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RESEARCH ARTICLE-CHEMICAL ENGINEERING

Synthesis, Characterization and Thermal Analysis of MWCNT-Transformer Oil-Based Nanofluid: An Experimental Study

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Abstract

Transformer oil is used to maintain the core and winding of the transformer. The main tasks of transformer oil as an industrial oil are insulation and cooling of a transformer. In the current study, the thermophysical and thermal properties of transformer oil nanofluid with volume percentages of 0.017% and 0.56% have been experimentally investigated which improves the performance of the base fluid due to the high thermal conductivity coefficient of carbon nanotubes compared to transformer oil. Ultrasonic baths and chemically functionalizing techniques were utilized in a two-step process to create nanofluids, which were stabilized by these techniques. In a double-tube carbon steel heat exchanger, the nanofluids were employed, and the thermal characteristics of the base fluid and nanofluids were evaluated. The findings indicated that the effective thermal conductivity improves with increasing temperature and CNT concentration, reaching its maximum value at a temperature of 45 °C in a volume fraction of 0.56. Observations showed that the heat transfer coefficient rose with rising Reynolds number and volume percentage, whereas the friction factor reduced when the hot fluid flowed at an intake temperature of 80 °C compared to the nanofluid in the outer tube. The flow rates for the nanofluids were calculated to be 0.2, 0.3, 0.4 lit/s, and 0.18 lit/s for the hot fluid, respectively. As a general conclusion, carbon nanotubes have a very high potential to improve the thermal performance of transformer oils, which is a serious challenge.

Keywords Carbon Nanotube · Thermophysical Properties · Heat Exchanger · Nanofluid · Transformer oil

1 Introduction

Due to their superior mass and heat transfer properties compared to more common fluids like water, ethylene glycol, and oil, nanofluids have a wide range of uses in various sectors, including electronics, medicine, and transportation. With the inclusion of nanoparticles, fluids' thermophysical characteristics alter. Researchers have thus presented many formulas to calculate density, viscosity, thermal conductivity, and specific heat. The concentration of nanoparticles, physical characteristics, temperature of the base fluid, and other variables all affect these qualities. Much study has been done recently on nanofluids' thermal behavior and thermophysical characteristics. However, since so many variables are involved, a complete model has yet to be given, and the models produced are incomprehensible. The majority of studies have looked at how temperature and nanoparticle concentrations in the base fluid interact. In the temperature range of 25–65 °C and volume fractions of 0.2, 0.4, 0.6, and 0.8%, Rehman et al. evaluated the impact of multi-walled carbon nanotubes on oil and its improvement in thermal conductivity, with the results showing a maximum enhancement of approximately 6.7% [1]. Graphene-based nanofluids have also been considered by many researchers, and Xian et al. investigated the role of hybrid nanofluids including graphene and titanium oxide nanoparticles in water-based fluid and ethylene glycol at temperatures between 30 and 70 °C and volume fractions between 0.025 and 0.1% and reported a 23.7% enhancement in thermal conductivity in this range. The highest improvement in viscosity was 32.45% at a fraction of 0.1, and the nanofluid was stabilized by using carboxyl and hexadecyl trimethyl ammonium bromide surfactants [2]. Askari et al. studied the thermal behavior of

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a hybrid nanofluid including kerosene as the base fluid and nanoparticles of carbon and graphene nanotubes in Reynolds between 2100 and 4450 in the temperature range between 20 and 60 °C and of 0.05–0.5 vol%, and they observed an improvement of 28% and 23% for carbon and graphene nanotubes, respectively, and introduced nanofluids with a fraction of 0.1% carbon nanotubes as optimal nanofluids [3]. Li et al. examined the impact of temperature and nanoparticle concentration on the thermal conductivity and viscosity of a liquid silicon dioxide-paraffin nanofluid containing oleic acid at temperatures between 25 and 70 °C and volume fractions of 0.005–0.5%. They presented a correlation for the thermal conductivity, which increased with increasing temperature and volume fraction [4]. Table 1 summarizes the research conducted on the use of nanoparticles in improving the thermal performance of conventional base fluids, the operating conditions of each research project, and the materials used.

According to a study by Hashemi et al., the heat transfer rate increases by 42.3% when the mass flow rate is 8.5 g/s for titanium oxide–water nanofluid at a volumetric percentage of 0.2 and a temperature of 20–24 °C [11]. Table 2 also presents some experimental correlations for calculating the Nusselt number and thermal conductivity, which are related to the use of nanofluids in cooling equipment and heat exchangers.

A lot of research has been done on parameters affecting the thermal properties of nanoparticles in base fluids, which shows the effect of nanoparticles in improving the thermal properties of nanofluids [18–31].

The use of hybrid nanofluids has recently attracted the attention of researchers, and the role of hybrid nanofluids in improving heat transfer has been investigated. A Al2O3:Cu hybrid nanoadditive was created by Suresh et al. [32, 33] using a thermochemical synthesis including hydrogen reduction. Then, using a two-step process, they created 0.1 vol%. Al_2O_3: Cu/water hybrid nanofluid and 0.1 vol% Al_2O_3/water mono nanofluid. An electrical heating wire covered a straight copper tube that was coiled with ceramic beads as the test section for the heat transfer studies. Analyses in the turbulent (Re from 2300 to 13,000) [33] and laminar (Re from 700 to 2300) [32] flow regimes were conducted. Al2O3:Cu/water hybrid nanofluid demonstrated greater average Nusselt number, Nu, increases than Al_2O_3/water mono nanofluid in both circumstances (10.9% compared to 6.1% in laminar flow settings and 8.0% versus 5.2% in turbulent flow conditions). Al_2O_3: Ag hybrid nanocomposite made by the sol–gel process was dispersed at 0.4 vol% in water in a study by Allahyar et al. [34] compared to a mono-Al_2O_3/water nanofluid at 0.4 vol%. With the investigated fluids primarily flowing in a laminar regime, the test section consisted of a helical copper coil submerged in a water tank that had been heated by an electric heater. While a 28.4% improvement was made for the one-step 0.4 vol% mono nanofluid, the 0.4 vol% hybrid nanofluid produced the highest Nu enhancement, 31.6%. While the hybrid sample had somewhat higher values, both nanofluids demonstrated comparable increases in pressure drop.

The primary objectives of Wang et al.'s research are to enhance the thermal performance of the heat exchangers and examine the exergy utilising the SIMPLE algorithm, the k-w turbulent model, and the Eulerian-Eulerian approach for multiphase flow. Therefore, using computational fluid mechanics techniques, the operation of an Al_2O_3 single-bond CuO-water hybrid nanofluid in a 3D shell-and-tube heat exchanger is modelled to improve the contact surface of hot and cold fluid streams. The volume fraction of nanoparticles is 2–6%, and the Reynolds numbers are 10,000, 15,000, 20,000, and 25,000. This study uses a hybrid nanofluid and turbulator, which are advances. According to the results, a 6% increase in the volume fraction of hybrid nanoparticles and an increase in Reynolds number from minimum to maximum result in a 126% improvement in thermal performance when the turbulator is present [35].

Using a 0.01 vol% CuO-ZnO (80:20)/water hybrid nanofluid at Reynolds numbers (NRe) ranging from 1900 to 17,500, Malika et al. conducted experimental research. The heated fluid (60 °C on the shell side) is subsequently cooled using stabilised hybrid nanofluids (30 °C on the tube side), and the convective heat transfer coefficient, Nusselt number, friction factor, and pressure drop findings are presented. This paper's main objective is to examine how different operating

Table 1 A review of research conducted on nanofluids and role of parameters

References	Flow	Volume fraction	Tem. (°C)	Size (nm)	Particle	Base fluid
[5]	30–70 g/s	0.05–0.16	50–80	5–10	CNT	Water
[6]	2,4,6 L/min	0.5,0.25,0.1	85	20–30	CNT	Water/EG
[7]	11,12.5,13.5 L/min	0.05,0.5,0.1	80	40	Al2O3	EG
[8]	4–8 L/min	0.05–0.8	34,44,54	60	Cu_2O	Water/EG
[9]	2–8 L/min	1–2.5	60–80	30	SiO_2	Water
[10]	8–16 L/min	0.06,0.09,0.12	56,60,64	20	MgO	Water

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Table 2 An overview of experimental correlations of the Nusselt number and thermal conductivity

References	Correlation	Range	Particle	Base fluid
[12]	$\mathrm{Nu} = \frac{\left(\frac{f}{8}\right)\mathrm{Re}\cdot\mathrm{Pr}}{1.07+12.7\left(\frac{f}{8}\right)^{0.5}(\mathrm{Pr}^{2/3}-1)}$	Re = 3000–5 × 106	AL2O3	Water
[13]	$\mathrm{Nu} = 0.085\mathrm{Re}^{0.71}\,\mathrm{Pr}^{0.35}$	$\Phi = 0$–10% Re = 10,000–100000	AL_2O_3	Water
[14]	$K_{nf} = 0.1534 + 0.00026T + 1.1193\varphi$	$\Phi = 0.125$ -1.5% $T = 25$–50 °C	Al_2O_3-CNT	Thermal oil
[15]	$\frac{K_{nf}}{K_{bf}} = 1+0.004503\varphi^{0.8717} * T^{0.7972}$	$\Phi = 0.125$–2% $T = 25$–50 °C	Al_2O_3-Cu	EG
[16]	$\frac{K_{nf}}{K_{bf}} = 1 + 0.0162\varphi^{0.7038} * T^{0.6009}$	$\Phi = 0.1$–2.3% $T = 25$–50 °C	CNTs-Fe_3O_4	EG
[17]	$\frac{K_{nf}}{K_{bf}} = 0.963 + 0.008379\varphi^{0.4439} * T^{0.9246}$	$\Phi = 0.04$–2.5% $T = 30$–50 °C	CNTs-Al_2O_3	EG

Table 3 Physical and chemical properties of nanoparticles

– COOH Content: 1.23 wt%	Multi-walled nanotubes (MWNTs) > 98 wt%
ID: 5–10 nm	L: 10–30 μm
Density: ~ 2.1 g/cm^3	Outside diameter: 20–30 nm

conditions affect the effect of hybrid nanoparticle mixing ratio optimisation on STHE heat transfer efficiency. The results showed that for all Reynolds numbers, the CuO-ZnO (80:20)/water hybrid nanofluid enhanced the heat transfer performance of the STHE. The Nusselt number and pressure drop were increased by around 33% and 13%, respectively, when employing nanofluid over water. At NRe = 17,500, the hybrid nanofluid had a maximum thermal performance factor and a 7% thermal efficiency gain. After ten trials, the study found that the thermal conductivity of nanofluid varied by just 5% [36].

Bantan et al. examined the effects of using a porous zone on the flow of a hybrid nanofluid via a duct by employing the FVM technique. Momentum equations now include related terms that are based on the Darcy model in three-dimensional steady flow forms. Hybrid nanofluids are made when water, nanoparticles (MWCNT and Al_2O_3), and other substances are combined. Helical tape was added to enhance heat absorption. The middle 40 cm of the duct, where the porous zone and helical tapes were placed, is the test portion. The most accurate results are produced at the lowest computational cost through validation based on previously published work and grid analysis. On the handling of working fluid, the effects of Da,, and Re have been investigated. Selecting more Remakes Nu results in intensifications of 7.27% and 35.58%, respectively. Nu decreases by around 6.78% as the zone's permeability rises because fluid may travel along the axial direction more quickly [37].

Since the simultaneous study of thermophysical and rheological properties of nanofluids for transformer oil has not been done so far, the study of the rheological behavior of samples along with the study of thermal conductivity and thermal behavior of suspension in a heat exchanger is one of the advantages of the present study. It is expected that due to the use of multi-walled carbon nanotubes, the suspension, and the very high heat transfer coefficient relative to the base fluid, a significant enhancement in the thermal properties of transformer oil will be observed. The reason why we use nanofluids can be because of their capacity in heat transfer equipment, and the results should be able to confirm this issue.

2 Experimental

2.1 Nanofluid Fabrication

Multi-walled carbon nanotubes were purchased from US Research Nanomaterials, Inc., and their physical and chemical properties are listed in Table 3. Then the required amounts of nanoparticles in volume fractions of 0.017% and 0.56% were added to the transformer oil, and then the desired nanofluid was prepared in a two-step method using a magnetic stirrer and an ultrasonic bath. In order to stabilize the suspension, a surfactant and functionalization method with carboxyl groups was used, in which sodium dodecyl sulphate

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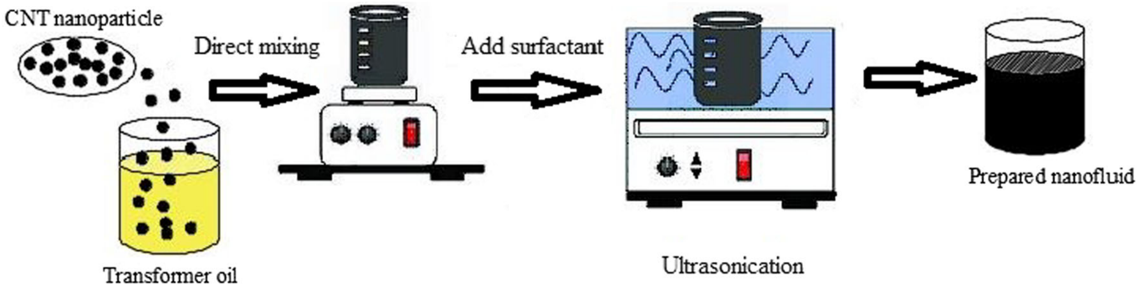

Fig. 1 Nanofluid preparation procedure

surfactant was used in the suspension. All three chemical, magnetic and ultrasonic processes were performed for greater stability of the solution, and the preparation time of the nanofluid using a stirrer and an ultrasonic bath was about one and a half hours. The procedure for nanofluid preparation is shown in Fig. 1.

Experimental measurements have been made of the density, viscosity, and effective thermal conductivity of nanofluids. The thermal conductivity of the base fluid and the nanofluids has been specifically measured using the KD-2 Pro, and the results are moderate. In a double-tube heat exchanger made of carbon steel grade 40 with inner tubes that were 1.5 inches in diameter and outer tubes that were 2 inches in diameter, experiments pertaining to the heat transfer coefficient and the overall heat transfer coefficient were carried out. In order to reduce heat loss between the heat exchanger and its surroundings, the whole exchanger is insulated using fiberglass. The hot fluid, which in this study is hot water, flows in the outer tube at an input temperature of 80 °C and is in countercurrent with the nanofluid. Temperature indicators are installed at the intake and outlet of each tube to measure the temperature of the hot fluid and nanofluid. Two pumps circulate the flow of hot and cold fluids, as well as two 6-L tanks with flow metres and other equipment used in the apparatus of the present research.

3 Results

The results of the FTIR test were analyzed by IRPal software and Fig. 2 shows the results related to the passage intensity emitted to the base fluid and nanofluid relative to the wave number corresponding to the wavelength of infrared light emitted in cm^{-1} that each peak corresponds to a specific chemical bond, the results of which are summarized in Table 4.

The degree of carbon nanotube functionalization alters the wettability of the materials with different surfactants, which may alter their toxicity. According to the research's findings for the samples it examined, there are several peaks in the data, including the peak 1459 cm^{-1}, which is unique to carbon nanotubes, and the presence of O–H bending, which has a weak bonding force and denotes the start of the formation of carboxylic groups as a result of surface oxidation. Since carboxylic acids are found in the range of 2500–3300 cm^{-1}, the peaks at 2726, 2856, and 2924 cm^{-1} point to the presence of these groups, which form a strong bond. Additionally, the peak at 1605 cm^{-1} points to C=C stretching, which demonstrates the presence of a carbon double bond and is connected to the aromatic ring. The 812 cm^{-1} peak is associated with C=C bending, the 1727 cm^{-1} peak is associated with the strong C=C bending bond, and the 1160 cm^{-1} peak is associated with the strong link between C–O. Peaks at 1449 and 11,605 cm^{-1} that correlate to the MWCNT's vibration mode are also noticeable. The G band, which is visible at 1600 cm^{-1}, is the most powerful mode of CNT. However, the existence of the G band following functionalization demonstrates that the structure of nanotubes has been maintained. After oxidation, the G band's intensity is reduced in the carbon nanotubes' spectra. The appropriate attachment of oxygen-based functional groups on the surface of nanotubes may be the cause of this issue. Chemically functionalized nanotubes exhibit hydrophilic behavior as a result of the production of OH groups on their surfaces during the acid washing procedure, which results in the formation of hydrogen bonds with water molecules. As a result, the creation of functional groups O–H, C–O, and C–H on the surface of carbon nanotubes was confirmed by the findings of the FTIR analysis, and the necessary functional groups were produced.

The rheological behavior of transformer oil as well as nanofluids has been investigated by Brookfield viscometers; in the present study, it changes with the shear rate. Also, according to the results obtained in Fig. 3, it can be seen that by adding nanoparticles to the base fluid, the viscosity of the nanofluid does not show much increase, which means that no more energy is needed to pump the nanofluid. This is especially true for a 0.017% by volume sample, which minimizes the risk of sedimentation. Increasing the amount of viscosity by adding nanoparticles can be justified in this way: by increasing the concentration of nanofluid due to Van

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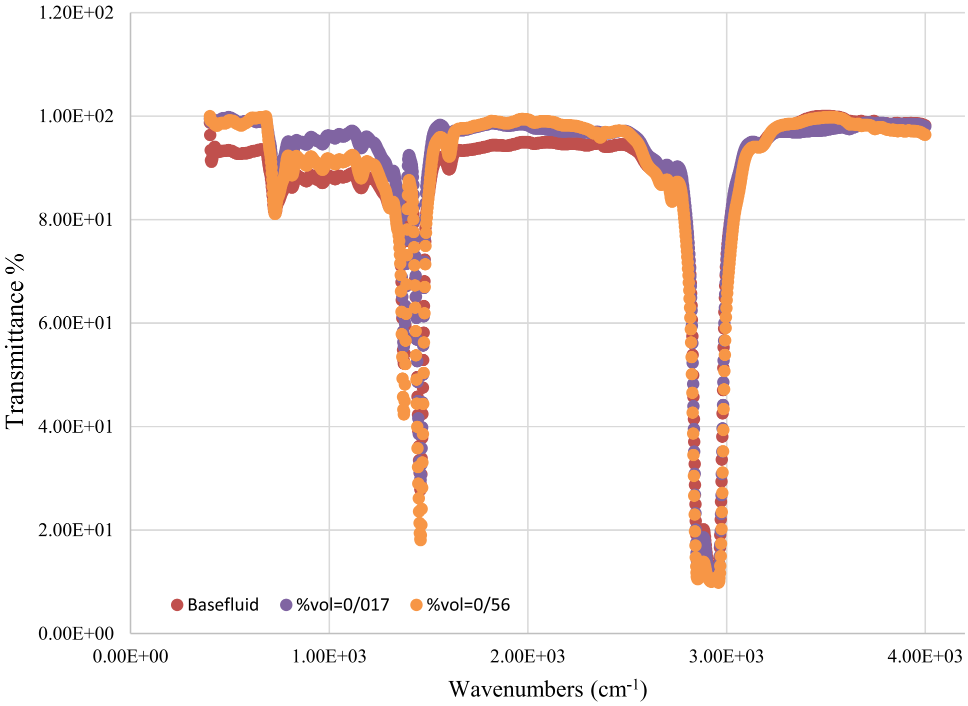

Fig. 2 Samples FTIR results

Table 4 FTIR test results of samples

Peak (cm^{-1})	Group	Structure	Bonding power	Modification
2956	Carboxylic acid	RCO-OH	Strong	Dimer OH
2856	Carboxylic acid	RCO-OH	Strong	Dimer OH
1604	Carboxylic acid	RCO-OH	Medium	C–O stretch
1459	Alkane	RCH_2CH_3	Strong	CH_2, CH_3
1375	Alkane	RCH_2CH_3	Strong	CH_2, CH_3
727	Alkane	1,2,3-trisub	Medium	C–H out of plane

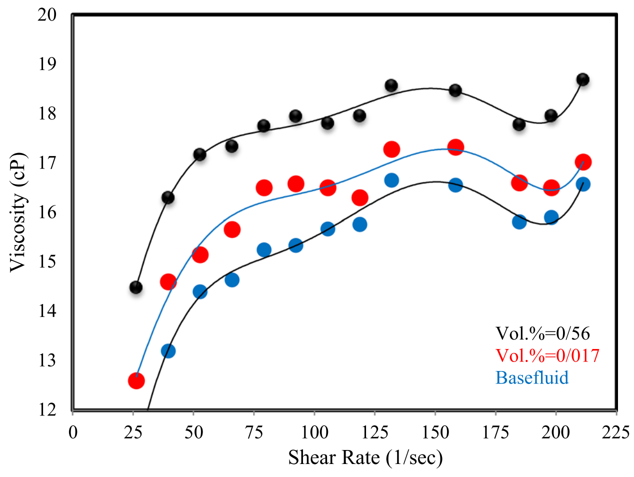

Fig. 3 Changes in the viscosity of the samples relative to the shear rate

der Waals forces between particles and increasing the number of nanoparticles per unit volume of the base fluid, larger nanoclusters are created, which in turn increases the resistance because they are against the movement of the layers and thus increase the viscosity.

Investigation and determination of the thermal conductivity of fluids used in the field of heat transfer have been topics of interest in recent years because it affects the thermal properties as well as the efficiency of equipment, and existing theoretical models are not able to predict thermal behaviour because they are not accurate and each model is limited to the suspension and operating conditions of the same research. The results of the thermophysical properties have been reported on average three times. Figure 4A shows the changes of the base oil thermal conductivity and nanofluid relative to the temperature, which clearly increase significantly with increasing temperature, which is linear, so that with increasing temperature from 25 to 45 °C, it increases about 15% for nanofluids of 0.56%.

The movement of nanoparticles, as well as the increase of interactions within the base fluid and Brownian motions, can be considered the main reason for increasing the thermal

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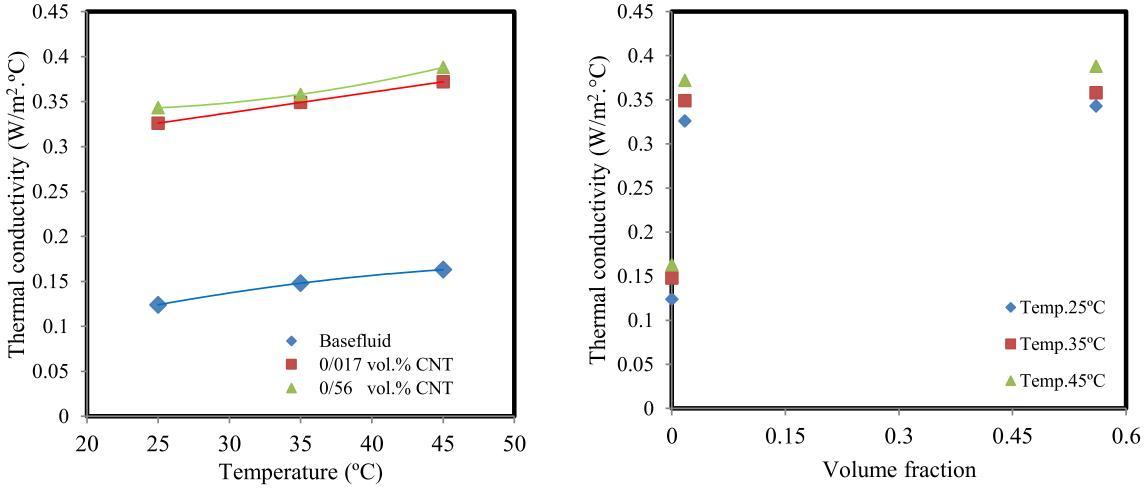

A- Thermal conductivity coefficient of the samples versus temperature

B- Thermal conductivity coefficient versus volume fraction at different temperatures

Fig. 4 **A** Thermal conductivity coefficient of the samples versus temperature. **B** Thermal conductivity coefficient versus volume fraction at different temperatures

Table 5 Thermal conductivity versus Temperature results

Temperature (°C)	Basefluid	0/017%	0/56%
25	0.124	0.326	0.343
35	0.148	0.349	0.358
45	0.163	0.372	0.388

conductivity of nanofluids compared to conventional base fluids, which increase with temperature and the concentration of nanoparticles. The interface between the nanoparticle and the base fluid is also about a few nanometers, but it can be considered another effective factor and change the atomic structure at the interface. Figure 4B illustrates the relationship between thermal conductivity and volume percent at various temperatures. It is obvious that as temperature and volume percent rise, so does the value of this coefficient, which is equal to 140% at 45 °C. According to the results, it can be concluded that the effect of temperature is greater than the volume fraction. The rate at which heat passes through a substance increases with its thermal conductivity. However, when heat transport is impacted by place and time, thermal conductivity is both essential and not enough to define the phenomenon. The results are summarized in Table 5.

The Seider equation was used to calculate the Nusselt number in the laminar regime ($\mathrm{Re} \le 2300$), and the Gnielinski equation was used for the transient and turbulent regimes ($\mathrm{Re} > 2300$). At the average exit and intake temperatures of every stream, the physical characteristics of hot fluids and nanofluids have been computed and incorporated into the pertinent equations. Finally, after calculating the Nusselt number for each stream, the convective heat transfer coefficient has been calculated using Formula 1.

$$\mathrm{Nu} = \frac{h * D_e}{k} \tag{1}$$

In the present study, the hot fluid flow rate was considered constant and equal to 0.18 L per second. The conditions for using transformer oil with hot water were also considered in conditions quite similar to nanofluid and hot water. In the present study, the flow rate of hot fluid was considered constant and equal to 0.18 L per second, and for nanofluids, three different flow rates of 0.2, 0.3, and 0.4 L per second flowed as countercurrent to hot fluid, and the results were compared with the base fluid without nanoparticles. The conditions for using transformer oil with hot water were also considered under the same conditions as nanofluid and hot water.

$$h = -10^{-5}\mathrm{Re}^2 + 0.1443\mathrm{Re} - 208.9,\ R^2 = 1,\ \text{for basefluid} \tag{2}$$

$$h = -3 * 10^{-5}\mathrm{Re}^2 + 0.297\mathrm{Re} - 423.13,\ R^2 = 1,\ \text{for } 0.017 \text{ vol\%} \tag{3}$$

$$h = -10^{-6}\mathrm{Re}^2 + 0.1096\mathrm{Re} - 67.8,\ R^2 = 1,\ \text{for } 0.56 \text{ vol\%} \tag{4}$$

The heat transfer coefficient is one of the most important parameters used to study and evaluate the efficiency of heat transfer systems, especially heat exchangers. The role of nanofluid flow change as well as volume fraction in increasing the amount of heat transfer coefficient has been studied. As shown in Fig. 5, increasing these two parameters has

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Table 6 Heat transfer in comparison of Reynolds and nanoparticles percentage results

Nanoparticle percentage	0%		0.017%		0.56%	
Re. Versus heat transfer coefficient	Re	h (W/m^2 °C)	Re	h (W/m^2 °C)	Re	h (W/m^2 °C)
Re No @ 11LPM & 12LPM	2173	50.009	2190	107.005	2316	180.625
Re No @ 11LPM & 18/5 LPM	3473	152.512	3285	280.872	3473	300.787
Re No @ 11 LPM & 25LPM	4641	211.194	4381	394.013	4632	418.499

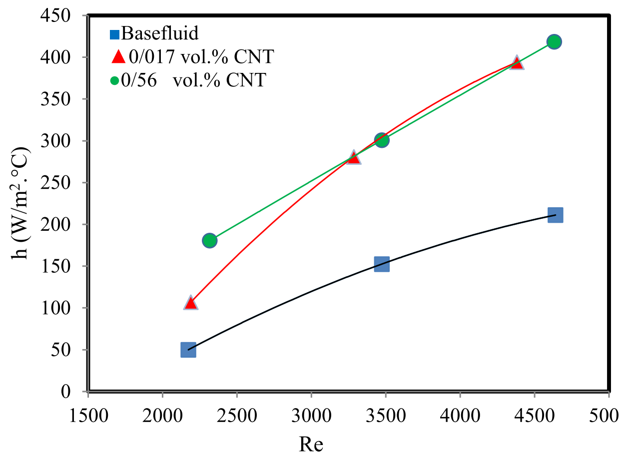

Fig. 5 Heat transfer coefficient relative to Reynolds in different volume fractions

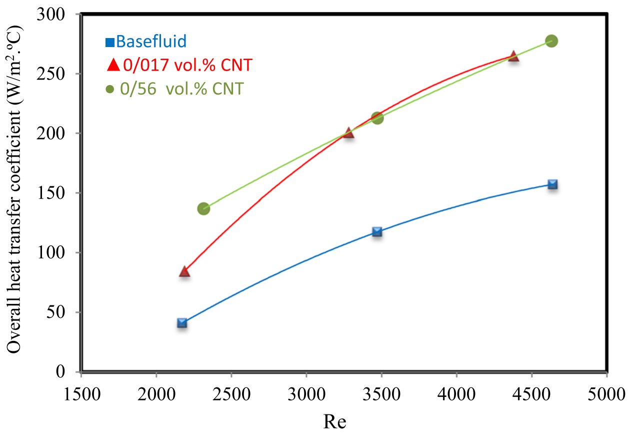

Fig. 6 Reynolds number and overall heat transfer coefficient

a positive effect and increases the value of this parameter. The findings unambiguously demonstrate that, for a certain volume fraction, the amount of heat transfer rate improves noticeably when nanofluid flow rate increases, and that, for the same Reynolds heat transfer coefficient, a change in volume percent from 0.17 to 0.56% leads to an increase of around 68%, which suggests a possible benefit for nanofluids. The results of heat transfer in comparison of Reynolds and nanoparticle percentages are summarized in Table 6.

In order to predict the behavior of nanofluids, the heat transfer coefficient of fluid with respect to different Reynolds numbers for all three fluids is shown in formulas 2, 3, 4.

The overall coefficient of heat transfer in different Reynolds is investigated in Fig. 6. The maximum value is equal to 277 W/m^2. and is obtained when the nanofluid volume fraction is 0.56%, which shows an enhancement of 76.4% compared to the base fluid under similar conditions. The addition of nanoparticles to transformer oil at constant Reynolds increases the overall heat transfer coefficient and consequently improves the thermal properties of the nanofluid. At a constant concentration, with increasing Reynolds from 2316 to 4632, the overall heat transfer coefficient value increases from 137 to 277 W/m^2 °C, and the slope of the changes is almost constant for all samples.

According to the results of Table 7, it can be concluded that the effect of increasing the volume fraction is greater than increasing Reynolds, and the highest value is related to the highest volume fraction and the highest Reynolds, which can be due to various factors such as increasing thermal conductivity, decreasing boundary layer thickness, increasing transfer coefficient, and the heat transfer coefficient of the nanofluid being relative to the base fluid.

The results for friction coefficient relative to Reynolds number are summarized in Table 8.

$$f = -0.01 \ln(\mathrm{Re}) + 0.1266, \quad R^2 = 0.9995 \tag{5}$$

The relationship between the changes in the coefficient of friction and the dimensionless Reynolds number is shown in Fig. 7. It is in complete agreement with the Moody diagram and shows a decrease of approximately 17% in Reynolds's increase in the experimental range. In order to use nanofluids on an industrial scale, it is necessary to calculate the pressure drop to estimate the fluid pumping and hydrodynamic performance and costs. This study examined the pressure drop of base fluid and nanofluid, and the results showed that the amounts were nearly identical for both, indicating that the pressure drop is insignificant. Equation 5 formulates the friction coefficient as a function of the Re number.

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Table 7 Overall heat transfer in comparison of Reynolds and nanoparticles percentage results

Nanoparticle percentage	0%		0.017%		0.56%	
Re. Versus overall heat transfer coefficient	Re	U (W/m^2 °C)	Re	U (W/m^2 °C)	Re	U (W/m^2 °C)
11LPM & 12LPM	2173	41.048	2190	84.775	2316	136.913
11LPM & 18/5 LPM	3473	117.532	3285	200.851	3473	212.679
11 LPM & 25LPM	4641	157.174	4381	265.043	4632	277.489

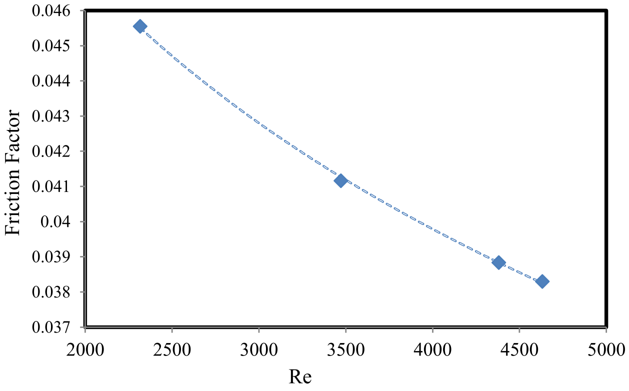

Fig. 7 Reynolds number effect on friction factor

Table 8 Friction factor versus Re. results

Re	f
2316	0.045551
3473	0.041163
4632	0.038304
4381	0.038841

4 Conclusion

The goal of this study was to examine the thermal behavior of a nanofluid containing multi-walled carbon nanotubes and transformer oil in a heat exchanger made of carbon steel. Nanofluid at volume fractions of 0.017% and 0.56% flowed inside the heat exchanger in a counter-current state, and the heat transfer coefficient and coefficient of friction were measured. Similar to other physical properties, thermophysical properties were initially calculated at the average temperature between the inlet and outlet streams. The findings of this study can be summed up as follows:

- As the volume percentage and Reynolds number grow, the heat transfer coefficient of the nanofluid increases in comparison to the base fluid.
- In comparison to transformer oil, the thermophysical characteristics of nanofluids, such as thermal conductivity, viscosity, and density, rise with increasing volume fraction.
- The friction factor reduces as the Reynolds number rises.
- Compared to the base fluid, the pressure drop brought on by the nanofluid is marginally different and can be disregarded.

As a suggestion for future research, hybrid nanofluids can be used to investigate the effect of combining several nanoparticles with the base fluid.

Data Availability No Data associated in the manuscript.

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