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Original Article

Pumping Power and Friction Factor in a Plate Fin Heat Exchanger with MgO-CuO based Hybrid Nano-Transformer Oil

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Abstract - *An exclusive investigation is conducted to determine the pumping power and friction factor of MgO-CuO-based hybrid nano-transformer oil pumped through a plate-fin heat exchanger. A candidate nano transformer oil is synthesized using MgO and CuO nanoparticles with varying volume concentrations from 0.002% to 0.012%. The developed nano-transformer oil is characterized by its viscosity and density as a function of temperature in the range of 30 to 70 ºC. The experiments are conducted with flow rate of nano-fluids from 1lit/min to 4lit/min for different mean bulk temperatures in the range of 30 to 70 ºC, such that the Reynolds Number varies in the range of 85 to 1180. When the temperature is increased from 30 to 70 ℃, the friction factor decreased by 22.17% for the corresponding Reynolds number increase from 85 to 1180. It is observed that at a given temperature, the pumping power increases with respect to mass flow rate. Whereas the pumping power decreased by at least 22.28% as the temperature increased from 30 to 70 ℃. When compared to the base fluid, it was found that there is only 2.9% excess power consumption in the case of MgO-CuO-based hybrid nano-transformer oil, which does not appear to significantly contribute to the economics of pump operations. The results of this investigation are presented in graphical form. An uncertainty analysis was carried out for Reynolds number, pumping power, and friction factor, and it was found to be less than 5% for all conditions investigated.*

Keywords - *Friction factor, MgO-CuO hybrid nano transformer oil, Plate fin heat exchangers, Pumping power.*

1. Introduction

Due to the technological advancements in nano-technology, nano - fluids are increasingly becoming popular in engineering applications. These nano-fluids exhibit superior properties in terms of their ability to transmit heat and momentum in a variety of thermal systems. While in service, these fluids must be transported or pumped from one location to another through pipes or channels. A pump is an essential device in the system for the transportation of these fluids. Generally, in any manufacturing industry, such as petrochemicals or water treatment plants, as per certain sources of energy audit, the power consumed by all the pumps put together contributes to nearly 30% of the total energy consumption. As a result, the performance of the pump for handling different liquids plays a significant role in the economics of the entire production plant. Any small upward revision in power consumption can lead to a reduction in profits and result in a negative impact. Further, pumping power and friction factor are the two key elements that need the most attention. Moreover, pumping power is essential in fluid transportation across multiple industries.

2. Literature Review

It is observed that only a few research findings focus on the determination of pumping power and friction factor. However, there are a few studies that are exclusively devoted to the determination of pumping power and friction factor for nano-fluids. Also, there are some studies in which the pumping power and friction factor are determined on the sidelines while investigating the thermal performance of systems that run with nano-fluids as a heat transfer medium. An exclusive study on friction factor and pumping power has not been conducted widely in the published literature. Therefore, the present investigation is oriented towards the determination of the pumping power and friction factor for hybrid nano transformer oil. In view of the objectives of the present study, pertinent and comprehensive literature published during the last 5 to 10 years has been reviewed critically. The following are most of the research studies published and available in the open literature for reference. Awais et al. (2021), in their investigation, concluded that nanoparticles dispersed in the base fluid contributed to considerable improvement in the thermal performance with

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little more excess power consumption by the pump. They emphasized that though there is additional power consumption on account of nanoparticles, the benefits due to enhancement in the thermal performance will offset the penalty of excess power consumption. Vajjha et al. (2010) developed a correlation for the friction factor as a part of their study on convective heat transfer coefficient in turbulent flow regions for nano-fluids with Al_2O_3 nanoparticles. Alshayji et al. (2020) presented their results on the penalty imposed on the pumping power due to the addition of diamond nanoparticles to water. They found that the penalty in pumping power is less once the flow reaches the turbulent conditions due to an increase in the mass flow rate. Minea (2020) conducted a detailed numerical investigation in laminar as well as turbulent flow regions using Al_2O_3–SiO_2 hybrid nano-fluids, taking water as base fluid. In her study, it was assumed that a single-phase model was implemented in the numerical code. Comparisons were drawn for pumping power and pressure drop with theorical correlations. This study is focused on a specific application of solar energy. Tiecher & Parise et al. (2013) conducted a study in which they compared Al_2O_3 water-based nano-fluid with pure water.

One of the objectives in their investigation was to compare the enhancement factors and the pressure drop. From their experimental investigation, they concluded that the addition of Al_2O_3 nanoparticles to the water (base fluid) substantially increased the pumping power requirements. Sahin et al. (2013) investigated Al_2O_3- water-based nano-fluids for thermal performance and pressure drop. From their studies, they concluded that, due to the increased volume concentration of nanoparticles, viscosity and friction factor increase considerably. They also recommended that volume concentration above 1% is not beneficial. Pandey & Nema (2012) examined the friction factor of Al_2O_3 nano fluids experimentally in a corrugated plate heat exchanger. As the particle concentration of the nano-fluid increased, the necessary pumping power required for a particular heat load also increased accordingly. Additionally, the nano-fluid had a greater pressure drop than water.

However, a lower flow rate is needed for a given heat load. It was discovered that the nano-fluids with the lowest concentration exhibited a higher heat transfer rate when compared to the base fluid, and the nano-fluids were able to remove more heat than water for a given pumping power. Routbort et al. (2011) examined the pumping power of SiC nano-fluids in a flowing system. For the calculation of the pumping power required, they assumed nano fluids to be single-phase liquids with equivalent properties. The ratios of pumping power were determined and compared. Additionally, the penalty on the pumping power and the enhancements in heat transfer for SiC nano-fluids were discovered to indicate the possibility of creating workable heat transfer fluids. Ehsan & Noor et al. (2016) investigate the enhancement of nano-fluid's heat transfer performance and pumping power using a rough circular tube. When compared to water, the nano-fluid with the optimal volume proportion of nanoparticles requires less pumping power. Better thermal performance is achieved by calculating the reduction in mass flow rate of the nano-fluid. Mu'az Muhammad et al. (2019) investigate how nano-fluids affect the diverging-convergent mini channel heat sinks' pressure drop and heat transfer characteristics. The findings showed that while the rise in Reynolds number and nanoparticle loading had a considerable influence on the improvement of the heat transfer coefficient, the change in pressure drops with a variation in nano-fluid loadings was negligible. Chammam et al. (2023) calculated the heat transfer coefficient and friction factor when a water-based hybrid nano-fluid consisting of aluminum nitride and alumina is sprayed into a tube with a twisted tape insert.

In their study, CFD and ANSYS-FLUENT software were used to assess the performance of AIN– Al_2O_3/water hybrid nano-fluid. When compared to a plain tube without a turbulator, it was shown that adding twisted tape to the tube greatly increases both the thermal performance and the friction factor. Noor et al. (2014) studied heat transfer and power pumping in a corrugated tube using nano-fluid. The minimal pumping power for a 3% vol concentration of nano-fluid, which is 40% less than that of water, is achieved for a fixed heat transfer coefficient of 10,000 w/m2k.

Marzouk et al., 2023, In a numerical study conducted on plate heat exchanges in which nano-fluids are taken as heat transfer medium with a view to determining heat transmission, friction factor and energy efficiency. In their study, it was concluded that when Re increases, there is a reduction in the friction factor. From their study, nano-fluids with 0.4 mass percent of nano-fluids produced the lowest friction factor, with values ranging from 0.17 to 0.33. Mukesh Kumar and Chandrasekar (2021) conducted an analysis on the heat transfer and friction factor of nano-fluids prepared with MWCNT flowing in a tube heat exchanger. They found that MWCNT nano-fluids have a 40% higher friction factor than water, with a Dean number between 1400 and 2400. Ultimately, it is determined that the MWCNT water-based nano-fluids are a superior substitute for any other heat transfer medium with a negligible friction factor. Alklaibi et al. (2024) used artificial neural network models to predict the friction factor of Fe_3O_4–SiO_2/Water hybrid nano-fluids in a plate heat exchanger.

Their study found that using 1.0 vol% of Fe_3O_4-SiO_2/water hybrid nano-fluids increased the friction factor by 37.59% when compared to the base fluid. Using the experimental data, the Bayesian regularization- artificial neural network analysis reliably predicts the friction factor. Using the ANN technique, the friction factor is predicted from the data collected through experiments and using a multi-linear regression fit. Syam Sundar et al. (2020) investigated Co_3O_4-deposited rGO hybrid nano-fluids and longitudinal strip inserts to assess the thermal performance, friction factor, heat transmission, and thermal characteristics. The results show that the Nusselt number increased by 25.65% when hybrid nanoparticles were diluted to a 0.2% concentration in water. This is further increased by 110.56% when a straight strip with an aspect ratio of 1.0 is used. Fluid friction is slightly reduced when straight strip inserts and hybrid nano-fluids are used. They concluded that the penalty due to the increased friction factor is 11% for a 0.2% concentration. The penalty due to the friction factor further increased to 69.8% with 0.2% particle concentration for a straight strip insert with an aspect ratio of 1.0.

Ramadhan et al. (2020) studied heat transmission and friction factor of a plain tube with hybrid nano-fluids, which were investigated experimentally and numerically. Their article presents the impact of nano-fluids on friction factors and heat transfer coefficients. According to the experimental and numerical studies, heat transport in a simple tube increases with Reynolds number. The maximum Nusselt number and friction factor were found in hybrid nano-fluids with a volume concentration of 3.0%, followed by 2.0% and 1.0%. Comparing the experimental and numerical data, the mean deviation of the Nusselt number for the volume concentrations of 1.0, 2.0, and 3.0% in their study was 8.8, 8.9, and 7.9%. For volume concentrations of 1.0, 2.0, and 3.0%, the average variance of the friction factor is 4.1, 3.8, and 3.5%, respectively. Azhar Hussain Shah et al. (2024) employed a tube-in-tube heat exchanger to determine heat transfer, pumping power and friction factor for a ZnO and Fe2O3 nano-hydraulic oil with a fixed inlet temperature of 60℃. The focus of their investigation is on pumping power, taking water as a baseline with iron oxide and zinc oxide nano-fluids. The investigation was conducted for both laminar and turbulent flow conditions to look for improvements in the friction factor, heat transfer coefficient, pumping power and Reynolds number.

Their findings demonstrated that at volume concentrations of 0.100, 0.125, 0.150, and 0.175%, the heat transfer coefficient, friction factor, and pumping power of Fe_2O_3 and ZnO nano-fluids were marginally higher than those of baseline water. Anto Joseph Deeyoko et al. (2019) analysed the performance of the flat plate solar water heaters using the Second Law of Thermodynamics to determine the economics and pumping power through a thermal performance enhancer in absorber tubes. The analysis of the performance factors reveals that, in comparison to square thermal performance enhancers, rectangular thermal performance enhancers provide higher energy and exergy efficiency with an improvement in the convective heat transfer coefficient and the least amount of pumping power increase. Sundar et al. (2024) investigated nano-fluids based on water and Ionic liquid mixtures in a heat exchanger with helical coil tube inserts in a shell. Heat transfer coefficient, effectiveness, frictional entropy generation, friction factor, pressure drop, and Nusselt number are, in the order, 45.59%, 28.27%, 15.19%, 12.56%, 17.20%, and 16.21% respectively. At the same time, there is a 46.23% reduction in thermal entropy generation and a 20.08% decrease in total exergy destruction. At 1.0 weight percent and a Re 3598, the thermal performance factor and second law (exergy) efficiency are enhanced by 1.384 and 34.04%, respectively, with reference to the base fluid. A correlation is developed to estimate the friction factor and Nusselt number using the data points generated in their investigation. Lyu et al. (2020) studied the performance of MWCNT-Water nano fluids as a heat transfer medium in microchannel heat sinks. They conducted a combined theoretical and experimental investigation to determine the heat transfer and pumping power based on various merit Figures. The pumping power is very critical in applications such as the flow of microchannel heat sinks in the cooling of electronic devices. They established that the penalty in pumping power due to the addition of MWCNT particles is insignificant. Dardan et al. (2016) investigated the change in the rheological behaviour of engine oil due to the addition of hybrid nanoparticles.

The viscosity of the hybrid nano-fluid increased proportionately as the concentration of nano-additives increased. The hybrid nano-fluid relative viscosity results indicated that the viscosity might increase up to 46%. According to the results of a sensitivity analysis, viscosity is more sensitive to solid volume fraction than it is to temperature changes. Additionally, a precise correlation was put out to forecast the hybrid nano-fluids' viscosity for use in thermal engineering. Lastly, there have been reports on how nano-additives affect the oil flow pumping power. Attalla & Maghrabie et al., 2020, Examine the efficiency of a rough-surfaced plate heat exchanger and pumping power requirements. The efficiency and pumping power of a Plate Heat Exchanger (PHE) with a rough surface were experimentally investigated in their work. The studies were designed for Reynolds numbers (Re) ranging from 500 to 5000 and for a range of roughness. Estimates were made for the average heat transfer rate, which determines the efficacy of the plate heat exchanger, NTU, the pressure drop, which determines the pumping power, PP, and the specific heat rate, SHR. Amir Hossein Shiravi et al. (2020) conducted an investigation of the pressure drop and pumping power of carbon nano-fluids by experimentation.

This research examines the impact of varying carbon nano-fluid concentrations (0.1 to 0.4 weight percent) in water on fluid flow pressure drop across the Reynolds range of 14,000 to 28,000. Pumping power variation was examined, and the related results showed that the friction factor of the nano-fluid increased from 0.4 to 70% at concentrations of 0.4, resulting in a 68% increase in pumping power. Misagh Irandoost Shahrestani et al. (2021) performed an exclusive investigation on the convective heat transfer and pumping power requirements for hybrid nano-fluids prepared from

MWCNT + Fe_3O_4 in water. In their experimental setup, they employed a heat exchanger that consists of a helical coil with orthogonal rib turbulators. They used 0.1 and 0.3 per cent volume fractions of the hybrid nano-fluid with laminar water flow conditions. Mital Manu 2013 conducted an analytical investigation and determined the enhancements in convective heat transfer using nano-fluids flowing in a heat sink with growing laminar flow. Their study accounted for the pumping power penalty and determined the heat transfer enhancement ratio. Further, they concluded that the smaller the nano particle diameter, the better the heat transfer enhancement ratio. Z. Said et al. (2014) performed an analyses of the pumping power and energy efficiency of a traditional flat plate solar collector using a nano-fluid based on SWCNTs. When compared to water as an absorbing fluid, the SWCNTs nano-fluid was found to theoretically increase the heat transfer coefficient by 15.33% and decrease entropy formation by 4.34%. Compared to using water as a working fluid, the pumping power penalty of a nanofluid-operated solar collector was found to be 1.20 percent higher. From the literature review, it is understood that the pumping power and friction factor have been studied as a small part of the main investigation with a secondary level of attention. The novelty of this paper comes from the fact that, in the present investigation, the primary focus is on the measurement of pumping power and friction factor determined from the measurement of flow rate and the corresponding pressure drop. Further, the main objective of the current study is to exclusively focus on experimentally determining the effect of the addition of MgO and CuO nanoparticles to the transformer oil on the pumping power and friction factor. The range of investigation is to conduct experiments from 30°C to 70°C for particle volume concentrations at 0.002%, 0.004%, 0.008%, and 0.012%, taking pure transformer oil as reference.

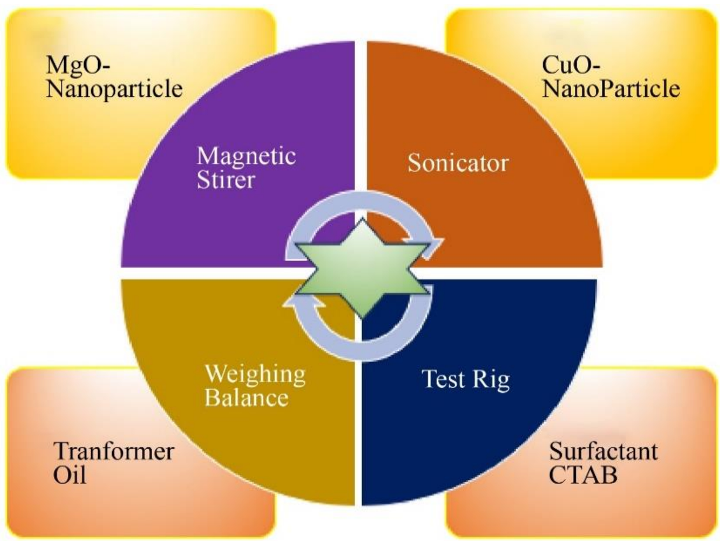

Fig. 1 Materials and instruments used

3. Materials and Methods

Commercially available nanoparticles from Sigma Aldrich are utilized in this study to prepare nano-transfomer oil. To make nano-fluids with different volume concentrations, a measured quantity of MgO and CuO is added to the base fluid. A surfactant, CTAB, is employed to prevent agglomerations of nanoparticles. The weight of the surfactant to be added to the fluid is estimated with reference to the weight of the MgO and CuO nanoparticles. In the present investigation, one-tenth of the weight of the nanoparticle is taken to determine the surfactant's weight. As per the specifications provided by the manufacturer, the average size of MgO and CuO nanoparticles is less than 50nm, and the purity is >99.99%. In this experiment, various volume concentrations are used, including 0.002%, 0.004%, 0.008%, and 0.012%. Figure 1 indicates the materials and instruments employed in the present investigation in the preparation of nano transformer oil. The two-step method, as shown in Figure 2, is followed in the preparation of nano-fluids. The method involves adding the nanoparticle and the surfactant CTAB to the transformer oil, mixing it for eight hours with a magnetic stirrer, and then sonicating it for two hours to create a homogenous mixture. The choice of nanomaterials for this investigation is based on their relative advantages over other possible materials.

4. Preparation of a Hybrid Nano-Transformer Oil

Two distinct nanomaterials, MgO and CuO, which are both ≤ 50 nm in size, were purchased from Sigma Aldrich in order to prepare a hybrid nano-fluid (nano transformer oil). The necessary amount of nanoparticles was computed using Equation 1, and the precise weight of MgO and CuO nanoparticles was ascertained using a precision digital micro-balance (provided by Labotech) with a resolution of 1 microgram. By adding the right amounts of nanomaterials to the base fluid (transformer oil from SABS-approved SANS Envir Oil), various concentrations of nano-fluids are prepared. Agglomeration and lump formation of the nanoparticle are prevented by adding surfactant CTAB, which was also purchased from Sigma Aldrich and mixed in the base fluid. The nano-fluid is formed when the mixer is kept on a mechanical stirrer for more than 12 hours. The system is filled with 20 litres of hybrid nano transformer oil prepared for this purpose, as shown in the Figure 2. The volume concentration used to calculate the nanoparticles can be estimated using Equation (1).

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

Where wtnp is the weight of the nanoparticle and wtbf is the weight of the base fluid, ρnp and ρbf are the density of the nanoparticle and the density of the base fluid.

5. Experimental Test Rig

Advanced experimental testing equipment is developed, evaluated, and used to determine the performance of hybrid *nano-thermo-fluids. The experimental test rig consists of two* subsystems: a hydraulic circuit for the oil to flow through and instrumentation to measure various parameters of interest. The details of these two subsystems are described in the following subsections in greater detail, and a schematic diagram is shown in Figure 2.

5.1. Constructional Details

A test rig, which consists of a plate-fin heat exchanger, is designed and fabricated and is commercially available in the automotive industry, as shown in Figure 4. The test rig has a provision for two fluids to pass through; one for the hot liquid and another for moving the cold fluid, which is cold air that flows through the finned structure.

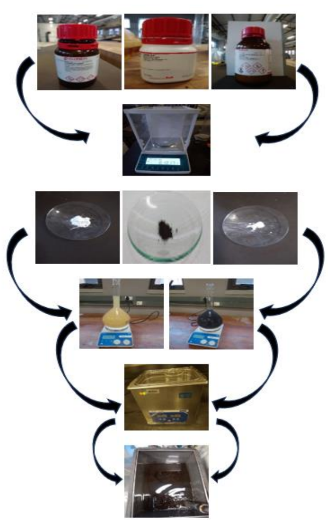

Fig. 2 Two-step method used in the preparation of nano-fluids

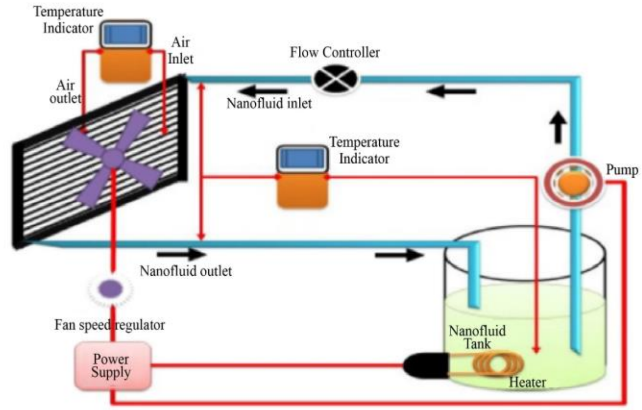

Fig. 3 Schematic diagram of test rig

A stainless-steel tank is fitted with a 1.5 kW heater and an 80 W high-temperature durable pump (Leo Innovation Type LRP15-60/130), which is installed to drive the hot fluid through the circuit. All the temperature sensors are pre-calibrated and connected to the data acquisition system. Using the software installed on the computer (laptop), the data acquisition is facilitated. The arrangement is as shown in Figure 3.

Nine parallel-mounted channels carry the heated fluid through the radiator, and 153 aluminium fins that are fastened to the tubes allow air to pass through. Ambient air is used as the cold fluid in this study. A suction fan, which is attached to a duct, pulls ambient air through the fins of the heat exchanger. An anemometer placed between the heat exchanger and the suction fan is employed to measure the air velocity. Air velocity measurements and air density are used to assess the mass flow rate of the cold fluid (air) passing through the heat exchanger. Figure 5 depicts the heat exchanger, and Table 1 provides corresponding specifications.

Here, heated coolant from the tank is pumped through a bundle of nine tubes incorporated in the radiator. Thus, they will conduct heat to the aluminium fins, which will be cooled by air flowing via the fan. Thus, the air, while passing through the finned structure, cools the hot liquid that is passing through the tubes. The suction fan is mounted behind the radiator at the end of the duct. The fan cools the hot fluid by forcing air into it. As a result, the hot fluid entering the radiator gets cooled, comes out, and is collected in the tank.

The convective heat transfer coefficient of the flowing fluids significantly impacts the heat transfer performance of compact heat exchangers. Due to the improved thermal conductivity, hybrid nano-fluids can help increase the rate of heat transfer by raising the convective heat transfer coefficient for a constant value of heat transfer area and temperature difference. While this test rig creates all the conditions close to the in-service working conditions for a heat exchanger, our objective and focus are on the assessment of hybrid nano-transformer oils for pumping power and friction factor.

5.2. Instrumentation

The instrumentation consists of three subsystems, namely flow measurements, pressure measurements, and temperature measurements.

5.2.1. Temperature Measurements

A total of seven pre-calibrated K-type thermocouples of 36 gauge are employed to measure the temperature at various points in the system.

Inlet and outlet temperatures of the fluid were measured by using two thermocouples; inlet and outlet temperatures of the air were measured using another two thermocouples: one thermocouple is used to measure the oil temperature in the tank, and one thermocouple is used to measure the air ambient temperature; one thermocouple is used to measure the temperature of the plate surface. The mean bulk temperature is taken as the average of the inlet and outlet temperatures. From calibration data, the resolution of the temperature measurement is ±0.1 ℃. A built-in cold junction compensation is incorporated in the display device.

5.2.2. Flow Measurements

The hot fluid (transformer oil) flow rate is measured using a rotameter, and a digital meter (Macnaught M Series Flow Meter, Model M2rsp-1H) is integrated.

A rotameter with a 0 to 4lit/min range is connected in series in the oil circuit. Additionally, the digital flow metre indicates information on the flow rate in a digital form with a resolution of ± 0.01lit/min.

The flow control is achieved through a regulating value connected at the inlet port of the rotameter.

Fig. 4 Experimental test rig

Fig. 5 Radiator

5.2.3. Pressure Measurements

In the calculation of pumping power, the pressure drop across the device is an important parameter. Two measuring devices (supplied by IO-Link from Germany) are incorporated into the oil circuit to measure the pressure drop. One pressure measuring device is installed at the inlet port, and the other one is incorporated at the outlet port. The resolution of the pressure probes given by the supplier is 0.001bar. The above instrumentation is connected to the laptop through a Digi logger, data acquisition software.

6. Experimental Procedure and Data Acquisition

Hybrid nano transformer oil is pumped through the system by switching the oil pump. The oil flow rate is adjusted with a flow control value incorporated in the liquid circuit. At a given flow rate, the temperature and pressure at the inlet and outlet are recorded. Air inlet temperature and air outlet temperature are also recorded simultaneously for a given flow rate. The procedure is repeated for different flow rates at 1, 2, 3, and 4lit/min. The same procedure is repeated for 0.004, 0.006, 0.008, and 0.012% volume concentrations of hybrid nano-fluids.

Table 1. Constructional details of radiator

Length of Radiator, RL	**0.325 m**
Width of the Radiator, RW	0.115 m
Width of Tube, TW	0.025 m
Height of Tube, TH	0.003 m
Width of Fin, FW	0.028 m
Height of Fin, FH	0.009 m
Thickness of the Fin, FT	0.0001 m
Distance between the Fins, FD	0.005 m
Number of Tubes, n	9
Number of Fins in each row	153

The friction factor was expressed as shown in Equation (2).

$$f = \frac{2\Delta P D_h}{\rho U^2 L} \tag{2}$$

Where ΔP, Dh, U, ρ are the pressure difference, hydraulic diameter of the radiator, U velocity of liquid, ρ density of the fluid.

The Reynolds Number is a non-dimensional number which is expressed as shown in Equation (3).

$$Re = \frac{2\dot{m}}{\mu(T_W + T_H)} \tag{3}$$

Where ṁ, TH, Tw, μ, mass flow rate, height of the tube, width of the radiator tube, and viscosity of fluid, respectively.

$$T_{bulk} = \frac{T_1 + T_2}{2} \tag{4}$$

Where T1 is the Inlet and T2 is the outlet temperature of the working fluids.

The Dh (hydraulic diameter) is determined using Equation (5).

$$D_h = \frac{4A_{Tube}}{P_{Tube}} \tag{5}$$

Where A_{Tube} and P_{Tube} are the Area and Perimeter of the tubes.

The pumping power is determined using Equation (6) (Dardan Ebrahim et al, 2016).

$$\dot{W} = \Delta P * Q \tag{6}$$

Where volume flow rate Q is measured experimentally using a rotameter and a digital flow meter. Pressure drop ΔP is measured using two sensitive pressure gauges installed in the circuit.

7. Results and Discussion

7.1. Friction Factor

The variation of the friction factor as a function of Reynolds number for pure transformer oil and hybrid nano transformer oil is shown in Figure 7. From Figure 7, it is observed that as the Reynolds number increases, the friction factor decreases. Reynolds number is a nondimensional number that captures the effect of change in density and change in viscosity due to temperature. As a result, the friction factor vs Reynolds number is an indicator of a change in viscosity and density of the fluid. In the current study, it is observed that the density and viscosity are also affected by hybridising the transformer oil into a nano transformer oil. The friction factor is affected by the friction between the fluid and the tube wall. The Reynolds number determines the flow regime, which has an impact on the friction factor.

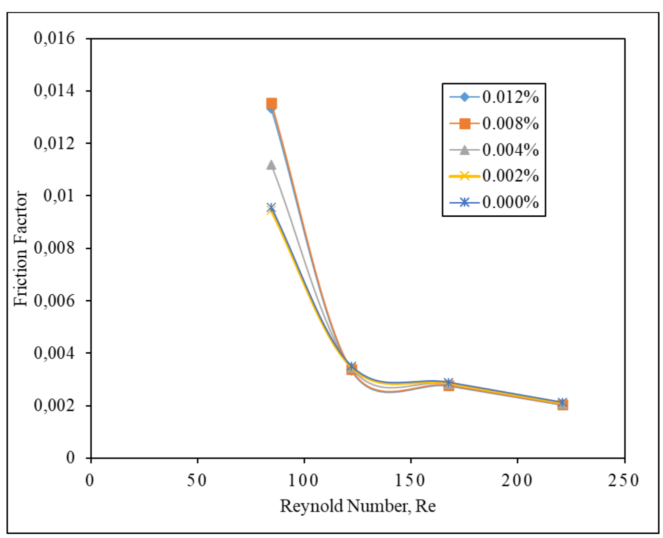

Fig. 6 Variation of friction factor with Reynolds number

As the Reynolds number rises, the friction factor in this regime normally lowers because of the improved momentum exchange between fluid particles. In the present investigation, at temperatures from 30 to 70 ℃, the friction factor dropped by 22.17% as the Reynolds number increased from 85 to 1180.

7.2. Pumping Power

As the temperature increases, pumping power often decreases due to the reduction in fluid viscosity. Generally, hot fluids flow more easily, which reduces the resistance encountered by the pump. This reduced viscosity allows the pump to move the fluid with less energy, resulting in lower pumping power as depicted in Figure 8. It is observed from Figure 8 that at a given temperature, the pumping power increased with respect to mass flow rate, while the pumping power decreased by at least 22.28% as the temperature increased from 30 to 70 ℃. With reference to the base fluid, it was observed that there is 2.9% excess power consumption that does not significantly contribute to the economics of pump operations. This observation establishes the fact that hybrid nano transformer oil is suitable for commercialization.

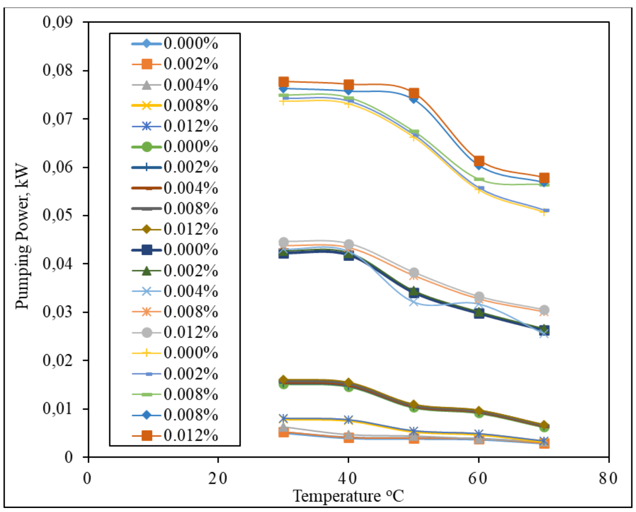

Fig. 7 Variation of pumping power with temperature and flow rate as a parameter

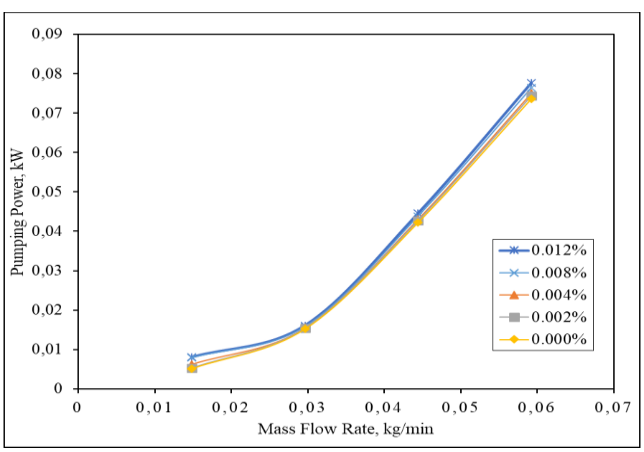

Fig. 8 Variation of pumping power with mass flow rate

In Figures 9 to 14, pumping power is presented as a function of Reynolds Number, taking temperature and volume concentration as parameters. It is found that pumping power increases with Reynolds number and reduces with increasing temperature. Similarly, it is observed that the increase in volume concentration of nanoparticles also contributes to an increase in pumping power. Figure 14 presents the combined effect of Reynolds number, temperatures, and volume concentration of nanoparticles on the pumping power. The influence of the addition of nanoparticles is not predominant, as seen in Figure 14. Finally, in Figure 14, it is clearly seen that the pumping power increases for a set of volume concentrations at different temperatures. With reference to the base fluid, it was found that the pumping power increases with volume concentration upto a maximum of 2.9 %, which does not substantially raise the pumping power penalty. The trends observed in the present investigation are similar to those published in the open literature. In the present investigation, finer details with regard to the pumping power and friction factor as a function of temperature and mass flow rate are captured. Therefore, hybrid nano transformer oil can be recommended for commercial applications in the thermal management of electrical equipment.

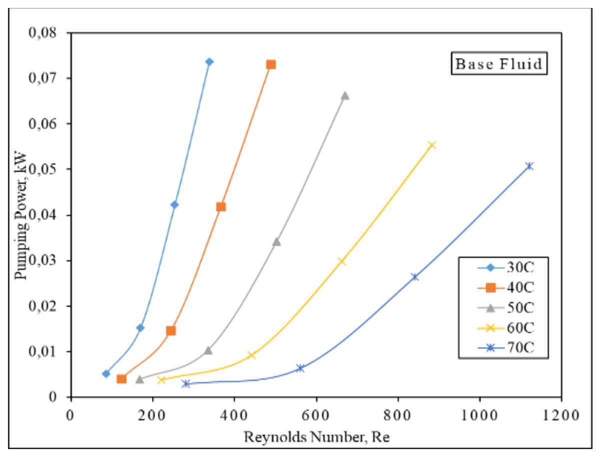

Fig. 9 Variation of pumping power with Reynolds number, taking temperature as a parameter for the base fluid

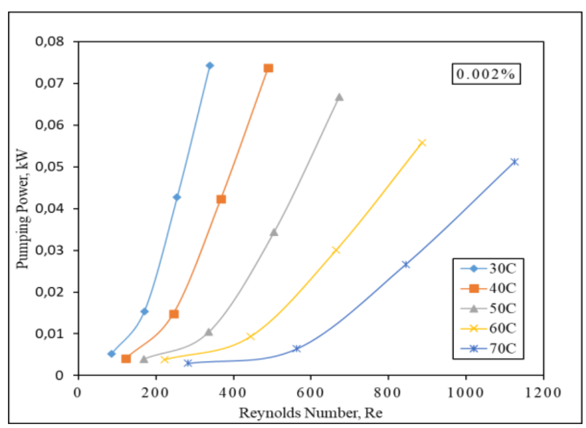

Fig. 10 Variation of pumping power with Reynolds number, taking temperature as a parameter for 0.002% volume concentration

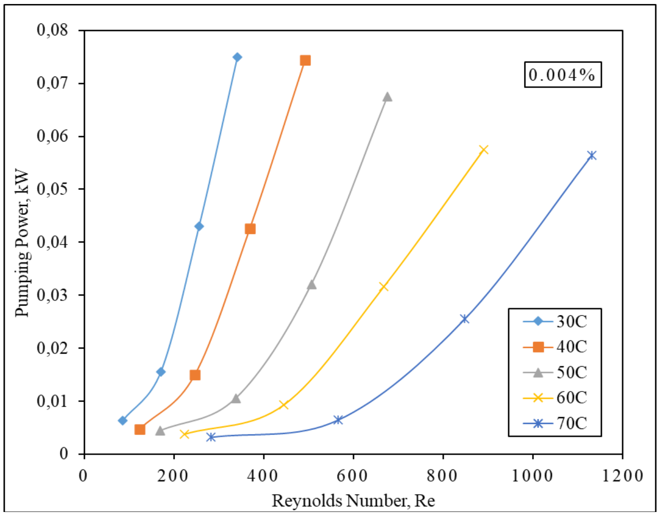

Fig. 11 Variation of pumping power with Reynolds number, taking temperature as a parameter for 0.004% volume concentration

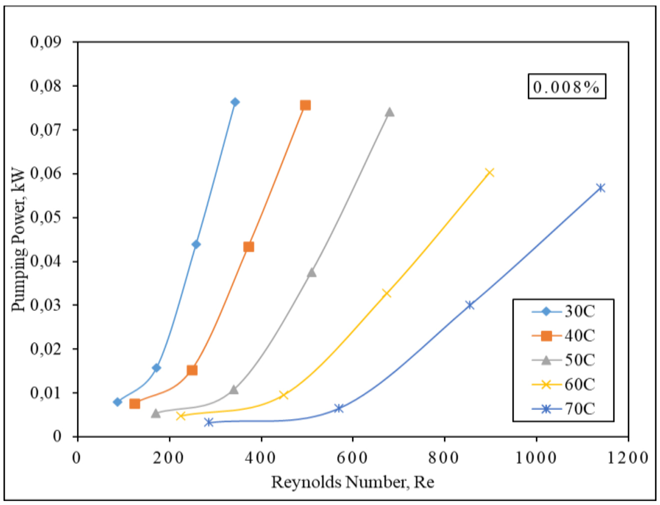

Fig. 12 Variation of pumping power with Reynolds number, taking temperature as a parameter for 0.008% volume concentration

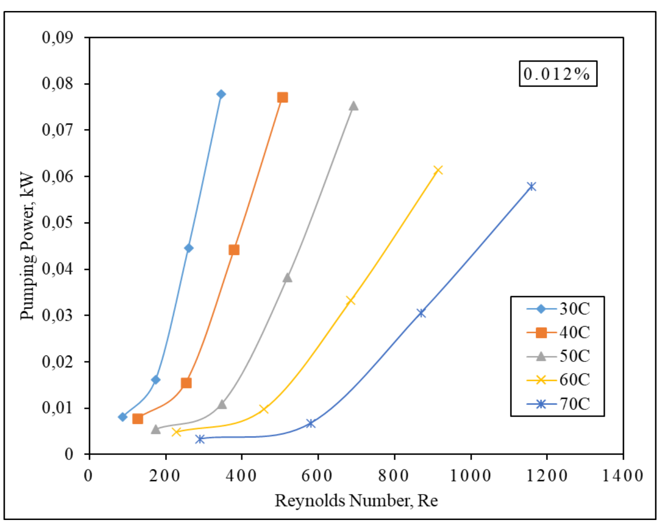

Fig. 13 Variation of pumping power with reynolds number, taking temperature as a parameter for 0.012% volume concentration

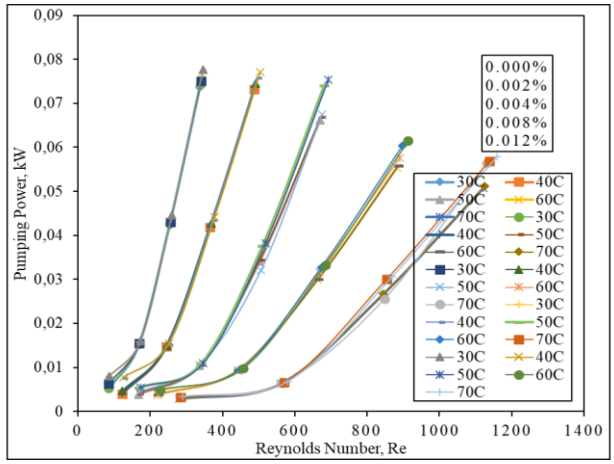

Fig. 14 Variation of pumping power with Reynolds number, taking temperature as a parameter for all volume concentrations

8. Uncertainty Analysis

An uncertainty analysis is conducted for Re, f and $\dot{W}$ as per Meysam Nazari et al. 2023. The results of the analysis are presented in the following Table 2.

Table 2. Uncertainty analysis [Meysam Nazari et al.]

Reynolds number, Re $Re = \frac{\rho v D}{\mu}$	$\frac{U_{Re}}{Re} = \sqrt{\left(\frac{U_\rho}{\rho}\right)^2 + \left(\frac{U_v}{v}\right)^2 + \left(\frac{U_\mu}{\mu}\right)^2}$	4.96%
Friction factor, f $f = \frac{\Delta P}{\left(\frac{L}{d}\right)\left(\frac{\rho v^2}{2}\right)}$	$\frac{U_f}{f} = \sqrt{\left(\frac{U_{\Delta P}}{P}\right)^2 + \left(\frac{U_\rho}{\rho}\right)^2 + \left(\frac{U_v}{v}\right)^2}$	4.39%
Pumping Power, PP $\dot{W} = \Delta P * Q$	$\frac{U_{\dot{W}}}{\dot{W}} = \sqrt{\left(\frac{U_{\Delta P}}{P}\right)^2 + \left(\frac{U_Q}{Q}\right)^2}$	4.36%

9. Conclusion

The novelty of this paper comes from the fact that, in this present investigation, the primary focus is on the measurement of pumping power and friction factor determined from the measurement of flow rate and the corresponding pressure drop. Further, in the current study, the effect of the addition of MgO and CuO nanoparticles to the transformer oil on the pumping power and friction factor is experimentally determined. The experiments were conducted from 30 to 70℃ for particle volume concentrations at 0.002%, 0.004%, 0.008%, and 0.012%, using pure transformer oil as a reference.

For temperatures of 30 to 70℃, the friction factor decreased by 22.17% when the Reynolds number increased from 85 to 1180. In conclusion, at a given temperature, the pumping power increased with respect to mass flow rate. Also, the pumping power decreased by at least 22.28% with an increase in temperature from 30 to 70 ℃. With reference to the base fluid, it is found that the effect of volume concentration on the pumping power is only up to 2.9%. This establishes the fact that there is no substantial penalty for pumping power due to the addition of nanoparticles. Thus, it is concluded that the nano transformer oil developed in this investigation can be used as a potential candidate for commercial coolant applications in the thermal management of electrical equipment.

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