Thermal Transport Feasibility of (Water + Ethylene Glycol)-Based Nanofluids Containing Metallic Oxides: Mathematical Approach

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Abstract. A mathematical approach was used to predict the heat transfer performance of CuO nanoparticles with three different filling ratios [DW], [DW70:30EG] and [DW50:50EG]. There was a discussion on the thermophysical properties. Thermal diffusivity, Prandtl number and pumping power were predicted to find the optimal filling ratio. The effect of nanoparticle shapes on the thermal conductivity and dynamic viscosity was examined. The base fluid of [DW50:50EG] showed significant improvement while DW was optimal for thermal conductivity. Higher thermal conductivity was achieved by DW-based spherical nanofluids, while [DW50:50EG]-based platelets nanofluid showed the best improvement in dynamic viscosity. By increasing the temperature, thermal diffusivity increased while the Prandtl number decreased. The loading of nanofluids did not require more power consumption, and the relative pumping power was less than 1.

Keywords: Metallic oxides nanofluids; Ethylene glycol + water; Thermal transport; Nanoparticle shape; Pumping power

1. Nomenclature

| Symbol | Description |
|--------|-------------|
| Al₂O₃  | Aluminium oxide |
| CuO    | Copper (II) oxide |
| DSC    | Differential scanning calorimetry |
| DW     | Distilled water |
| EG     | Ethylene glycol |
| Fe₃O₄  | Iron oxide |
| k      | Thermal conductivity, W m⁻¹ K⁻¹ |
| m      | Mass flow rate, kg s⁻¹ |
| Pr     | Prandtl number |
| SiO₂   | Silicon dioxide |
| TiO₂   | Titanium dioxide |
| ZnO    | Zinc oxide |
| ΔP     | Pressure drop, Pa m⁻¹ |

Greek symbols

| Symbol | Description |
|--------|-------------|
| α      | Thermal diffusivity, m² s⁻¹ |
| μ      | Dynamic viscosity, mPa.s |
| ν      | Momentum diffusivity, m² s⁻¹ |
| ρ      | Density, kg m⁻³ |
| φ      | Volume fraction of nanoparticles |
2. Introduction

In most engineering areas, heat transfer techniques have merged, and much attention has been paid in recent decades to developing more efficient and small heat exchangers. After extensive use of various approaches, such as modifying materials, using extended surfaces or improving process standards, many research activities are now focused on improving the low heat transfer capacities of conventional liquids such as water (DW), ethylene glycol (EG) or engine oils [1]. In this sense, the improvement of heat transfer fluid thermal transport capabilities by dispersing high-conductivity nanoparticles, also known as nanofluids, has become prominent research tools [2].

Nanofluids, including metallic oxides, organic and inorganic materials, were produced using a wide variety of nano-additives. Several studies have shown that nano coolants can be an operational technique for enhancing the performance of heat transport schemes utilizing a combination of EG/DW as a base fluid. [3]. For instance, the experimental results of Vajjha and Das [4] investigated that the thermal conductivity of the [EG60:40DW] combination could be increased by about 12.3% by mixing ZnO solid particles (29 nm) with a volume fraction of 2%. An experimental investigation of the effectiveness of Fe3O4 nanoparticles (13nm) was performed on three various forms of ethylene glycol/water mixture with weights 20:80, 40:60, and 60:40 [10]. The researchers realized that the thermal conductivity improvements of the three EG/water combinations stated directly above were 46%, 42% and 33% respectively, with a temperature of 60°C and a volume fraction of 2%.

Thermal conductivity ($k$) of nanofluids has received much consideration in recent decades due to the high impact of its characteristic on heat transfer performance of thermal installations [5], [6], [7]. However, other thermophysical properties, such as dynamic viscosity ($\mu$), density ($\rho$) or even specific heat capacity ($c_p$), should also be considered to determine whether the replacement of the conventional liquid with the novel nanofluid would be useful to conduct technical calculations for thermal installations.

Thermophysical properties are very significant factors affecting the nanofluids heat and mass transfer efficiency [8]. Since dynamic viscosity presented a significant impact on internal flow resistance, the Reynolds number, and low pressure, many investigations have been performed on dynamic viscosity of different nanofluids types. As Azmi et al. [9] reported by dispersing TiO2 nanoparticles, the dynamic viscosity of the [EG40:60DW] (volume ratio) mixture could be augmented. For example, if the volume fraction of nanoparticles increased from 0.5% to 1.5%, the dynamic viscosity increase was about 12%. The viscosity variations of (EG/water)-based Fe3O4 nanofluid with different fractions of nanoparticle and preparation temperatures were investigated by Sundar et al. [10]. The researchers exhibited that the dynamic viscosity of (EG/water)-based nanofluids could be improved by increasing the concentration of nanoparticles and lowering the production temperature. The dynamic viscosity of the base fluid could be improved by 2.9 times by adding a 1% volume fraction of nanoparticles. The dynamic viscosity of various (EG/water)-based nanofluids with the influences of different factors were measured by many studies [6], [11]. Based on their experimental results, the suspension of nanoparticles could increase the viscosity of the base fluid in different amounts. Furthermore, the characteristics of temperature, base fluid, and nanoparticles, including the concentration, particle size, particle type, and particle shape, were the significant factors affecting the viscosity of nanofluids.

The use of water-EG mixture provided a wider range of operating temperatures in the heat transfer study due to the combined properties of water and EG. The current analysis objective is to predict heat transfer performance with three water-EG mixture ratios using CuO nanoparticles. The thermophysical properties and effects of nanoparticles shapes have been investigated. The rate of heat transfer and electricity consumption were predicted.
3. The Study Methodology

Heat transfer characteristics of (Water + Ethylene Glycol)-based nanofluids containing CuO with a volume fraction of 4% have been investigated using several mathematical correlations. In this research, three different filling ratios [DW, (DW70:30EG), (DW50:50EG)] were discussed. The preparation temperature of nanofluids ranged from 25-50°C and nanoparticle shapes (blades, platelets, cylindrical, bricks, and spherical) to estimate the impact of effective thermal performance of nanofluids. The significance of Prandtl number, thermal diffusivity, the property of enhancement and pumping power have been explained. Base fluids and nanoparticles properties have been listed in Tables 1-4 (data were taken from the National Institute of Standards and Technology).

| Temp. (°C) | Density (kg/m³) | Cp (J/kg-K) | K (W/m-K) | μ (mPa-s) | Pr | α (m²/s) |
|------------|----------------|-------------|-----------|-----------|----|----------|
| 25         | 997            | 4073        | 0.612     | 0.868     | 5.8 | 1.51E-07 |
| 30         | 995            | 4070        | 0.619     | 0.777     | 5.1 | 1.53E-07 |
| 35         | 994            | 4069        | 0.626     | 0.701     | 4.6 | 1.55E-07 |
| 40         | 992            | 4067        | 0.632     | 0.635     | 4.1 | 1.57E-07 |
| 45         | 990            | 4067        | 0.638     | 0.580     | 3.7 | 1.59E-07 |
| 50         | 988            | 4066        | 0.644     | 0.532     | 3.4 | 1.60E-07 |

| Temp. (°C) | Density (kg/m³) | Cp (J/kg-K) | K (W/m-K) | μ (mPa-s) | Pr | α (m²/s) |
|------------|----------------|-------------|-----------|-----------|----|----------|
| 25         | 1035           | 3730        | 0.487     | 1.864     | 14.3 | 1.26E-07 |
| 30         | 1032           | 3746        | 0.490     | 1.623     | 12.4 | 1.27E-07 |
| 35         | 1030           | 3761        | 0.493     | 1.428     | 10.9 | 1.27E-07 |
| 40         | 1027           | 3776        | 0.495     | 1.269     | 9.7  | 1.28E-07 |
| 45         | 1024           | 3791        | 0.497     | 1.137     | 8.7  | 1.28E-07 |
| 50         | 1021           | 3806        | 0.499     | 1.026     | 7.8  | 1.29E-07 |

| Temp. (°C) | Density (kg/m³) | Cp (J/kg-K) | K (W/m-K) | μ (mPa-s) | Pr | α (m²/s) |
|------------|----------------|-------------|-----------|-----------|----|----------|
| 25         | 1053           | 3298        | 0.430     | 3.367     | 25.8 | 1.24E-07 |
| 30         | 1050           | 3308        | 0.434     | 2.936     | 22.4 | 1.25E-07 |
| 35         | 1048           | 3319        | 0.438     | 2.565     | 19.4 | 1.26E-07 |
| 40         | 1045           | 3329        | 0.442     | 2.244     | 16.9 | 1.27E-07 |
| 45         | 1042           | 3340        | 0.445     | 1.968     | 14.8 | 1.28E-07 |
| 50         | 1039           | 3351        | 0.449     | 1.730     | 12.9 | 1.29E-07 |

| Thermophysical properties | CuO |
|---------------------------|-----|
| Density, ρ (kg/m³)        | 6500|
| Dynamic viscosity, μ (mPa-s) | -  |
| Thermal conductivity, k (W/m-K) | 20 |
| Specific heat, cp (J/kg-K) | 535.6 |
3.1. Thermophysical Properties

The thermal conductivity enhancement ratio in the literature was defined as the thermal conductivity ratio of the nanofluid to the thermal conductivity of the base fluid ($K_{\text{nf}}/K_{\text{bf}}$). To estimate the thermal conductivity measurements, Maxwell model [13] has been used in current research to estimate thermal conductivity measurements.

$$k_{\text{eff}} = \frac{k_{\text{nf}} + 2k_{\text{bf}} + 2\varphi(k_{\text{bf}} - k_{\text{nf}})}{k_{\text{nf}} + 2k_{\text{bf}} - \varphi(k_{\text{bf}} - k_{\text{nf}})} \quad (1)$$

Nanofluid viscosity, like thermal conductivity, is a vital transport property. Compared to thermal conductivity, nanofluid viscosity literature is still difficult to find. The majority of formulations were extended to express viscosity in accordance with the concentration of the nanoparticles. Temperature is also a significant factor in viscosity, and some correlations have therefore been designed to analyze the effects of temperature on viscosity. Einstein’s model [14] was used to estimate the effective viscosity in the present study.

$$\mu_{\text{eff}} = \mu_{\text{bf}}(1 + 2.5\varphi), \varphi < 0.05 \quad (2)$$

The nanofluid density is usually given to be a mixed density property of base fluid $\rho_{\text{bf}}$ and nanoparticles $\rho_{\text{np}}$. Various density meters were employed to evaluate the nanofluid density [15],[16]. The measurement results showed the density of nanofluids using Eq. (3) the mixing theory can be estimated very precisely. Specific heat capacity can simply be described as the heat required to raise 1 g of a substance’s temperature by 1°C. The specific heat of solids is normally lower than that of liquids. So, when solid nanoparticles are added to the base fluid, the specific heat is reduced. However, to remove more heat from an ideal coolant, a higher value of specific heat is preferred [17]. For the calculation of the particular nanofluid heat, Eq. (4) is a commonly accepted correlation [18].

$$\rho_{\text{nf}} = \frac{(1 - \varphi)\rho_{\text{bf}} + \varphi\rho_{\text{np}}}{(1 - \varphi)\rho_{\text{bf}} + \varphi\rho_{\text{np}}} \quad (3)$$

$$C_{\text{p,nf}} = \frac{(1 - \varphi)(C_{\text{p,bf}} + \varphi(C_{\text{p,bf}} + \varphi C_{\text{p,npj}}))}{(1 - \varphi)\rho_{\text{bf}} + \varphi\rho_{\text{np}}} \quad (4)$$

3.2. Different Nanoparticle Shapes

This paper discusses five different shapes of nanoparticles (sphere, plates, blades, cylindrical and bricks). To study the influences of these nanoparticle shapes on the thermophysical characteristics of nanofluid, Timofeeva et al. [19] presented the following equations:

$$\frac{k_{\text{eff}}}{k_{\text{bf}}} = 1 + \left(C_{k}^{\text{shape}} + C_{k}^{\text{surface}}\right)\varphi = 1 + C_{k}^{\varphi} \quad (5)$$

The effective thermal conductivity can be achieved by utilizing the data from Table 5.

$$\mu_{\text{eff}} = \mu_{\text{bf}}(1 + A_{1}\varphi + A_{2}\varphi^{2}) \quad (6)$$

Where $A_1$ and $A_2$ are the constants exhibited in Table 6.

**Table 5.** Effect of the particle shape and the thermal conductivity resistance of nanoparticles [20].

| Type     | Aspect Ratio | $C_k$ | $C_k^{\text{shape}}$ | $C_k^{\text{surface}}$ |
|----------|--------------|-------|-----------------------|-------------------------|
| Platelets| 1:1/8        | 2.61  | 5.72                  | -3.11                   |
| Blades   | 1:6:1/12     | 2.74  | 8.26                  | -5.52                   |
| Cylindrical | 1:8         | 3.95  | 4.82                  | -0.87                   |
| Bricks   | 1:1:1        | 3.37  | 3.72                  | -0.35                   |
3.3. Prandtl Number and Thermal Diffusivity
The Prandtl number is a non-dimensional number that describes the difference between momentum and thermal diffusivity. Thermal diffusivity is the rate of heat transport from the hot side of a material to the cold side; a measure of how fast a material can absorb heat from its environment. It can be calculated by taking thermal conductivity at constant pressure divided by density and specific thermal capacity.

\[ Pr = \frac{\text{Momentum diffusivity}}{\text{Heat diffusivity}} = \frac{\nu}{\alpha} = \frac{\mu/\rho}{\kappa/\rho c_p} = \frac{cp\mu}{\kappa} \] (7)

3.4. Pumping Power
The design of heat exchangers for efficient heat transfer and minimum pumping power is important in terms of energy savings and could cause significant errors in the assessment of nanofluid performance (pumping power and heat transfer) in different thermal applications. The pumping power or work required for the circulation of coolant can be calculated using Eq. 8.

\[ P_{pump} = \Delta P \frac{\dot{m}}{\rho} \] (8)

where \( \Delta P \) is the pressure drop, \( \dot{m} \) is the mass flow rate and \( \rho \) is the fluid density. In the case of a fully developed condition and a turbulent region in a circular tube with a uniform heat flow on the wall, Eq. 9 could be used to express the pumping power [21].

\[ \left( \frac{\dot{W}}{W_{bf}} \right) = \left( \frac{\mu}{\mu_{bf}} \right)^{0.25} \left( \frac{\rho_{bf}}{\rho} \right)^2 \] (9)

4. Results and Discussion
Thermophysical properties of CuO nanoparticles for different temperatures and different base fluids were shown in Figure 1. The values of thermal conductivity increased by increasing the temperature of preparation (25-50°C). CuO/DW nanofluids show the higher thermal conductivity values followed by CuO/(DW50:50EG) and CuO/(DW70:30EG), respectively. By increasing the temperature from 25 to 50°C, the thermal conductivities increased by 5.14%, 4.38% and 2.58% for CuO/DW, CuO/(DW50:50EG) and CuO/(DW70:30EG), respectively. The filling ratio of (DW50:50EG) based nanofluid showed the highest increment of effective viscosity, while distilled water-based nanofluid showed the lowest. Nanofluids containing solid nanoparticles have a higher viscosity than common working fluids; hence, measuring the viscosity is necessary for designing thermal systems and estimating the required pumping power. In engineering applications, it is interesting to investigate the effect of both concentration and temperature on thermophysical property. The density of CuO nanoparticles with a volume fraction of 4%, and the use of three different filling ratios [DW, (DW70:30EG), (DW50:50EG)] is shown in Figure 1. The values of density decreased by increasing the temperature of preparation from 25 to 50°C. CuO/DW based nanofluid showed the highest increase of 22.12% followed by (DW70:30EG) and (DW50:50EG) with 21.16% and 20.67%, respectively at 25°C.
Most researchers paid greater attention to the thermal conductivity of the nanofluids. Some others emphasized the viscosity of nanofluid. However, specific heat ($C_p$) is also extremely important for nanofluids. The most demanding properties for analyzing energy and exergy are the specific heat of nanofluid. The specific heat capacity of CuO nanoparticle with a volume fraction of 4%, and three different filling ratios [DW, (DW70:30EG), (DW50:50EG)] is displayed in Figure 1. Specific heat of (DW70:30EG) and (DW50:50EG) based nanofluids increased by increasing the temperature while distilled water behaved quite differently.

![Figure 1. Thermophysical properties of CuO nanoparticles for different temperatures and different basefluids.](image)

The effect of nanoparticle shapes on thermal conductivity and dynamic viscosity of CuO nanofluids was presented in Figure 2. Water-based CuO spherical nanoparticles showed the highest thermal conductivity enhancement of 11.2% while (DW50:50EG)-based CuO bricks nanoparticles showed the lowest at 5%. (DW50:50EG) based platelets nanofluids displayed the highest increment of effective viscosity followed permanently by (DW50:50EG) based cylindrical nanofluids. While the lowest increment was achieved by distilled water-based spherical nanofluids.
Figure 2. Effect of nanoparticles shapes on thermal conductivity and dynamic viscosity for different temperatures.

As shown in Figure 3, the thermal diffusivity of CuO nanofluids increased by increasing the temperature. The combination of distilled water-based nanofluids achieved the highest thermal diffusivity followed by (DW70:30EG) and (DW50:50EG) based nanofluids, respectively. As shown in Figure 3, Prandtl number decreased by increasing the temperature. CuO/(DW50:50EG) showed the highest values followed by CuO/(DW70:30EG) and CuO/DW.
Energy consumption and pumping power characteristics are serious limits in terms of economy and energy saving. Pumping power can be considered as an economic performance indicator in the thermal system for evaluating the operability test of fluid and performance of the power plant. Besides, the design of heat exchangers for effective heat transfer and minimum pumping power is important in terms of energy savings and could cause considerable errors when evaluating the performance of nanofluids (pumping power and heat transfer) in various thermal applications. The pumping power of different nanofluid types with three different filling ratios and at various temperatures is compared in Figure 4. Figure 4 showed that there was no increase in the pumping power with the nanofluids loading, and the effect of temperature variation is negligible [22].

Figure 3. Thermal diffusivity and Prandtl number of CuO nanofluid types at different filling ratios.

Figure 4. Relative pumping power of CuO nanofluid at different filling ratios and different temperatures.

5. Conclusions
The present paper has mathematically discussed the feasibility of heat transfer characterizes using CuO nanoparticles with three different base fluid mixture ratios [DW], [DW70:30EG] and [DW50:50EG].
Many parameters have been tested during the investigations; the following conclusions have been
drawn from the present study.

1. Density decreased by decreasing the temperature. [DW50:EG50] and [DW70:EG30]-based nanofluids exhibited a higher density than water-based nanofluids.
2. Specific heat of [DW50:EG50] and [DW70:EG30]-based nanofluids increased by increasing temperature whereas, the specific heat of water-based nanofluids decreased.
3. Water-based nanofluids showed the highest enhancement in thermal conductivity followed by [DW70:EG30] and [DW50:EG50]- based nanofluids.
4. Dynamic viscosity of water, [DW50:EG50] and [DW70:EG30]-based nanofluids decreased when preparation temperature increased.
5. Thermal diffusivity of water, [DW50:EG50] and [DW70:EG30]-based nanofluids increased by increasing temperature while Prandtl number decreased.
6. Relative pumping power was less than 1, this means no increase in the pumping power with the nanofluids loading, and the effect of temperature variation is negligible.
7. Water-based spherical nanofluids showed the highest thermal conductivity enhancement while [DW50:EG50]-based platelets nanofluids demonstrated the maximum viscosity enhancement.

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