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Original Article

Experimental Studies to Determine the Overall Heat Transfer Coefficient in Plate Fin Heat Exchanger with MgO-CuO Based Hybrid Nano-Transformer Oil

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Abstract - *In this experimental investigation, thermal performance and overall heat transfer coefficient of MgO-CuO based hybrid nano-transformer oil are determined using a special test rig developed for this purpose. MgO-CuO based hybrid nano transformer oil is prepared and characterized for its thermo-physical properties. Volume concentrations considered are in the range of 0.002% to 0.012% for the candidate hybrid nano transformer oil. The Reynolds number varies from 85 to 1140. In this investigation, 240 data points are collected and analysed. The results of all data points are presented in graphical form. The overall heat transfer coefficient is presented as a function of mass flow rate and mean bulk temperature of the nano-fluid. The non-dimensional heat transfer coefficient, Nu, is presented as a function of Reynolds number, taking volume concentration as a parameter. It is concluded that nano-particle dispersion improved the overall heat transfer coefficient to an extent of 110 to 113% with reference to the base fluid. The estimated uncertainty in the measurements is found to be less than 5%. Therefore, MgO-CuO hybrid nano transformer oil is found to be a potential candidate for use in the transformer industry.*

Keywords - *Heat transfer coefficient, MgO-CuO, Hybrid nano transformer oil, Plate fin heat exchangers, Thermal performance, Transformer oil.*

1. Introduction

Transformer oils are a class of thermal fluids that are frequently employed in heat transfer applications to dissipate heat and maintain the working temperature of the electrical transformers within the specified limits. Large electrical equipment, such as electrical transformers, is filled with transformer oils that include mineral and synthetic oils. The two primary functions of transformer oil are to provide insulation to prevent electrical short circuiting of the copper windings and to effectively dissipate a large quantity of heat generated by the transformer core. Likewise, transformer oils have specific applications in other engineering industries, including electric locomotives, automotive, aerospace, and marine industries, where high temperature is the primary barrier. Because transformer oil serves as both an electrical insulator and a cooling agent, it is essential to improve heat transfer characteristics from the point of view of equipment thermal control. This allows transformers to operate at maximum capacity for longer periods of time and at a much reduced construction cost. Because of the transformer oil's high cooling effectiveness, researchers studying the transformer industry are particularly interested in the potential applications of new knowledge, such as nanotechnology. The advent of nanotechnology and the availability of nanoparticles (nano powders) of numerous materials led to the development of nano-thermo-fluids. Recently, several studies have examined the efficacy of nano transformer oil as a coolant thermal fluid. Addition of nano particles to the transformer oil poses several other challenges, such as oil oxidation, deterioration of insulating property and settling of nano particles on surfaces. A more precise theoretical and practical analysis is required. Therefore, the present investigation assumes great importance and relevance to the applications of nano-thermo-fluids for cooling and improved thermal performance of heat-generating equipment in the industry.

The term "nano-fluid"- a dispersion of nanoparticles in ordinary fluids like water, ethylene glycol, and transformer oil, etc.—was first used by Choi [1]. This class of fluids, due to their attractive properties, has drawn the attention of scientists, researchers, and industrialists [2–19]. Additionally, researchers have studied the contributions made by various nano-fluids in a variety of applications, which include the use of nano-fluids in automotive [20], microchannel heat sinks [21], and electronics cooling [22], to improve the thermal performance through nano-fluids. A few articles also examined the results of previous investigations into the heat transfer efficiency and thermophysical properties of different types of nano-fluids. When 100 nm copper nanoparticles at a 7.5% concentration were tested by Xuan and Li [23], the thermal conductivity of nano-TrO was found to increase by 45%. Saeedinia et al. [24] investigated the rheological properties of copper oxide-based nano-oils and their thermophysical properties. According to their findings, transformer oil becomes more thermally conductive when nanoparticles are added. Nano-Transformer oil exhibits Newtonian fluid flow behaviour for volume concentrations below 2%.

Additionally, at high Reynolds numbers, their analysis found that at 2% vol concentration, the heat transfer coefficient increased by 12.7%. The effects of the addition of CNTs to TrO in forced convective heat transfer mode at volume concentrations less than 0.01% were examined by Beheshti et al. [25]. He also examined changes in density, breakdown voltage, and viscosity during his investigation. Rheological properties are some of the characteristics that are unique and important in the context of applications dealing with friction and lubrication, with a view to employing nano-fluids in place of conventional lubricants. Asadi and Asadi [26] conducted a study on MWCNT-ZnO based engine oil for their rheological properties for different particle concentrations at different temperatures. To determine the dynamic viscosity of the nano-fluid, they proposed a novel correlation. Afrand et al. [27] have examined the rheological behaviour of MWCNT-SiO2/SAE40 hybrid nano-fluid. An experimental investigation on the thermal and rheological characteristics of oil-based nano-fluids with different carbon nanostructures was carried out by Ettefaghi et al. [28]. Asadi et al. [29] examined the rheological behaviour of MWCNT/MgO (20–80)-SAE50 hybrid nano-fluid at various temperatures and solid concentrations in another experimental study. To predict the thermal conductivity of the nano-fluid, they used a correlation as a function of temperature and solid concentration in their investigation, which is given below.

$$\mathrm{k_{nf}} = (0.1534 + 0.00026T + 1.1193\emptyset)$$

Numerous investigations have focused on the determination of the thermal conductivity of a variety of nano-fluids. However, there were very limited studies on oil-based nano-fluids for their thermal conductivity [30-39]. Ettefaghi et al. [28] have conducted experimental studies on the MWCNT-nano engine oil for its thermal characteristics at 20 °C with a moderate concentration of nanomaterial ranging from 0.1 to o.5 Wt%. In their study, maximum improvement in thermal conductivity was observed at 0.5wt% of nano materials. Aberoumand and Jafarimoghaddam [40] conducted a limited study on Cu-based motor oils and their thermal conductivity. In their study, the thermal conductivity of nano-fluids progressively increased with an increase in temperature. Similar trends were observed for all three concentrations studied in their investigation. Aberoumand et al. [41] also studied the thermal conductivity of silver-based nano engine oil and proposed a new correlation for thermal conductivity based on their experimental findings. Das [38] published a detailed review of the thermal conductivity mechanism that is suitable for both regular and hybrid nano-fluids. It is evident from the discussion thus far that thermal oils used in industrial applications focus largely on the enhancement of their thermophysical properties. Nevertheless, the rheological behaviour of oil-based nano-fluids has been the subject of very few investigations. A study was undertaken by Asadi et al. [42] to determine the possibility of the use of nano fluids prepared from Mg (OH)2-MWCNT and transformer oils. The temperature range considered in their experiments is from 25 to 60 °C with solid concentrations in the 0.25 to 2% range. They observed that the highest thermal conductivity enhancement achieved is 50%. Asadi et al. [43] further investigated the suitability of Al2O3-MWCNT/transformer oil and concluded that it is very advantageous for internal laminar flow. The authors believe that adequate research was not done to investigate the possibility of employing nano coolants and lubricants with a low concentration of nano particles in the laminar flow region.

Based on the literature reviewed, several research gaps emerge, particularly concerning oil-based nano-fluids for applications like transformer cooling. The text explicitly states that comprehensive studies on the rheological behaviour of oil-based nano-fluids are notably scarce, despite their importance for flow and lubrication characteristics. Similarly, while various studies have measured thermal conductivity, the review indicates there is a very limited number of studies focusing systematically on the thermal conductivity of oil-based nano-fluids, suggesting a need for broader investigations across different materials, concentrations, and temperatures, specifically for thermal oils. Furthermore, explicitly identifying a gap in understanding the performance and applicability of nano coolants, research exploring the long-term stability and performance of these nano-fluids under operational conditions, and a deeper dive into the fundamental mechanisms driving the observed property enhancements for specific hybrid combinations, also represent areas needing further investigation.

The novelty of this experimental investigation primarily lies in its specific focus on the thermal performance of an MgO-CuO based hybrid nano-transformer oil. While research on nano-fluids exists, this study uniquely characterizes and evaluates this binary nanoparticle combination within transformer oil. Furthermore, the research employs a special test rig developed for this purpose, suggesting a potentially novel experimental setup designed for these measurements. The novelty is also reinforced by the systematic investigation across a defined range of very low volume concentrations (0.002% to 0.012%) and low Reynolds numbers (85-1140), providing specific data for this hybrid system under these laminar/transitional flow conditions. Finally, the demonstration of a substantial (110-113%) improvement in the overall heat transfer coefficient specifically for this MgO-CuO hybrid constitutes a significant and potentially novel finding within the field of transformer oil enhancement.

The primary objectives of this experimental investigation were to prepare MgO-CuO based hybrid nano-transformer oil across a specific range of low volume concentrations (0.002% to 0.012%) and to characterize its fundamental thermo-physical properties. Subsequently, the core aim was to experimentally determine the thermal performance and Overall Heat Transfer Coefficient (OHTC) of this nano-fluid using a purpose-built test rig. This involved investigating how the OHTC varies as a function of mass flow rate and the nano-fluid's mean bulk temperature, as well as how the non-dimensional Nusselt number (Nu) is influenced by Reynolds number (within the 85-1140 range) and volume concentration. Ultimately, a key objective was to evaluate the degree of heat transfer enhancement achieved by the MgO-CuO nanoparticle dispersion compared to the base transformer oil.

2. Materials and Methodology

In this investigation, commercially available nanomaterials sourced from Sigma Aldrich are used to prepare nano-fluids (nano-transformer oil). The average size of MgO and CuO < 50nm nanoparticles of purity >99.99% and CTAB, one-tenth of the nanoparticles is used to prepare the nano-fluid. Different volume concentrations, such as 0.002%, 0.004%, 0.008%, and 0.012% are used in the present experiment. Here, a two-step approach was implemented in which the nanoparticle and the surfactant CTAB are added to the base fluid (transformer oil), and mixing is carried out under a magnetic stirrer for 8 hours, followed by sonication for 2 hours to achieve a homogeneous mixture. The selection of the above nanomaterials is based on their relative merits when compared to other alternative materials. The following Tables 1 and 2 provide important properties of various nanomaterials that are available and useful in comparing their relative advantages in the context of nano-thermo-fluids used as heat transfer media in the operation of thermal systems.

2.1. Estimation of Thermophysical Properties of Hybrid Nano-Fluids

To determine the thermophysical properties of the prepared nano-fluid, both analytical and experimental methods were used, and it was assumed that the nanoparticles were dispersed uniformly in the base fluid so that a homogeneous mixture would be formed. There are several correlations proposed by researchers during the last couple of decades to predict thermophysical properties of nano-fluids. To estimate these properties, several parameters such as particle shape, size, type of base fluid, and operating temperature were used. The majority of the correlations available in the published literature are developed from experimental data and are suitable for mono-nano-fluids. However, the correlations to estimate thermophysical properties of hybrid nano-fluids are very limited. Extensive experimentation is required to predict the role of thermophysical properties and their influence on thermal and fluid flow characteristics. Published literature on hybrid nano-fluids was focused mostly on aspects such as preparation and characterisation. Thermo-physical properties required for the present investigation are estimated using correlations and compared with the measured values. The following section presents the correlations employed for each thermo-physical property.

Table 1. Thermo-physical properties and specifications of nanoparticles

Thermo-Physical Properties	TiO_2 [44]	ZnO [56]	Al_2O_3 [55]	MW CNTs [55]	MgO [56]	TrO [53]
Thermal Conductivity k (W/m K)	8.4	29	46	-	54.9	0.126
Specific Heat, Cp, (J/kg K)	710	514	385	-	937	1860
Density, ρ (kg/m3)	4157	5606	3890	2100	3580	880
Viscosity, μ (Pa.s)	-	-	-	-	-	13.7
Purity	99+%	99+%	-	>97%	99+%	-
Size (nm)	27	35-45	20	OD:5-15. ID: 3-5. L: 50μm	40	-
Specific Surface Area (SSA) m2/g	56.1	>60	>138	233	>60	-
Colour	White	White	White	Black	White	-

2.1.1. Estimation of Volume Concentration of Nanoparticles

It is necessary to determine the thermophysical properties of the working fluid precisely to estimate the performance of any thermal system. If the working fluid is a nano-thermo-fluid, then the properties of these fluids are a strong function of the volume concentration of nanoparticles. The volume concentration of the mono particle can be estimated by using Equation (1) [20].

Table 2. Thermo-physical properties and specification of nanoparticles (A. Kamyar et al.,) [54]

Thermo-Physical Properties	Alumina (Al_2O_3)	Aluminium (Al) Aluminium Nitride (AIN)	Aluminium Nitride (AIN)	Carbon Nanotube (CNT)	Copper (Cu)	Copper Oxide (CuO)	Diamond	Gold (Au)	Graphite	Silicon (Si)	Silicon Carbide (SiC)	Silver (Ag)	Sodium (Na)	Titanium Carbide (TiC)	Titanium Oxide (TiO_2)	Zirconia
Thermal Conductivity, k (W/m K)	40	237	285	3000	401	33	3300	317	120	148	150	429	72.3	330	8.4	30
Specific Heat, Cp, (J/kg K)	773	904	740	-	385	551	509	129	701	714	1340	235	1230	711	692	418
Density, ρ (kg/m3)	3960	2700	3260	1350	8940	6000	3530	19300	2160	2320	3370	10490	968	4930	4230	5680

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

In the case of hybrid nano fluids, two different nano particles are required to prepare the nano-fluid. To determine the volume fraction of hybrid nano-particles, the following equation is used, Equation (2) [11].

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

2.1.2. Estimation of the Density of Hybrid Nano Fluid

Hybrid nano-fluid density is estimated based on the principle of the mixture rule by Equation (3).

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

Density for mono nano-fluid was determined using Pak et al. [44], and it is presented in Equation (4).

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

Density of hybrid nano fluid is determined by extending the mixture rule formula, given by Takabi and Salehi et al [45] using Equation (5).

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

Where, Φ_{hyb} is the volume concentration of hybrid nanoparticles; Φ_{np1} is the volume concentration of type 1 nanoparticles; and Φ_{np2} is the volume concentration of type 2 nanoparticles.

2.1.3. Estimation of Heat Capacity of Hybrid Nano-Fluid

Similarly, for mono-nano-fluids, the Heat capacity is determined by using the method of Pak and Cho et al. [44] using the mixture rule Equation (6). It is assumed that the suspended particles are in complete thermal equilibrium with the fluid.

$$\frac{C_{p,nf}=(\emptyset\rho_{np}C_{p,np}+(1-\emptyset)\rho_{bf}C_{p,np})}{\rho_{np}} \quad (6)$$

The same mixture rule is extended to determine the heat capacity of hybrid nano-fluid using Equation (7) proposed by Takabi and Salehi et al [45].

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

The Specific Heat Capacity (Cp_{bf}) for Pure TrO as a function of temperature is taken from F. F. Mamedov et al, 1999 [51] and is given in the following Table 3.

2.1.4. Estimation and Measurement of the Viscosity of Hybrid Nano-Fluid

The viscosity of the working fluid is important in the context of pressure drop, friction factor, and pumping power. Viscosity is also responsible for determining the fluid flow characteristics.

Table 3. Specific heat capacity (J/kg.K) for pure TrO (F. F. Mamedov et al, 1999) [51]

Temp (°C)	30	35	40	45	50	55	60	65	70	75	80
Specific Heat Capacity, J/kg.K	1624.834	1594.005	1656.515	1671.881	1686.896	1702.912	1719.025	1173.943	1749.959	1771.916	1789.855

Therefore, the knowledge of the viscosity of the nano-fluids will determine the usefulness of these fluids and, in turn, the performance of thermal systems and effective heat management. There are several correlations available in the literature to predict dynamic viscosity. However, there are a few correlations that are precise in the prediction of the dynamic viscosity of the hybrid nano-fluids. These equations are presented below in the section for subsequent use in this investigation. Dynamic viscosity is estimated using Einstein's equation [46] and Wang [47], which are given below in Equations (8) and (9).

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

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

Taking Brownian motion into consideration, Bachelor [48] developed a correlation to estimate the viscosity of mono-nano-fluids. Further, Ho et al [49] established that Equation (10) can be employed to make a close prediction of the dynamic viscosity of hybrid nano-fluids.

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

Nguyen et al. [50] investigated the influence of the size of the nanoparticles and the temperature on dynamic viscosity. According to his studies, the viscosity of nano-fluids increases as a function of concentration of nanoparticles, while it decreases as a function of temperature. Nguyen et al. [50] developed a correlation to estimate the effective viscosity of nano-fluids with different particle sizes using Equations (11) to (13).

$$\frac{\mu_{nf}}{\mu_{bf}} = (1.475 - 0.319\emptyset + 0.051\emptyset^2 + 0.009\emptyset^3)\, for\ d_p = 29nm \quad (11)$$

$$\frac{\mu_{nf}}{\mu_{bf}} = (1 + 0.025\emptyset + 0.015\emptyset^2)\ for\ d_p = 36nm \quad (12)$$

$$\frac{\mu_{nf}}{\mu_{bf}} = (0.904\, exp(0.1483\emptyset))\, for\ d_p = 47nm \quad (13)$$

The dynamic viscosity ratio, which is influenced by temperature, is given below in Equation (14).

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

Fig. 1 Viscometer from Anton & Paar SVM-3001

In this investigation, A high precision Viscometer SVM 3001, shown in Figure 1, supplied by Anton Paar, is employed to experimentally determine the viscosity of nano-fluid and verify and compare the accuracy of correlations used in this investigation.

In Table 4, theoretical values and experimentally measured values of viscosity at different temperatures are presented for comparison.

2.1.5. Estimation of Thermal Conductivity of Hybrid Nano Fluid

Takabi B, Salehi S [45] applied the principle of mixture rule to estimate the k_{nf} (thermal conductivity of hybrid nano-fluids) using the modified Maxwell model, which is given in Equation (15) below.

$$\frac{k_{nf}}{k_b} = \frac{\frac{(\emptyset_{np1}k_{np1}+\emptyset_{np2}k_{np2})}{\emptyset_{hnf}} + 2k_{bf} + 2(\emptyset_{np1}k_{np1}+\emptyset_{np2}k_{np2}) - 2\emptyset k_{bf}}{\frac{(\emptyset_{np1}k_{np1}+\emptyset_{np2}k_{np2})}{\emptyset_{hnf}} + 2k_{bf} - 2(\emptyset_{np1}k_{np1}+\emptyset_{np2}k_{np2}) + 2\emptyset k_{bf}} \quad (15)$$

It was established that the deviation between the prediction and the experimental data is below 2% which is very accurate. The Thermal conductivity (k_{bf}) for Pure TrO as a function of temperature is taken from F. F. Mamedov et al, 1999 [51] and is given in the following Table 5.

Table 4. Experimental values of viscosity (mPa.s) from viscometer anton paar SVM-3001

Temperature	Pure Transformer Oil		0.002%		0.004%		0.008%	
°C	Experi-mental	Theoretical	Experi-mental	Theoretical	Experi-mental	Theoretical	Experi-mental	Theoretical
30	11.59	11.64	11.88	11.70	11.98	11.82	12.09	11.94
40	8.033	8.73	8.188	8.11	8.263	8.19	8.337	8.19
50	5.854	5.88	5.940	5.91	5.989	5.97	6.037	5.97
60	4.442	4.46	4.488	4.48	4.529	4.53	4.551	4.53
70	3.5	3.51	3.511	3.53	3.545	3.57	3.545	3.57

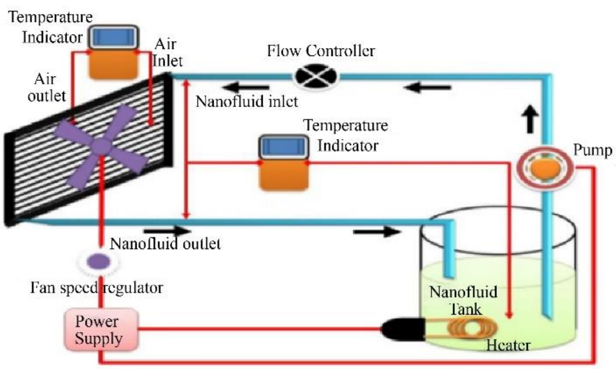

Fig. 2 Schematic diagram of test rig

3. Experimental Test Rig and Procedure

A state-of-the-art experimental test rig is designed, developed, tested, and commissioned to determine the performance of hybrid nano thermo-fluids. The test rig consists of a plate-fin heat exchanger commercially available in the automotive market, as shown in Figure 4. The test rig has two circuits: one to carry the hot liquid and the second one to carry cold air acting as a coolant that flows through the finned structure. Thermocouples are employed to measure the temperature of the hot fluid at the inlet/outlet of the heat exchanger, temperature of the air at the entrance and exit, atmospheric air temperature and plate surface temperature, as shown in Figure 2.

Two piezoresistive digital pressure sensors (supplied by Turck) are installed to measure the relative pressure of the hot oil at the inlet and outlet of the heat exchanger. The range of operating pressure of the sensors is -1 to 1 bar with a resolution of ±0.001 bar. A rotameter and a digital flow meter (Macnaught M series flow meter, model: M2RSP-1H) are incorporated to measure the flow rate of hybrid nano-fluid through the circuit.

The range of measurement of the flow rate is from 0-6lit/min with a resolution ±0.01lit/min. In this work, ambient air is taken as the cold fluid. A suction fan is attached to the end of a duct that draws atmospheric air through the heat exchanger. The air velocity is measured using an anemometer installed between the heat exchanger and the suction fan. The flow rate of the cold fluid (air) flowing through the heat exchanger is estimated from the air velocity measurements and the density of air. A stainless-steel tank is fitted with a heater, and a high-temperature durable pump (Leo Innovation Type LRP15-60/130) is installed to drive the hot fluid through the circuits. All the temperature sensors are pre-calibrated and connected to the data acquisition system using software installed on the computer (laptop), as shown in Figure 4. A heater with a 1.5 kW rating is installed in the nano-fluid tank to regulate the inlet oil temperature. A high-temperature, durable pump of 80 watts capacity is employed to pump the hot fluid through the circuit, as shown in Figure 2.

Table 5. Thermal conductivity (W/mK) for pure TrO F. F. mamedov et al, 1999 [51]

Temp (ºC)	30	35	40	45	50	55	60	65	70	75	80
Thermal Conductivity (W/mK)	0.1274	0.1268	0.1260	0.1253	0.1246	0.1239	0.1232	0.1225	0.1219	0.1208	0.1200

The hot fluid passes through the radiator with 9 rectangular tubes mounted in a parallel arrangement, and 153 aluminium fins are attached between the 9 rectangular tubes. Air passes through the aluminium fins that are attached to the tubes. This arrangement is shown in Figure 3, and the corresponding specifications are given in detail in Table 6. Here, the tubes are filled with hot fluid coming from the tank. The hot fluid dissipates the heat to the atmosphere through the fins attached to the tube surface. Air passing through the fins and carries the heat while passing through the fins. Thus, the fan blows the air and cools down the hot fluid because of the temperature difference. Hence, the hot fluid coming out of the radiator is cooler than when it entered and comes out through the outlet port of the radiator. The oil coming out from the outlet port is collected and returned to the reservoir/ tank. The heat transfer performance of compact heat exchangers greatly depends on the convective heat transfer coefficient of the flowing fluids. Hence, hybrid nano-fluids are helpful for enhancing the rate of heat transfer by increasing the convective heat transfer coefficient and enhancing thermal conductivity for a given heat transfer area and temperature difference.

Table 6. Constructional details of radiator

R_L-Radiator length	0.325 m
R_W- Radiator width	0.115 m
T_W -Tube width	0.025 m
T_H - Tube height	0.003 m
F_W -Fin width	0.028 m
F_H -Fin height	0.009 m
F_T-Fin thickness	0.0001 m
F_D -Distance between the fins	0.005 m
n-tubes- Number of tubes	9
Number of Fins in each row	153

Fig. 3 Radiator

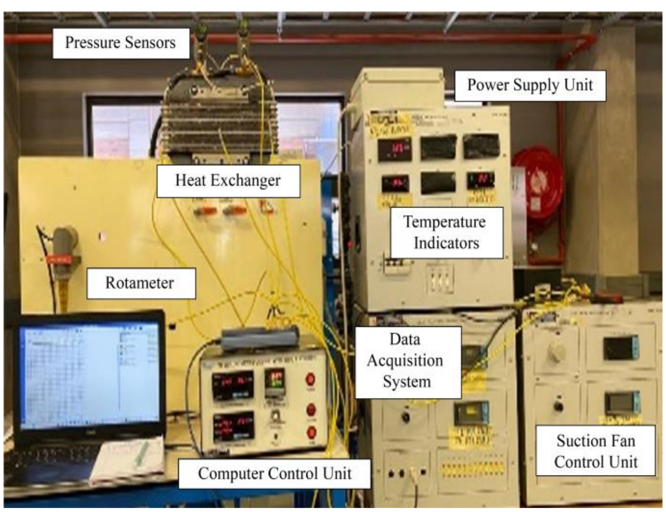

Fig. 4 Experimental test rig

4. Preparation of Nano-Hybrid Transformer Oil

To prepare a hybrid nano-fluid (nano transformer oil), two different nano materials, namely MgO and CuO, are used in the experiment that are ≤ 50nm in size, and were procured from Sigma Aldrich. Based on Equation (2), required quantities of nanoparticles were calculated, and a precision digital micro-balance (supplied by Labotech) with a resolution of 1 microgram was employed to determine the accurate weight of MgO and CuO nanoparticles. Different concentrations of nano-fluids are prepared by adding appropriate quantities of nano materials to the base fluid (transformer oil from SABS-approved SANS Envir Oil). The nanoparticle and surfactant CTAB bought from Sigma Aldrich are added to the based fluid to avoid agglomeration and formation of lumps. The procedure followed in the preparation of nano-fluids using a two-step method is illustrated in Figure 5 and Figure 6. Furthermore, keeping the mixer for more than 12 hrs on a mechanical stirrer, the desired nano-fluid is formed. Thus, the prepared nano-hybrid mixer is now ready to pour into the stainless-steel tank, which is insulated with asbestos with a holding capacity of 20 litres. The stability check was conducted by allowing the nano-fluid to remain undisturbed for a period of two weeks. It was observed that the nanoparticles were still found to be in the colloidal state with insignificant settlement. Therefore, it was assumed that the stability of the nano-fluid is very good. In addition, the thermophysical properties of the nano-fluids, such as their density, specific heat, and thermal conductivity, were determined by hybrid correlations [44, 45].

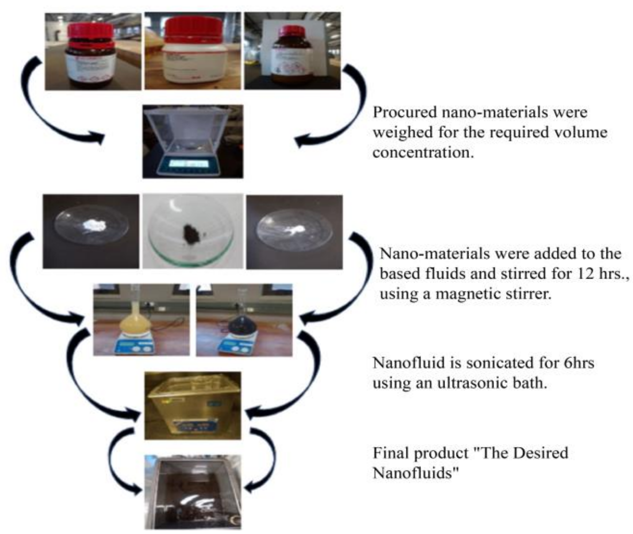

Fig. 5 Preparation of nano-hybrid-transformer oil

5. Data Reduction

The hot liquid side heat transfer rate can be calculated using Equation (16).

$$Q = \dot{m}C_p(T_{in} - T_{out}) \tag{16}$$

The Overall heat transfer coefficient can be calculated using the following Equation (17), Gabriela Huminic and Angel Huminic [52].

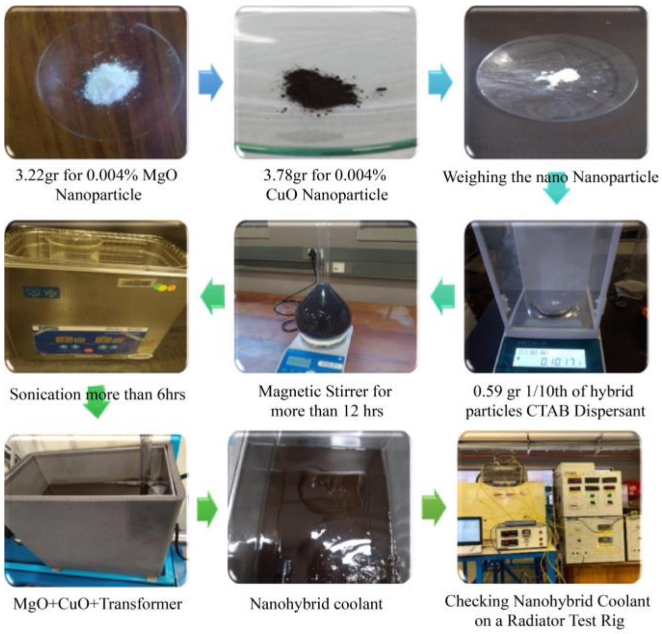

Fig. 6 Two-step method

$$U = \frac{Q}{A\,\Delta T_m} = \frac{\dot{m}C_p(T_{in}-T_{out})}{A\left(\frac{(T_W-T_{in})-(T_W-T_{out})}{ln\left(\frac{T_W-T_{in}}{T_W-T_{out}}\right)}\right)} \tag{17}$$

$$A = 2\pi L\sqrt{\frac{a^2+b^2}{2}} \tag{18}$$

A-Total internal surface area of tube.
ΔTm – logarithmic mean temperature difference.

The Reynolds Number was determined using Equation (19), which is given below.

$$Re = \frac{2\dot{m}}{\mu(T_W+T_H)} \tag{19}$$

The Prandtl Number was determined using Equation (20), as given below.

$$Pr = \frac{\mu\, C_p}{k} \tag{20}$$

The Nusselt Number was determined using Equation (21) given below.

$$Nu = \frac{htc\, D_h}{k} \tag{21}$$

The heat transfer coefficient used in Equation (21) is determined using the following Equation (22) from the experimental measurements.

$$htc = \frac{m\, C_p(T_{in}-T_{out})}{A(T_{Bulk}-T_{wall})} \tag{22}$$

Where, $$\mathrm{T_{bulk}} = \frac{\mathrm{T_1+T_2}}{2} \tag{23}$$

The hydraulic diameter Dh for the rectangular channel is calculated using Equation (24). The hot fluid from the tank passes through the radiator tubes.

$$D_h = \frac{4.A_{Tube}}{P_{Tube}} \tag{24}$$

6. Results and Discussions

6.1. Overall Heat Transfer Coefficient of Hybrid Nano-Fluid vs Mean Bulk Temperature

In the following Figure 7, the overall heat transfer coefficient is shown as a function of the mean bulk temperature of the hybrid nano-transformer oil. The figure represents four sets of experiments conducted at four different flow rates (1,2,3, and 4 lit/m) in the range of temperatures from 30 to 700C. In each set of graphs, the volume concentration of nanoparticles is increased progressively from 0.002% to 0.012%. It is observed that the overall heat transfer coefficient increases with the mean bulk temperature. Further, the overall heat transfer coefficient increased with an increase in volume concentration. One important point to be noted here is that the overall heat transfer coefficient is a strong function of mean bulk temperature and relatively a weak function of volume concentration. While the effect of volume concentration of nanoparticles is predominantly seen in the set of graphs that correspond to 1 lit/min, the effect is reduced at higher flow rates. It is observed that nano-particle dispersion improved the overall heat transfer coefficient to an extent of 110 to 113% at a higher volume concentration of 0.012% when compared to the base fluid.

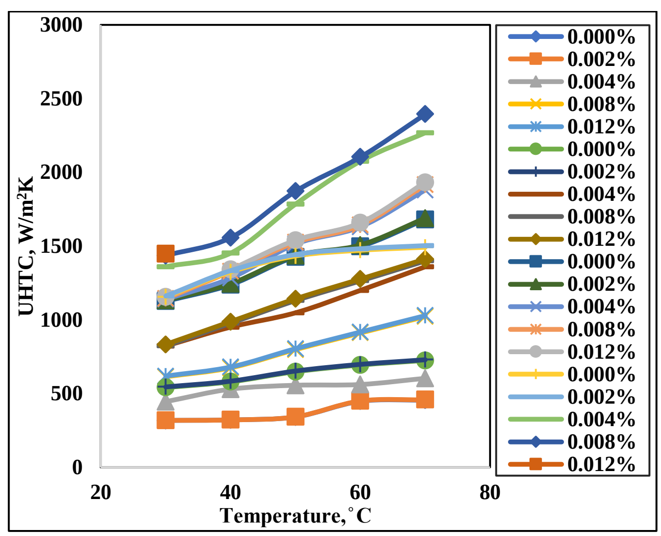

Fig. 7 Overall heat transfer coefficient as a function of temperature and flow rate as a parameter

In the following Figure 8, the overall heat transfer coefficient is shown as a function of the mass flow rate of the hybrid nano-transformer oil. The figure again represents four sets of experiments conducted at four different flow rates (1,2,3, and 4 lit/m) in the range of temperatures from 30 to

700C. In the present experimental test facility, there is a provision to measure the volume flow rate of the fluid with the help of a rotameter and a digital flow meter coupled with a display unit. The mass flow rate of the hybrid nano-fluid is determined by considering the density of the nano-fluid estimated using Equation (5) proposed by Takabi and Salehi et al. [45]. Again, in each set of graphs, the volume concentration of nanoparticles is increased progressively from 0.002% to 0.012%. From these experiments, it is observed that the overall heat transfer coefficient increases with the mass flow rate of the nano-fluid. It was found that the overall heat transfer coefficient improved with the increase in the mass flow rate and volume concentration. The effect of mass flow rate is relatively more on the heat transfer coefficient than the increase due to the volume concentration of nanoparticles. It can be observed that the increase in overall heat transfer coefficient is due to the combined effect of mass flow rate, mean bulk temperature and volume concentration of the nanoparticles.

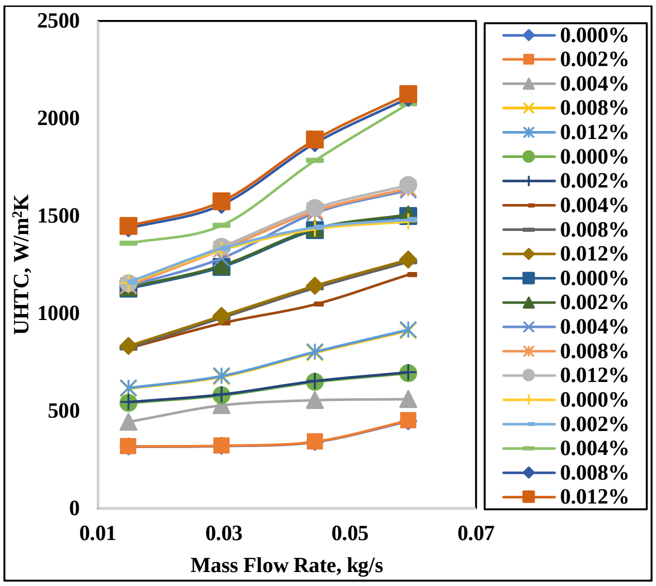

Fig. 8 Overall heat transfer coefficient as a function of mass flow rate and temperature as a parameter

6.2. Nusselt Number vs Reynolds Number and Mean Bulk Temperature

In Figure 9, the Nusselt number is shown as a function of Reynolds number of the hybrid nano-transformer oil. Figure 9 represents four sets of experiments conducted at four different flow rates (1,2,3, and 4 lit/min) in the range of temperatures from 30 to 700C. In each set of graphs, the volume concentration of nanoparticles is increased progressively from 0.002% to 0.012%. It is observed that the non-dimensional heat transfer coefficient, i.e, Nusselt number, increases with an increase in Reynolds number. The increasing trend in the Nusselt number as a function of Reynolds number indicates improvement in the heat transfer. Nusselt number 64 at 30℃ to 81 at 70℃ for 4lit/min at 0.012 volume concentration signifies more efficient convective heat transfer. On the other hand, the Reynolds number signifies the flow regime of the fluid, indicating whether the flow is laminar or turbulent.

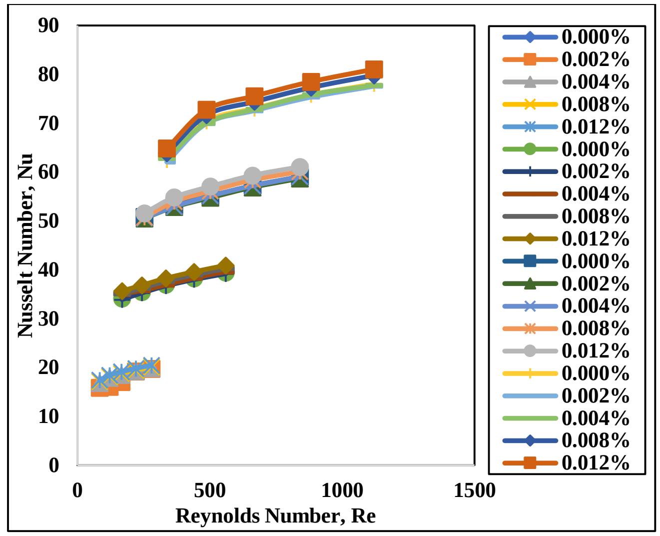

Fig. 9 Nusselt number as a function of reynolds number, flow rate as a parameter

Low Reynolds numbers 86 at 30℃ to 289 at 70℃ for 1lit/min at 0.012 volume concentration, 172 at 30℃ to 579 at 70℃ for 2lit/min at 0.012 volume concentration, 259 at 30℃ to 869 at 70℃ for 3lit/min at 0.012 volume concentration and 345 at 30℃ to 1159 at 70℃ for 4lit/min at 0.012 volume concentration typically suggest laminar flow (Re < 2000), where fluid moves in smooth layers.

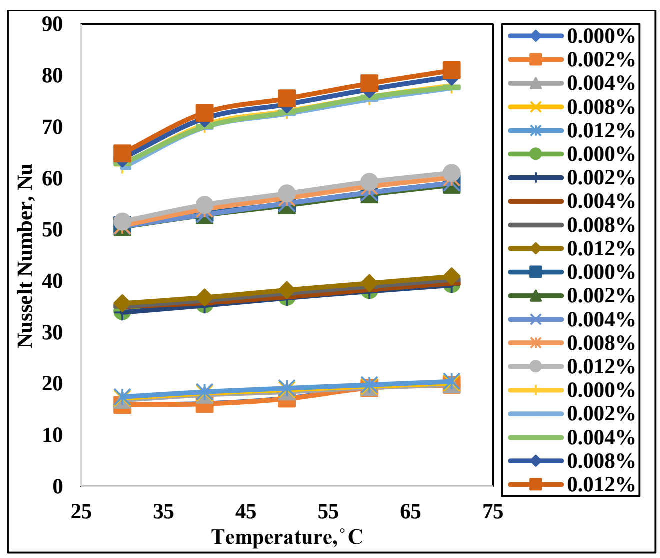

Fig. 10 Nusselt number as a function of temperature, flow rate as a parameter

The Nusselt number in Figure 10 shows that it is influenced by a change in temperatures; it can affect the properties of the fluid, such as viscosity, thermal conductivity, and density. These changes can significantly impact the convective heat transfer coefficient, thereby altering the Nusselt number. For instance, in a fluid heating or cooling process, the viscosity often decreases as temperature increases, which can enhance flow characteristics seen in the figure and potentially increase the Nusselt number. Overall, the interaction between Nusselt number and temperature underscores the dynamic nature of heat transfer in fluids. An Increase in Nusselt number 15 at 30℃ to 20 at 70℃ for 1lit/min at 0.002% volume concentration, 33 at 30℃ to 40 at 70℃ for 2lit/min at 0.004% volume concentration, 50 at 30℃ to 60 at 70℃ for 3lit/min at 0.008% volume concentration and 64 at 30℃ to 81 at 70℃ for 4lit/min at 0.012% volume concentration signifies efficient convective heat transfer.

6.3. Reynolds Number vs Mean Bulk Temperature

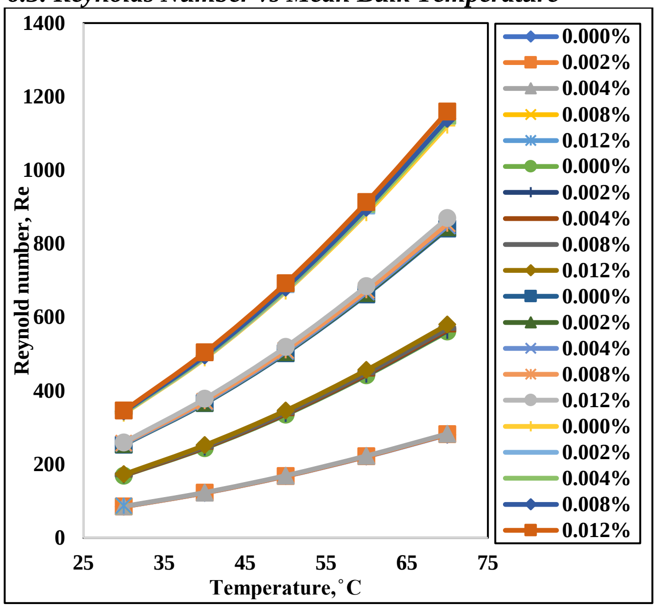

Fig. 11 Reynolds number as a function of temperature, flow rate as a parameter

Figure 11 reveals the effect of temperature on the Reynolds number, where the temperature was varied from 30℃ to 70℃, leading to a corresponding increase in the Reynolds number ranging from 84 to 1159. The Reynolds number is sensitive to temperature because temperature influences fluid properties such as viscosity and density. As temperature increases, the viscosity of most fluids decreases, which reduces the fluid's resistance to flow. This decrease in viscosity can lead to an increase in the Reynolds number. Temperature-related changes in fluid behaviour can also greatly affect the stability and characteristics of the flow.

6.4. Hot Liquid Side Convective Heat Transfer Coefficient vs Mass Flow Rate

In Figure 12, it is observed that the convective heat transfer coefficient increases by 12.2% for 1lit/min at 0.008% volume concentration, 8.1% for 2lit/min at 0.002% concentration, 13.2% for 3lit/min at 0.004% concentration and 19.5% for 4lit/min at 0.012% volume concentration for temperatures varying from 30˚C to 70 ˚C. Convective heat transfer occurs when a fluid transfers heat to or from a surface, and it is significantly influenced by the mass flow rate of the fluid.

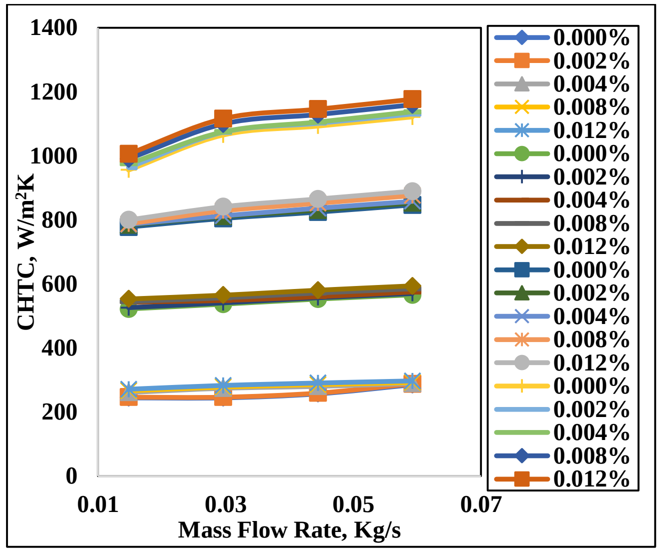

Fig. 12 Convective heat transfer coefficient vs mass flow rate

As the mass flow rate increases, more fluid passes over the surface per unit time, enhancing the heat exchange between the surface and the fluid. This increased flow promotes better mixing and reduces the thermal boundary layer thickness, leading to higher convective heat transfer coefficients.

Consequently, a higher mass flow rate typically results in improved heat transfer efficiency, which is crucial in our applications of heat exchangers in cooling systems. However, the excessively high mass flow rates can lead to increased pressure drops and associated energy costs, potentially negating the benefits of enhanced heat transfer. Therefore, optimizing the mass flow rate is essential to balance efficiency and operational feasibility in thermal systems.

7. Uncertainty Analysis

Uncertainty Analysis is conducted as per Meysam Nazari et al.2023 [53]. Uncertainty in the measured values is found to be in the range of ± 5%. An uncertainty analysis is conducted for the measured overall heat transfer coefficient using the equations given in Table 7. Uncertainty in the individual instruments is taken into consideration to determine overall uncertainty. Specifically, uncertainties were estimated for the Reynolds number, the Heat transfer coefficient and Nusselt's number are given below.

Table 7. A representative uncertainty analysis in the measurement of Re, h, and Nu. Meysam Nazari et al.2023 [53]

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%
Heat transfer coefficient, h $\boldsymbol{h = \frac{q}{T_w - T_b}}$	$\frac{U_h}{h} = \sqrt{\left(\frac{U_q}{q}\right)^2 + \left(\frac{U_{T_w - T_b}}{T_w - T_b}\right)^2}$	4.77%
Nusselt number, Nu $Nu = \frac{hd}{k}$	$\frac{U_{Nu}}{Nu} = \sqrt{\left(\frac{U_h}{h}\right)^2 + \left(\frac{U_d}{d}\right)^2 + \left(\frac{U_k}{k}\right)^2}$	4.06%

8. Conclusion

In the present investigation, MgO-CuO based hybrid nano transformer oil has been synthesised and characterised for its thermo-physical properties. The most important purpose of this experimental study, to evaluate the thermal performance of MgO-CuO based nano transformer oil in a plate-fin heat exchanger, is successfully achieved. A special test rig created for this study is used to experimentally assess the overall heat transfer coefficient. The thermo-physical characteristics of MgO-CuO based nano transformer oil are determined in laboratory conditions. The following are the key findings from this investigation:

- From the present experimental investigation, it is concluded that the overall heat transfer coefficient increases with both temperature and the mass flow rate. It is concluded that the UHTC, CHTC enhancement is 135%, 28,86% with reference to the pure transformer oil.
- The stability of this nano-fluid is established by observing the settlement of nanoparticles over a prolonged period of time, nearly 2 weeks.
- The non-dimensional heat transfer coefficient, Nu, increases with the Reynolds number, Re, and the mean bulk temperature of the hybrid nano-transformer oil.
- For any given set of operating conditions, the performance of hybrid nano-transformer oil improved with the increase in the percentage of nano-particle concentrations.

The results established that using this nano-transformer oil is highly beneficial in the operating temperature range from 30 to 70℃., with volume concentrations ranging from 0.002 to 0.012%.

From the present experimental investigation, it is concluded that MgO-CuO nano transformer oil is a suitable candidate for implementation in the transformer industry.

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