The primary purpose of this comparison was to determine the Margin of Deviation (MOD) of the mathematical correlations used to predict the thermophysical properties of Cu/damper oil nanofluid. The margin of deviation between the experimental and correlation outputs was calculated using Eq. (2).

$$\mathrm{MOD}(\%)=\left[\frac{\left(k,C_p,\rho,\mu\right)_{\text{experimental}}-\left(k,C_p,\rho,\mu\right)_{\text{predicted}}}{\left(k,C_p,\rho,\mu\right)_{\text{experimental}}}\right] \cdot 100 \quad (2)$$

Fig. 11 illustrates the discrepancy between observed and predicted results. Most data points are located on or near the bisector, demonstrating the validity of the proposed relationship. The predicted density values exhibit a MOD between −0.24% and 0.15%. Similarly, the predicted viscosity values display a MOD range of −0.35% to 1.33%. The predicted thermal conductivity values also demonstrate a MOD range of −1.06% to 1.64%. Finally, the predicted specific heat values of Cu/damper oil nanofluids. have a MOD range from −3.72% to 7.55%. In summary, the MOD ranges for the various properties indicate the extent of deviation between the predicted and the experimental results.

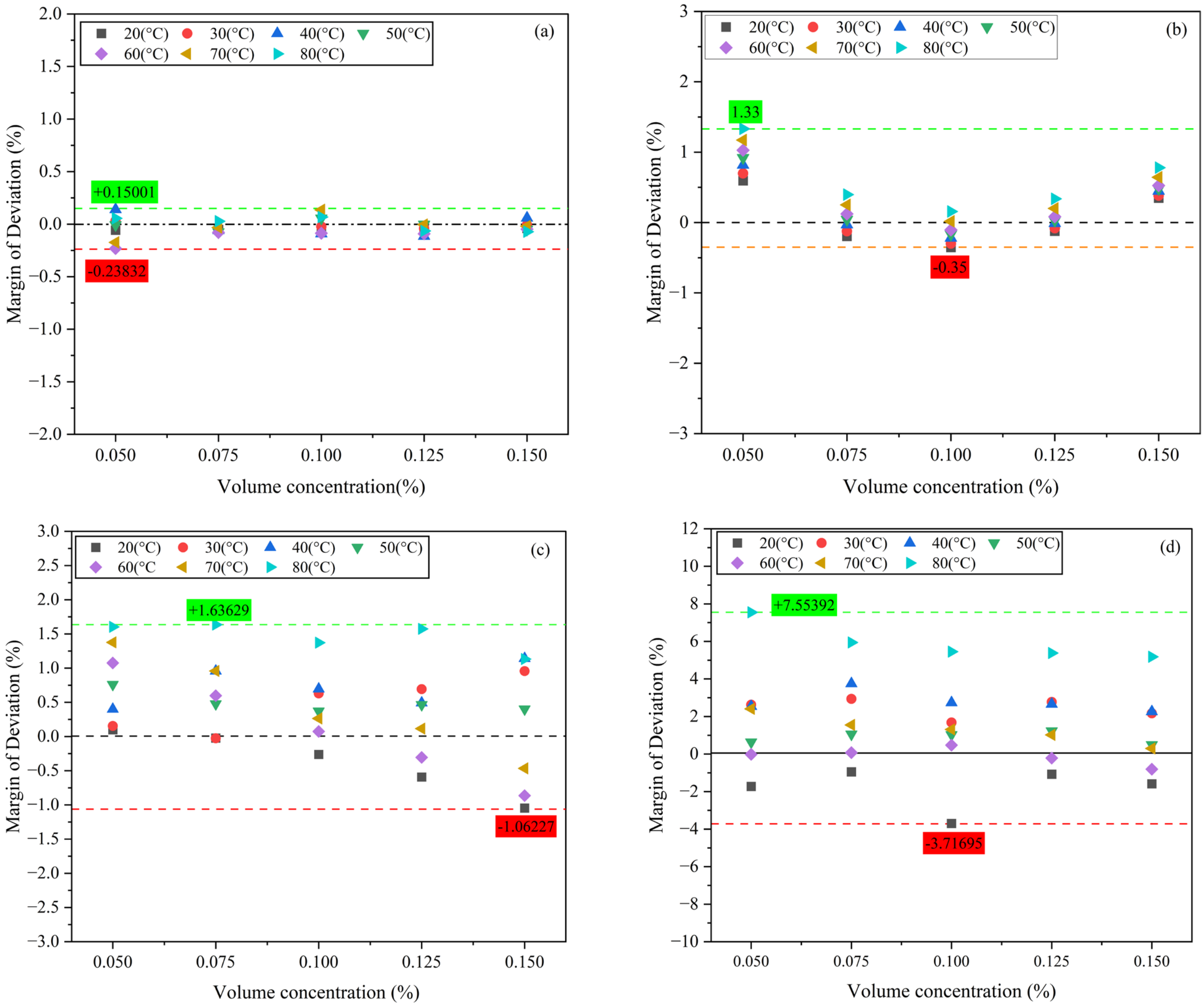


Fig. 11 Margin of deviation between the thermophysical properties experimental data and proposed correlation output at different temperatures and volume concentration; (a) density ratio, (b) dynamic viscosity ratio, (c) thermal conductivity ratio, (d) specific heat ratio.

4 Conclusion

Automotive damper oil, commonly used in suspension systems, is being studied to improve its thermophysical properties. Nanofluids composed of Cu nanoparticles and damper oil are investigated regarding their atomic structure and surface properties. The properties are examined at 20 °C to 80 °C and 0.05% to 0.150% nanoparticle concentrations. An increase in density of 149% and an increase in viscosity of 222% are observed at 0.150% volume concentration. In addition to a 33.28% improvement in thermal conductivity, heat capacity has a reduction of 30.15% at higher levels of volume concentrations of 0.150% at 80 °C. Cu/damper oil nanofluid properties are modeled using these correlations within a −3.7% to 7% accuracy within the conditions of the study. Further research on nanofluids' potential in automotive damping systems could reshape the design and enhance vehicle suspension and ride quality.

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Nomenclature

W - mass (g)
ρ - density (kg/m^3)
μ - dynamic viscosity (mPa·s)
k - thermal conductivity (W/m·K)
C_p - specific heat capacity (MJ/m^3·k)
Φ - volume concentration (%)
T - temperature (°C)

Subscripts and superscripts

bf - base fluid
nf - nano fluid

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