Advances in Mechanical and Materials Engineering

Volume 43, 2026, Pages 43-54
https://doi.org/10.7862/rm.2026.4

THE FACULTY OF MECHANICAL ENGINEERING AND AERONAUTICS
RZESZOW UNIVERSITY OF TECHNOLOGY

Original Research

Relative Thermo-Hydraulic Performance of Mono and Hybrid Transformer Nanofluid in a Plate Fin Heat Exchanger - An Experimental Study

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Received: 11 October 2025 / Accepted: 3 January 2026 / Published online: 12 January 2026

Abstract

This investigation conducts a comparative study on the thermo-hydraulic performance of magnesium oxide nanoparticles dispersed in transformer oil (MgO/TrO) and a hybrid nanofluid containing both magnesium oxide and copper oxide nanoparticles (MgO-CuO/TrO). Key performance metrics including Overall Heat Transfer Coefficient (UHTC), Convective Heat Transfer Coefficient (CHTC), Nusselt number (Nu), friction factor (FF), and pumping power (PP) were evaluated across relevant ranges of temperature (30-70˚C) and Reynolds number. Results indicate that the hybrid (MgO-CuO/TrO) nanofluid consistently demonstrates significantly enhanced heat transfer characteristics. Compared to the MgO/TO fluid, the hybrid formulation exhibited superior UHTC up to 55% enhancement, CHTC 14-24% enhancement, and Nusselt number 4-27% enhancement. The hybrid nanofluid showed higher friction factors in the range of 8-11% and consequently required 2.2-3.8% greater pumping power under similar operating conditions. While the incorporation of CuO nanoparticles improves the thermal performance of the MgO-based transformer oil with an increased oil pumping power effect.

Keywords: MgO, MgO-CuO/TiO, plate-fin heat exchanger, pumping power, thermal performance, transformer oil

Nomenclature

Acronyms

CHTC	Convective heat transfer coefficient, W/m^2·K
FF	Friction factor
TrO	Transformer oil
UHTC	Overall heat transfer coefficient, W/m^2·K

Symbols

$C_{pn,p}$	Thermal capacity of the nanoparticle, J/kg·K
$C_{pn.f}$	Thermal capacity of the nanofluid, J/kg·K
D_h	Hydraulic diameter of the tube, m
k_{nf}	Thermal conductivity of nano fluid W/m·K
m	Mass, kg
m_{bf}	Mass of base fluid, g
m_{np}	Mass of nanoparticle
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
V	Volume, m^3
wt_{bf}	Weight of base fluid, g
wt_{CuO}	Weight of CuO nanoparticles, g
wt_{MgO}	Weight of MgO nanoparticles, g
wt_{np}	Weight of nanoparticles, g
$Ø_{hnf}$	% vol. concentration of hybrid nanofluid
$Ø_{hyb}$	% vol. concentration of hybrid nanoparticles
$Ø_{ρnp}$	% vol. concentration of nanoparticle

Greek symbols

ρ_{bf}	Density of base fluid, g/m^3
ρ_{CuO}	Density of CuO nanoparticles, g/m^3
ρ_{MgO}	Density of MgO nanoparticles, g/m^3
ρ_{np}	Density of nanoparticles, g/m^3
ρ_{TrO}	Density of transformer oil, g/m^3
μ_{nf}	Dynamic viscosity of nano fluid, kg/m·s

Subscripts

bf	Base fluid
nf	Nanofluid
np	Nanoparticle

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1. Introduction

Magnesium oxide (MgO) is a well-established inorganic compound known for its high thermal stability, refractory properties, large surface area, and relatively low toxicity, making it useful in applications ranging from catalysis and adsorption to refractory materials and biomedical uses. When synthesized at the nanoscale, MgO nanoparticles exhibit significantly enhanced surface reactivity and unique optical and electronic properties due to quantum confinement and high surface-area-to-volume ratios. Building upon this, MgO-CuO nanoparticles represent a class of composite nanomaterials designed to synergistically combine the attributes of both magnesium oxide and copper (II) oxide (CuO). CuO nanoparticles themselves are recognized for their potent antimicrobial activity, catalytic efficiency (particularly in oxidation reactions), and semiconducting properties. By integrating CuO with MgO at the nanoscale, researchers aim to create materials with enhanced stability, improved catalytic performance, broader-spectrum antimicrobial action, or tailored electronic properties, leveraging the supportive or modifying role of MgO alongside the specific functionalities of CuO.

Jeyanthi (2025) authored a paper in which magnesium oxide nanofluids improved thermal conductivity in automotive cooling systems, leading to significant energy savings and more efficient thermal management designs. Kumar and Hassan (2024) authored a paper where using car radiator with CuO-MgO-TrO ternary hybrid nanofluid show improved heat transfer, with a 7.65% higher overall heat transfer coefficient (UHTC) compared to base fluid, and a reduced friction factor and pumping power. Azizi et al. (2024) published a paper where the water/MgO-TrO hybrid nanofluid exhibited the highest thermal performance in a shell-and-coil heat exchanger, with the MgO-TrO/water hybrid nanofluid showing the highest thermal performance at the lowest Dean number. Aytaç et al. (2023) investigated the effects of using MgO-CuO/water hybrid nanofluid in an evacuated solar water collector. Using MgO-CuO/water hybrid nanofluid in heat pipe evacuated solar water collectors significantly improved thermal performance and reduced payback period, leading to significant CO_2 savings. Kumar et al. (2023) mixed MgO in CuO/water nanofluid for thermal conductivity improvement. Mixing MgO nanoparticles in CuO/water nanofluid improved thermal conductivity, particularly at higher temperatures, with a 12.5 percent increase at 55 °C and 1.5 % volume fraction. Nfawa et al. (2021) added MgO nanoparticles to CuO/water nanofluid resulting in a significantly enhanced thermal conductivity, with the highest enhancement achieved at 1.25% concentration and 50 °C temperature. Loong et al. (2021) investigated the metal oxide water-based nanofluids which showed promising thermal performance in cooling systems, but their excessive viscosity raises concerns in practical applications. Arya et al. (2020) authored a paper where MgO/water-ethylene glycol nanofluids showed great potential as a coolant in double-pipe heat exchangers, enhancing heat transfer coefficient, friction factor, and fluid pressure drop.

Based on the recent literature, MgO-based nanofluids, both as single-component systems and as hybrid mixtures (e.g., MgO-CuO, MgO-TrO, CuO-MgO-TrO), consistently demonstrate significant potential for enhancing thermal performance across various applications. Studies highlight marked improvements in thermal conductivity and overall heat transfer coefficients when these nanofluids replace conventional base fluids like water or water-ethylene glycol mixtures. Specifically, adding MgO nanoparticles to CuO/water nanofluids synergistically boosts thermal conductivity, with enhancements observed to be dependent on concentration and temperature. These enhancements translate into tangible benefits such as improved efficiency in automotive radiators, better performance in heat exchangers, and increased thermal efficiency coupled with economic advantages (reduced payback period, CO2 savings) in solar collectors. While some studies note associated increases in friction factor and pressure drop, others report reductions, suggesting system-specific effects. Nevertheless, the overarching conclusion is that MgO and its hybrid nanofluids offer a promising route towards more efficient thermal systems, although practical implementation must consider factors like viscosity and pumping power requirements.

The novelty highlighted in this present work, centers on the thermal conductivity enhancement observed specifically when combining MgO nanoparticles with CuO/water nanofluids, indicating an interaction that surpasses the individual contributions of each component. Furthermore, the paragraph emphasizes the consistent demonstration of improved thermal performance across a diverse range of applications – from automotive cooling and industrial heat exchangers to solar energy systems – suggesting a broad applicability for MgO-based nanofluids (both single and hybrid) as advanced heat transfer fluids. Finally, a novel aspect of this summary is its balanced perspective, integrating the significant thermal and economic benefits with the practical challenges reported, such as potential viscosity increases and variable effects on pressure drop, thus providing a comprehensive overview of the current state-of-the-art and its implications for real-world implementation.

To comparatively evaluate the thermo-hydraulic performance of magnesium oxide (MgO/TrO) and hybrid magnesium oxide-copper oxide (MgO-CuO/TrO) nanofluids in transformer oil by analyzing key metrics like heat transfer coefficients (UHTC, convective heat transfer coefficient (CHTC)), Nusselt number (Nu), friction factor (FF), and pumping power (PP) across ranges of temperature and Reynolds number. Essentially, the goal is to determine which nanofluid offers better heat transfer capabilities and understand the associated impact on flow resistance and energy consumption (pumping power).

2. Materials

In this study, MgO and CuO nano materials were prepared in a mannar similar to the method described by Sandhya et al. (2025). A surfactant called CTAB that weights one-tenth of the MgO nanoparticle is used. Different volume concentrations such as 0.002%, 0.004%, 0.006%, and 0.008%, are used in this present experiment. A precision digital micro-balance (supplied by Labotech) with a resolution of 1 micro-gram is employed to determine the weight of nanoparticles to be added to the base fluid. Measured quantities of MgO nanoparticles and CTAB are added to base fluid. Here two-step approach was implemented, for preparation of nanofluids. The mixer is kept on a magnetic stirrer (model no. EINS SCI E-MS20-H3-T) for 8 hr at 470 rpm and further sonicated for 6 hr to achieve uniform dispersion of nanoparticles. The superior thermophysical characteristics of MgO and its compatibility with transformer oil are displayed in Table 1 in contrast to other nanoparticles like TiO_2, ZnO, and Al_2O_3. The inherent compatibility, stability, purity, and good dispersion nature of nano MgO particles into transformer oil can yield a robust and reliable nanofluid. Addition of MgO does not deteriorate the transformer oil and no hazardous byproducts are produced by the reaction of MgO with the oil.

Table 1. Thermo-physical properties and specifications of nanoparticles.

Thermo-physical properties	TiO_2 (Pak & Cho; 1998)	ZnO (Asadi & Pourfattah, 2019)	Al_2O_3 (Dardan et al., 2016)	MgO (Asadi & Pourfattah, 2019)
Thermal conductivity k, W/m K	8.4	29	46	54.9
Specific heat C_p, J/kg K	710	514	385	937
Density ρ, kg/m^3	4157	5606	3890	3580
Purity	99+%	99+%	-	-
Size, nm	27	35-45	20	-
Specific surface area (SSA), m^2/g	56.1	>60	>138	-
Colour	white	white	white	-

3. Experimental test rig

An experimental test rig shown in Fig. 1a is used to obtain the performance of MgO nano thermofluids. The test rig consists of a plate-fin heat exchanger which is shown in the Fig. 1b. The constructional details and the dimensions of the heat exchanger are shown in work by Sithebe et al. (2025). The test rig consist of 2 circuits; for the nonofluid and the other for the cooling air that flows across the radiator. Six thermocouples gives 1) inlet/outlet liquid temperature, 2) air inlet/outlet temperature, 3) atmospheric air temperature and 4) plate surface temperature as shown in the Fig. 1a. Two pressure sensors are installed to measure inlet and outlet oil pressure. One rotameter is used for the nanofluid flowrate. A fan blows air through the heat exchanger. An anenomter measured the air velocity through the heatexchanger. A high-temperature durable pump was used for pumping the nanofluid. Sensors were calibrated and used with the data loggers connected to the laptop as shown in the Fig. 1a. Experimental data is collected for different volume concentrations at different flow rates of nano-fluids. Further, a schematic diagram is show in Fig. 1b.

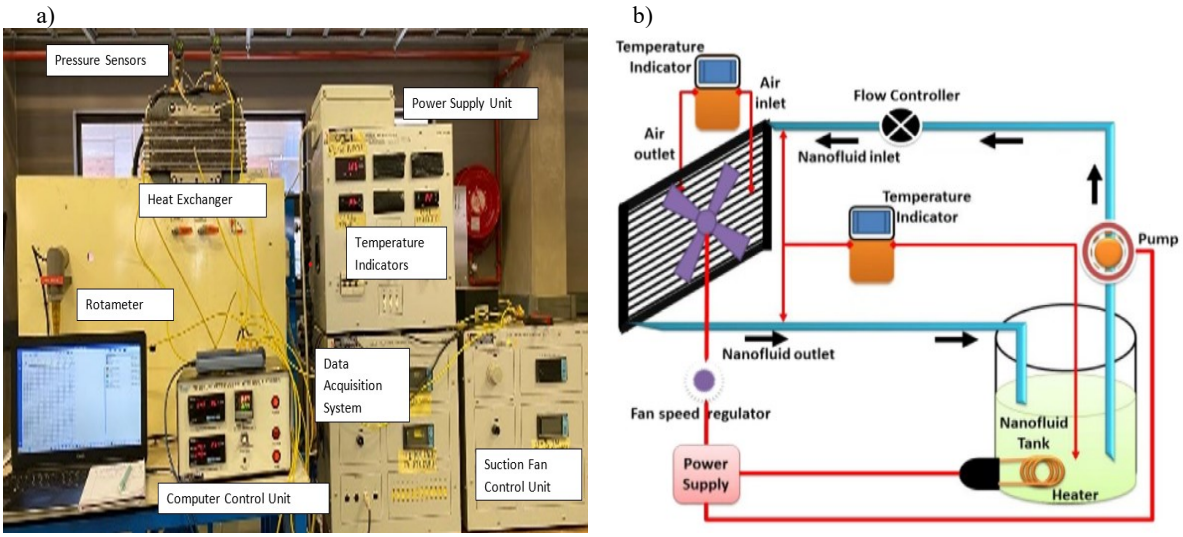

Fig. 1. a) experimental test rig and b) schematic diagram.

4. Preparation of nanofluids

Two-step method is employed in the preparation of MgO nanofluid. Nanoparticles are dispersed into a base fluid, such as transformer oil, using techniques like mechanical stirring, ultrasonication to ensure even distribution. To maintain a stable suspension and prevent the nanoparticles from agglomeration, surfactants, or stabilizing agents such as Cetyltrimethylammonium bromide (CTAB) is added. The incorporation of CTAB modifies interfacial interactions and aids in the prevention of particle aggregation by disrupting the attractive forces at play. Given that surfactants enhance the dispersion of nanoparticles via various mechanisms, it is imperative to consider factors such as the nature of the base fluid, the selection of surfactant, and its concentration during the formulation of stable nanofluids. Frequently employed surfactants encompass oleic acid, CTAB, stearic acid, and sorbitan monooleate Farade et al (2024). This method is known to be cost-effective, and flexible that allows preparation of nanofluids with various volume concentrations and is applied in this study. Nanoparticles were obtained by using Eq. (1). A digital micro-balance (supplied by Labotech) with a resolution of 1 μm was used to get quantities of MgO nanoparticles at different concentration that was added to the base fluid (transformer oil from SABS approved SANS Enviro Oil). The due processes are followed for stirring and sonication to ensure homogeneous mixer of nanofluids. This prepared nano MgO mix was poured in the stainless-steel tank which is insulated with asbestos with a cubic capacity of 20 litres. Thermophysical properties of the nanofluid were acuratelty determined. The properties of the nanofluid are depended on the % volume concentration of nanoparticles, determined from Eq (1) (Einstein, 1906).

$$\emptyset\% = \frac{\left(\frac{wt_{np}}{\rho_{np}}\right)}{\left(\frac{wt_{np}}{\rho_{np}} + \frac{wt_{bf}}{\rho_{bf}}\right)} \tag{1}$$

where wt_{np} is the weight of nanoparticle in grams, ρ_{np} is the density of nanoparticles in g/m^3 and bf denotes base fluid. Eq. (1) is used to determine the % volume concentration in which one type of nanoparticle is added into the base fluid.

In the case of hybrid nano fluids, two different nanoparticles are required to prepare the nanofluid. To determine the volume fraction of hybrid nanoparticles, the following equation Eq. (2) is used (Goodarzi et al., 2018).

$$\emptyset\% = \frac{\left(\frac{wt_{MgO}}{\rho_{MgO}} + \frac{wt_{CuO}}{\rho_{CuO}}\right)}{\left(\frac{wt_{MgO}}{\rho_{MgO}} + \frac{wt_{CuO}}{\rho_{CuO}} + \frac{wt_{TrO}}{\rho_{TrO}}\right)} \tag{2}$$

where wt_{MgO} is the weiht of MgO nanoparticles in grams, wt_{CuO} is the weight of CuO nanoparticles in grams, wt_{TrO} weight in grams of transformer oil in grams and ρ_{MgO} applies to the density of MgO

nanoparticles in g/m^3. This applies to CuO in the equation. Eq. (2) is used to determine the % volume concetration of a fluid in which two different nanoparticles are added.

5. Estimation of density of hybrid nanofluid

5.1 Estimation of heat capacity of hybrid nanofluid

The hydrid nanofluid density is calculated from Eq. (3).

$$\rho_{\mathrm{nf}} = \left(\frac{m}{V}\right)_{\mathrm{nf}} = \left(\frac{m_{\mathrm{bf}} + m_{\mathrm{np}}}{V_{\mathrm{bf}} + V_{\mathrm{np}}}\right) = \left(\frac{\rho_{\mathrm{bf}} V_{\mathrm{bf}} + \rho_{\mathrm{np}} V_{\mathrm{np}}}{V_{\mathrm{bf}} + V_{\mathrm{np}}}\right) \tag{3}$$

Density for mono nanofluid was determined by Pak and Cho (1998) and it is presented in Eq. (4).

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

Density of hybrid nano fluid is determined by extending the mixture rule formula, given by Takabi and Salehi (2014), using Eq. (5).

$$\rho_{\mathrm{nf}} = \emptyset_{\mathrm{np1}} \rho_{\mathrm{np1}} + \emptyset_{\mathrm{np2}} \rho_{\mathrm{np2}} + (1 - \emptyset_{\mathrm{hyb}})\rho_{\mathrm{bf}} \tag{5}$$

where, $\emptyset_{\mathrm{hyb}}$ is volume concentration of hybrid nanoparticles; $\emptyset_{\mathrm{np1}}$ is volume concentration of type 1 nanoparticle; and $\emptyset_{\mathrm{np2}}$ is volume concentration of type 2 nanoparticle.

The heat capacity is determined by using the method presented by Pak and Cho (1998), using mixture rule (Eq. (6)). The mixure is assumed not to contain any suspended particles.

$$C_{\mathrm{p,nf}} = (\emptyset \rho_{\mathrm{np}} C_{\mathrm{p,np}} + (1 - \emptyset)\rho_{\mathrm{bf}} C_{\mathrm{p,np}})/\rho_{\mathrm{np}} \tag{6}$$

The same mixture rule is extended to determine the heat capacity of hybrid nanofluid using Eq. (7) proposed by Takabi and Salehi (2014).

$$C_{\mathrm{p,nf}} = (\emptyset_{\mathrm{np1}} \rho_{\mathrm{np1}} C_{\mathrm{p,np1}} + \emptyset_{\mathrm{np2}} \rho_{\mathrm{np2}} C_{\mathrm{p,np2}} + (1 - \emptyset_{\mathrm{hyb}})\rho_{\mathrm{bf}} C_{\mathrm{p,bf}})/\rho_{\mathrm{hybnp}} \tag{7}$$

The specific heat capacity (C_{pbf}) for pure TrO as a function of temperature was taken from work of Mamedov et al. (1999) and was obtained based on the work of Sandhya et al. (2025).

5.2 Estimation and measurement of viscosity of hybrid nanofluid

The viscocity of the nanofluid has some impact on the behaviour of pressure drop, pumping power, the friction factor and the flow characteristics. Therefore, viscocity plays a role in the rheological properties of these fluids. The following equations present useful relationships concerning viscosity.

Dynamic viscosity is estimated using Eq. (8) (Einstein, 1906) and Eq. (9) (Wang et al., 1999) that are given below.

$$\mu_{\mathrm{nf_{Einstein}}} = (1 + 2.5\emptyset)\mu_{\mathrm{bf}} \tag{8}$$

$$\mu_{\mathrm{nf_{Wang}}} = (1 + 7.3\emptyset + 123\emptyset^2)\mu_{\mathrm{bf}} \tag{9}$$

Taking Brownian motion into consideration, Batchelor (1977) developed a correlation to estimate the viscosity of mono nanofluids. Further, Ho et al. (2010) established that Eq. (10) can be employed to make close prediction of dynamic viscosity of hybrid nanofluids.

$$\mu_{\mathrm{nf_{Bachelor}}} = (1 + 2.5\emptyset + 6.2\emptyset^2)\mu_{\mathrm{bf}} \tag{10}$$

Nguyen et al. (2007) investigated the influence of size of the nanoparticle and the temperature on dynamic viscosity. According to his studies the viscosity of nanofluids increase as a function of concentration of nanoparticles, while it decreases as a function of temperature. Nguyen et al. (2007) developed a correlation to estimate the effective viscosity of nanofluids with different particle sizes using Eqs. (11) to (13).

$$\frac{\mu_{\mathrm{nf}}}{\mu_{\mathrm{bf}}} = (1.475 - 0.319\emptyset + 0.051\emptyset^2 + 0.009\emptyset^3) \text{for } d_{\mathrm{p}} = 29 \text{ nm} \tag{11}$$

$$\frac{\mu_{\mathrm{nf}}}{\mu_{\mathrm{bf}}} = (1 + 0.025\emptyset + 0.015\emptyset^2) \qquad \text{for } d_{\mathrm{p}} = 36 \text{ nm} \tag{12}$$

$$\frac{\mu_{\mathrm{nf}}}{\mu_{\mathrm{bf}}} = (0.904 \exp(0.1483\emptyset)) \qquad \text{for } d_{\mathrm{p}} = 47 \text{ nm} \tag{13}$$

Dynamic viscosity ratio which is influenced by temperature is given below in Eq.(14).

$$\frac{\mu_{\mathrm{nf}}}{\mu_{\mathrm{bf}}} = (2.1275 - 0.0215T + 0.00027T^2) \tag{14}$$

The instrument in Fig 2 was used to detemine of viscocity as shown in Sandhya et al. (2025).

Fig. 2. Viscometer from Anton & Paar SVM-3001.

5.3 Estimation of thermal conductivity of hybrid nano fluid

Takabi and Salehi (2014) estimated the k_{nf} (thermal conductivity of hybrid nanofluids) using modified Maxwell model which is given in Eq. (15) below.

$$\frac{k_{\mathrm{nf}}}{k_{\mathrm{b}}} = \frac{\frac{\left(\emptyset_{\mathrm{np1}}k_{\mathrm{np1}} + \emptyset_{\mathrm{np2}}k_{\mathrm{np2}}\right)}{\emptyset_{\mathrm{hnf}}} + 2k_{\mathrm{bf}} + 2\left(\emptyset_{\mathrm{np1}}k_{\mathrm{np1}} + \emptyset_{\mathrm{np2}}k_{\mathrm{np2}}\right) - 2\emptyset k_{\mathrm{bf}}}{\frac{\left(\emptyset_{\mathrm{np1}}k_{\mathrm{np1}} + \emptyset_{\mathrm{np2}}k_{\mathrm{np2}}\right)}{\emptyset_{\mathrm{hnf}}} + 2k_{\mathrm{bf}} - 2\left(\emptyset_{\mathrm{np1}}k_{\mathrm{np1}} + \emptyset_{\mathrm{np2}}k_{\mathrm{np2}}\right) + 2\emptyset k_{\mathrm{bf}}} \tag{15}$$

It was established that the deviation between prediction and the experimental data is below 2% which is very accurate, the details of which are shown in Sandhya et al. (2025).

6. Data Deduction

6.1. Liquid side calculation

The Reynolds number is evaluated from Eq. (16).

$$Re_{\mathrm{liquid}} = \frac{\rho_{\mathrm{liquid}} V_{\mathrm{liquid}} D_{\mathrm{h}}}{\mu_{\mathrm{liquid}}} \tag{16}$$

where D_{h}, V_{liquid}, ρ_{liquid} and μ_{liquid} are the hydraulic diameter of the tube, the flow velocity, density, and viscosity of the working fluid, respectively. The velocity can be calculated by the following equation.

$$V_{\mathrm{liquid}} = \frac{Q_{\mathrm{Liquid}}}{N_{\mathrm{Tube}} A_{\mathrm{Tube}}} \tag{17}$$

The hot fluid pumped travels through the tubes of the radiator. The hydraulic diameter D_{h} can be calculated by Eq. (18).

$$D_{\mathrm{h}} = \frac{4 \cdot A_{\mathrm{Tube}}}{P_{\mathrm{Tube}}} \tag{18}$$

The liquid side heat transfer coefficient was attained by evaluating Eq. (19).

$$h_{\mathrm{exp}} = \frac{\mathrm{Nu}_{\mathrm{exp}}.k_{\mathrm{nf}}}{D_{\mathrm{h}}} \tag{19}$$

The Nusselt number was found for a rectangular cross-section from a fully developed laminar flow. For laminar flow, Eq. (20) (Vajjha et al., 2015) is used to determine the Nusselt number.

$$\mathrm{Nu} = 0.023 \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{1/3} \tag{20}$$

6.2. Air side calculation

The air velocity can be calculated by the following equation.

$$V_{\mathrm{Air}} = \frac{Q_{\mathrm{Air}}}{A_{\mathrm{radiator}} - (N_{\mathrm{Tube}} H_{\mathrm{Tube}} L_{\mathrm{radiator}})} \tag{21}$$

The Reynolds number was calculated using Eq. (22).

$$Re_{Air} = \frac{\rho_{\mathrm{Air}} V_{\mathrm{Air}} D_{\mathrm{hAir}}}{\mu_{\mathrm{Air}}} \tag{22}$$

where D_{Air}, V_{Air}, ρ_{Air} and μ_{Air} are the hydraulic diameter of the tube, the flow velocity, density, and viscosity of the working fluid respectively. The velocity of the air through each passage must be found to calculate the Reynolds number. Looking at the geometry of fins, it can be assumed that the flow of air is in the laminar region. Eq. (23) is used to determine the Nusselt number.

$$\mathrm{Nu} = 0.664 \cdot Re_{Air}^{1/2} \cdot Pr_{Air}^{1/3} \tag{23}$$

The air-side heat transfer coefficient was determined using Eq. (24).

$$h_{\mathrm{Air}} = \frac{\mathrm{Nu}_{\mathrm{Air}}.k_{\mathrm{Air}}}{D_{\mathrm{hAir}}} \tag{24}$$

Overall heat transfer coefficient is calculated using Eq. (25).

$$\mathrm{U} = \frac{Q}{A\Delta T_{\mathrm{m}}} = \frac{mC_{\mathrm{p}}(T_{\mathrm{in}} - T_{\mathrm{out}})}{A\left(\frac{(T_{\mathrm{w}} - T_{\mathrm{in}}) - (T_{\mathrm{w}} - T_{\mathrm{out}})}{ln\left(\frac{T_{\mathrm{w}} - T_{\mathrm{in}}}{T_{\mathrm{w}} - T_{\mathrm{out}}}\right)}\right)} \tag{25}$$

where A is total internal surface area of tube, ΔT_{m} is logarithmic mean temperature difference.
The pumping power is calculated using Eq. (26).

$$\dot{W} = \Delta P \cdot Q \tag{26}$$

where, Q is the volume flow rate measured experimentally using a rotameter and a digital flow meter. Pressure drop ΔP across the system (heat exchanger) is measured using two sensitive pressure gauges installed in the circuit.

7. Results and discussion

Fig. 3a displays the overall heat transfer coefficient (UHTC) in W/m²K plotted against temperature in degrees Celsius for two different transformer oil (TrO) based mixtures: one containing magnesium oxide (MgO) nanoparticles MgO/TrO and another containing a hybrid mix of magnesium oxide and copper oxide nanoparticles MgO-CuO/TrO. Both mixtures show an increasing trend in UHTC as the temperature rises from 30 to 70 °C. Crucially, the hybrid MgO-CuO/TrO mixture consistently exhibits

a higher UHTC compared to the MgO/TrO mixture across the entire temperature range. The addition of CuO significantly enhances heat transfer performance; specifically, the MgO-CuO/TrO mixture shows an improvement over the MgO/TrO mixture of 21% at 30 °C, 19% at 40 °C, 36% at 50 °C, 40% at 60 °C, and a substantial 55% at 70 °C. This indicates that the synergistic effect of adding CuO nanoparticles becomes increasingly beneficial at higher temperatures.

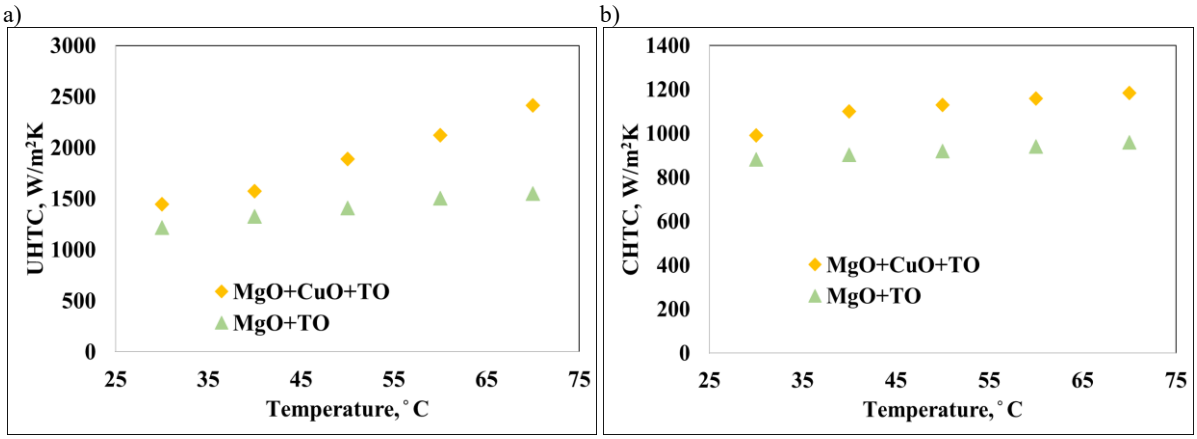

Fig. 3. a) overall heat transfer coefficient as a function of temperature and b) convective heat transfer coefficient as a function of temperature.

Fig. 3b illustrates the convective heat transfer coefficient in W/m²K as a function of temperature in degrees Celsius for two different transformer oil (TrO) based nanofluids: MgO/TrO and a hybrid MgO-CuO/TrO. Both nanofluids exhibit an increase in CHTC as the temperature rises from 30 to 70 °C. Consistently across the measured temperature range, the hybrid MgO-CuO/TrO nanofluid demonstrates a superior CHTC compared to the MgO/TrO nanofluid. The percentage improvement reveals that the addition of CuO enhances the CHTC by 14% at 30 °C, 22% at 40 °C, 23% at 50 °C, 23% at 60 °C, and 24% at 70 °C. This indicates a significant and relatively stable enhancement in convective heat transfer performance due to the inclusion of CuO nanoparticles alongside MgO in the transformer oil base.

Fig. 4a plots the dimensionless Nusselt Number, which represents the ratio of convective to conductive heat transfer, against the dimensionless Reynolds Number, which characterizes the flow regime, for two transformer oil (TrO) based nanofluids: MgO/TrO and a hybrid MgO-CuO/TrO. As expected, for both nanofluids, the Nusselt number generally increases with increasing Reynolds number, indicating enhanced convective heat transfer at higher flow velocities. Crucially, the hybrid MgO-CuO/TrO nanofluid exhibits a consistently higher Nusselt number compared to the MgO/TrO nanofluid across the tested range of Reynolds numbers 350 to 1150. The enhancement, the hybrid nanofluid shows an improvement over the MgO/TrO fluid of roughly 14% at Re ≈ 350, 24% at Re ≈ 500, 25% at Re ≈ 680, 26% at Re ≈ 900, and 27% at Re ≈ 1150. This demonstrates a significant enhancement in convective heat transfer performance due to the inclusion of CuO nanoparticles, with the relative improvement slightly increasing as the flow.

Fig. 4b presents the variation of the dimensionless Reynolds number (Re) with temperature in degrees Celsius for two transformer oil (TrO) based nanofluids: MgO/TrO and the hybrid MgO-CuO/TrO. For both fluids, the Reynolds number increases significantly as the temperature rises from approximately 30 °C to 70 °C, primarily due to the decrease in the fluid's viscosity at higher temperatures. Comparing the two nanofluids, the hybrid MgO-CuO/TrO consistently exhibits a higher Reynolds number than the MgO/TrO nanofluid at all measured temperatures.

Quantitatively, the Reynolds number for the hybrid fluid is higher by 26% at 30 °C, 28% at 40 °C, 26% at 50 °C, 27% at 60 °C, and 26% at 70 °C compared to the single MgO nanofluid. This indicates that, under the conditions tested, the addition of CuO nanoparticles results in a fluid system characterized by a consistently higher. Reynolds number for a given temperature, likely reflecting differences in fluid properties like viscosity between the two nanofluids.

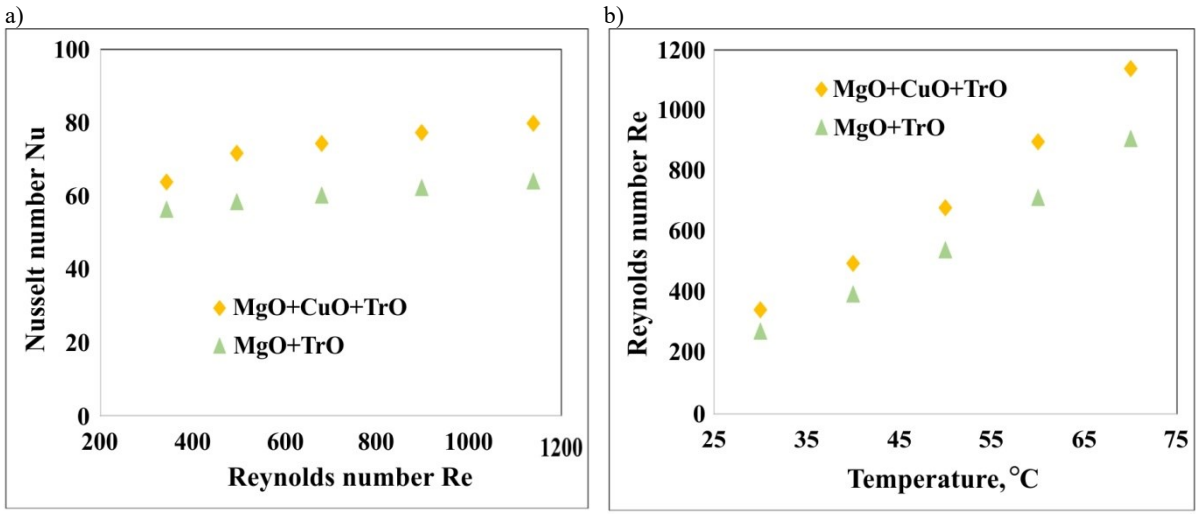

Fig. 4. a) Nusselts number as a function of Re and b) Reynolds number vs. temperature.

Fig. 5a illustrates the relationship between the dimensionless friction factor and the dimensionless Reynolds Number for the two-transformer oil based nanofluids: MgO/TrO and MgO-CuO/TrO. For both fluids, the friction factor decreases as the Reynolds number increases, which is the expected behavior for fluid flow in a pipe, indicating reduced relative flow resistance at higher flow rates or lower viscosities. When comparing the two nanofluids, the hybrid MgO-CuO/TrO consistently shows a slightly higher friction factor than the MgO/TrO fluid across the tested Reynolds number range 350 to 1150. Calculating the percentage increase, the friction factor for the hybrid nanofluid is roughly 11% higher at Re ≈ 350, 8% higher at Re ≈ 500, 9% higher at Re ≈ 680, 10% higher at Re ≈ 900, and 11% higher at Re ≈ 1150 compared to the MgO/TrO fluid. This suggests that the addition of CuO nanoparticles, while potentially enhancing heat transfer, also introduces a modest penalty in terms of increased frictional losses, leading to a higher pressure drop for the same flow conditions.

Fig. 5b depicts the pumping power required for two transformer oils based nanofluids, MgO/TrO and the hybrid MgO-CuO/TrO, plotted against temperature in degrees Celsius. For both fluids, the required pumping power clearly decreases as the temperature increases from approximately 30 °C to 70 °C. This trend is expected, as fluid viscosity typically decreases significantly with rising temperature, leading to lower frictional losses and thus less power needed to maintain a given flow rate. Comparing the two nanofluids, the hybrid MgO-CuO/TrO consistently requires a higher pumping power than the MgO/TrO nanofluid across the entire temperature range. Quantifying this difference, the hybrid fluid requires 2.4% more pumping power at 30 °C, 3.7% more at 40 °C, 3.8% more at 50 °C, 3.6% more at 60 °C, and 2.3% more at 70 °C compared to the MgO/TrO fluid. This increased pumping power requirement signifies a higher energy cost to circulate the hybrid nanofluid, likely stemming from its higher viscosity and/or density compared to the MgO/TrO fluid, which is consistent with the higher friction factor previously observed.

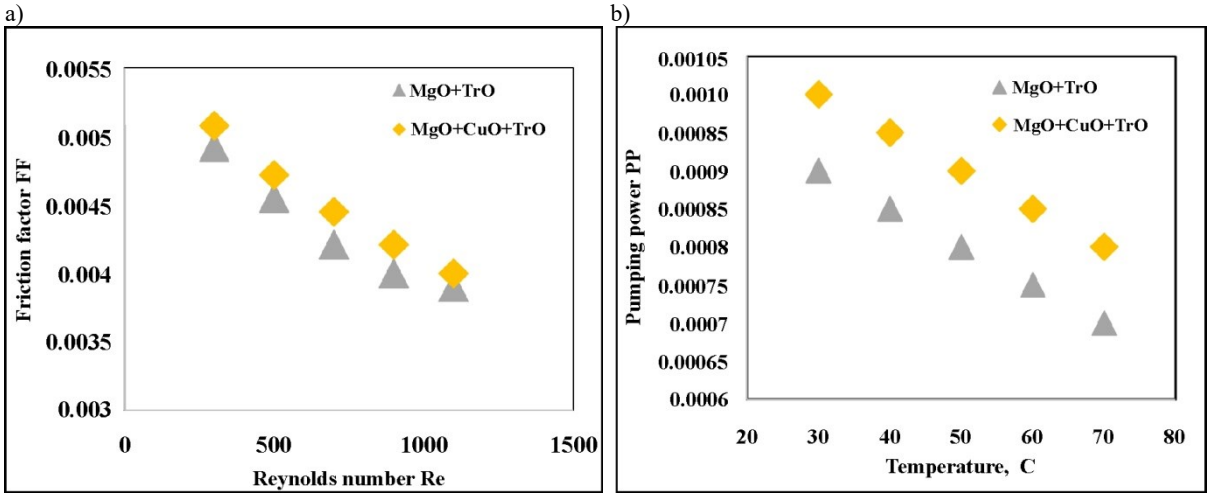

Fig. 5. a) friction factor vs. Reynolds number and b) pumping power vs. temperature.

8. Conclusions

In conclusion, the analysis of the provided graphs, a comprehensive conclusion can be drawn regarding the performance comparison between the MgO/TrO and the hybrid MgO-CuO/TrO nanofluids in transformer oil: the addition of CuO nanoparticles to the MgO/TrO base fluid demonstrably enhances its heat transfer capabilities.

The hybrid MgO-CuO/TrO nanofluid consistently exhibits superior performance in terms of overall heat transfer coefficient, convective heat transfer coefficient and Nusselt number across the tested ranges of temperature and Reynolds number. The improvement in UHTC was particularly significant, reaching up to 55% enhancement at the highest temperature 70 °C, while CHTC and Nu showed substantial and relatively consistent enhancements 14-27% compared to the MgO/TrO fluid.

Very interestingly, the hybrid nanofluid also displayed a higher Reynolds number at equivalent temperatures compared to the MgO/TrO fluid 26-28% higher, suggesting altered fluid dynamic properties, likely related to viscosity and density changes.

However, this enhanced thermal performance comes with a notable trade-off. The hybrid MgO-CuO/TrO nanofluid consistently showed a higher friction factor 8-11% increase compared to the MgO/TrO fluid at similar Reynolds numbers. Consequently, this resulted in a significantly higher pumping power requirement 2.3-3.8% increase across the temperature range to circulate the hybrid nanofluid.

In summary, while the hybrid MgO-CuO/TrO nanofluid offers substantial benefits in heat transfer efficiency, its application necessitates consideration of the increased pumping energy penalty due to higher frictional losses compared to the MgO/TrO nanofluid. The optimal choice between these fluids would depend on the specific application's priorities, balancing the need for enhanced thermal performance against the tolerance for increased operational energy costs.

Declarations

Authors' contributions: Devireddy Sandhya: development of the manuscript and compilation of results, conducting laboratory experiments and data collection; Veeredhi Vasudeva Rao: critical analysis and interpretation of results and conclusions; Thembelani Sithebe: data analysis and the refinement of the manuscript and responses to reviewer's queries.

Funding: This research received no external funding.

Declaration of competing interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement: The data used to support the findings of this study are already included in the article.

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Względna Wydajność Termohydrauliczna Mono i Hybrydowego Nanopłynu Transformatorowego w Płytowym Wymienniku Ciepła – Badania Eksperymentalne

Streszczenie

W artykule przedstawiono wyniki analizy porównawczej właściwości termohydraulicznych nanocząstek tlenku magnezu rozproszonych w oleju transformatorowym (MgO/TrO) oraz hybrydowego nanopłynu zawierającego zarówno nanocząstki tlenku magnezu, jak i tlenku miedzi (MgO-CuO/TrO). Kluczowe parametry wydajności, takie jak całkowity współczynnik przenikania ciepła (UHTC), konwekcyjny współczynnik przenikania ciepła, liczba Nusselta (Nu), współczynnik tarcia oraz moc pompowania, oceniono w odpowiednich zakresach temperatur (30–70°C) i liczby Reynoldsa. Wyniki wykazały, że hybrydowy nanopłyn (MgO-CuO/TrO) wykazuje znacząco polepszone właściwości w zakresie przenikania ciepła. W porównaniu z płynem MgO/TrO, hybrydowa formuła charakteryzowała się lepszym współczynnikiem całkowitego współczynnik przenikania ciepła aż do 55%, konwekcyjnym współczynnikiem przenikania ciepła w zakresie 14-24% i liczbą Nusselta w zakresie 4-27%. Hybrydowy nanopłyn charakteryzował się wyższym współczynnikiem tarcia w zakresie 8-11%, i w konsekwencji wymagał o 2,2-3,8% większej mocy pompowania w podobnych warunkach pracy. Wprowadzenie nanocząsteczek CuO poprawia parametry cieplne oleju transformatorowego na bazie MgO z jednoczesnym zwiększeniem wymaganej mocy pompowania.

Słowa kluczowe: MgO, MgO-CuO/TiO, płytowy wymiennik ciepła, moc pompowania, wydajność cieplna, olej transformatorowy