CI&CEQ
Chemical Industry & Chemical Engineering Quarterly
Available online at
Association of the Chemical Engineers of Serbia *AChE*
www.ache.org.rs/CICEQ
Chem. Ind. Chem. Eng. Q. 29 (3) 225−233 (2023) CI&CEQ

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SCIENTIFIC PAPER

UDC 621.4:621.892:536.2

HEAT TRANSFER STUDIES IN A PLATE HEAT EXCHANGER USING Fe_2O_3-WATER-ENGINE OIL NANOFLUID

Article Highlights

- Fe_2O_3/engine oil/ Water mixed nanofluid were prepared using a high-pressure homogenizer
- The heat transfer performance of Fe_2O_3 suspended base fluid was studied in a plate heat exchanger
- Convective heat transfer coefficient, Reynolds, Prandtl, and Nusselt numbers were determined and analyzed

Abstract

Improving the heat transfer performance of conventional fluid creates significant energy savings in process Industries. In this aspect, an experimental study was performed to evaluate the heat transfer performance of Fe_2O_3-water (W)-engine oil (EO) nanofluid at different concentrations and hot fluid inlet temperatures in a plate heat exchanger. Experiments were conducted by mixing Fe_2O_3 nanoparticles (45 nm) in a W-EO mixture base fluid with volume fractions of 5% EO + 95% W and 10% EO +90% W. The main aim of the present study was to assess the impacts of nanoparticle volume fraction and hot fluid inlet temperature variations on the heat transfer performance of the prepared nanofluid. The convective heat transfer coefficient, Reynolds, Prandtl, and Nusselt numbers were determined based on the experimental results. The result shows that at the hot fluid inlet temperature of 75 °C, the increase in Nusselt number and convective heat transfer coefficient are optimum at 0.9 vol. % nanoparticle for both the base fluid mixtures. The increase in heat transfer coefficient is because of the Brownian motion (increasing thermal conductivity) effect, motion caused by the temperature gradient (Thermo-phoretic), and motion due to concentration gradient (Osmophoretic). If the volume fraction of the nanoparticle increases, then the Reynolds number increment is higher than the Prandtl number decrement, which augments the Nusselt number and convective heat transfer coefficient.

Keywords: engine oil, Fe_2O_3, heat transfer, nanofluid, plate heat exchanger, water.

The most important manufacturing operations in process industries are heating and cooling [1]. Glycols, engine oil, and water are mostly used as base fluids in heat transfer applications. To improve the heat transfer performance of these fluids, their thermal conductivity and heat transfer properties have to be enhanced [2]. Many research works are undergoing in this area by adding metal/metal oxide nanoparticles [3,4]. Recent advancement in energy reduction using nanofluid is noticed from a significant volume of research publications from the technical community. This nanofluid is also a new engineering fluid because of its unique application and capability for cost-cutting in heat transfer processes. Furthermore, researchers worked on developing nanoparticle-suspended heat transfer fluid in heat transfer equipment [5]. The following

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Paper received: 30 April, 2022
Paper revised: 22 November, 2022
Paper accepted: 23 November, 2022

https://doi.org/10.2298/CICEQ220430029S

section provides significant research performed with metal/ metal oxide and hybrid nanomaterials with different base fluids applied in heat exchangers.

To improve the thermal conductivity of heat transfer fluids, Choi *et al.* [6] proposed that adding small-size metals and metal oxide nanoparticles in a base fluid is a promising technique. The detailed review of challenges and applications of nanofluid in various sectors such as solar water heating, cooling of electronics, heat exchanging devices, engines, and cooling in machining, domestic refrigerator-freezers, diesel generators, chillers, and nuclear reactors were reported by Saidur *et al.* [7]. An experimental study in a heat exchanger with the addition of CuO nanoparticles in the water reported a notable enhancement in the heat transfer coefficient because of nanoparticle addition [8]. Furthermore, heat transfer studies with aluminum oxide/water nanofluid in a plate heat exchanger showed better heat transfer enhancement at a constant Reynolds number [9].

Mare *et al.* [10] prepared γ - Al_2O_3 and CNTs nanoparticles in a base fluid water and studied them in a plate heat exchanger. The study reports that the effect concerning the viscosity and pressure drop is significant at low pressure. Hence, this effect has to be considered while preparing nanofluid for heat transfer studies. The experimental study by Kwon *et al.* [11] in a plate heat exchanger showed a 30% increase in heat transfer coefficient at an Al_2O_3 nanoparticle concentration of 6 vol.%. Wang and Xu [12] used the steady-state parallel plate technique to measure the thermal conductivity with the Al_2O_3 and CuO nanoparticle suspension system in engine oil, vacuum pump fluid, distilled water, and ethylene glycol. The study concluded that the thermal conductivity of the nanoparticle-fluid mixtures increases significantly with nanoparticle addition, and more studies on heat transfer in the fluid flow are needed to extract its maximum benefit. The experimental thermal conductivity and heat transfer studies were done in a natural convection heat transfer apparatus [13,14] with a base fluid (ethylene glycol-water mixture). They observed a significant enhancement in heat transfer coefficient and thermal conductivity. The heat transfer effect of Al_2O_3 nanoparticles with volume fractions of 0.25 vol.%, 0.5 vol.%, 0.75 vol.%, and 1 vol.% was analyzed [15], and an increase in Nusselt number with respect to the Reynolds number and volume fraction was observed. Sarafraz *et al.* [16] used nanofluid consisting of biologically produced silver/coconut oil and assessed the effect on viscosity, thermal conductivity, and heat transfer coefficient in an annular heat exchanger and reported that this nanofluid could be applied as a lubricant as well as a coolant in engines due to the enhancement in thermal conductivity and viscosity of the base fluid. Many similar studies with the addition of nanoparticles in a base fluid were shown to enhance the overall heat transfer (e.g., the addition of copper [17], TiO_2 and ZnO [18], MgO-TiO_2, ZrO_2-CeO_2 [19,20], graphene [21,22] in a base fluid Ethylene Glycol-Water mixture). With Fe_2O_3/water -The ethylene glycol mixture nanofluid studies were conducted in shell and tube heat exchangers and reported [23] with significant increment in heat transfer coefficient and thermal conductivity with the particle volume fractions (0.02%–0.06%). The hybrid nanofluid containing Fe_2O_3 and MWCNT nanoparticles significantly enhance electrical and thermal conductivities [24]. Also, it proposes a correlation equation to determine the thermal conductivity of a hybrid nanofluid. To extract the application of nanofluid in the building sectors, Sarafraz *et al.* [25] used therminol 66 oil as a heat transfer fluid with iron oxide (III) nanoparticle to perform heat transfer behavior of the prepared nanofluid and found better enhancement in the thermal performance of the therminol 66 oil (by the nanoparticle addition and obtained 19% increase in heat transfer coefficient at 0.3 wt. % of nanosuspension. Studies in an oscillating heat pipe (OHP) with a magnetic field show an increased heat transfer coefficient with the heat flux of Fe_2O_3/kerosene nanofluid [26].

Studies with water-Fe_3O_4 nanofluid revealed that the thermal conductivity ratio increases proportionally with temperature and nanoparticle volume fraction [27]. The study showed a thermal conductivity enhancement of 48% (60°C and 2.0 vol.%) compared to the distilled water. Thermal performance of magnetite (Fe_3O_4) nanofluid in ethylene glycol (EG) and water (W) mixture shows 33%, 42%, and 46% thermal conductivity enhancements for 60:40% EG/W, 40:60% EG/W, and 20:80% EG/W based nanofluid, respectively [28]. Fe_3O_4 nanoparticles in paraffin show a 20% enhancement in thermal conductivity with the nanoparticle addition of 0.1 vol.% [29]. Kerosene-based Fe_3O_4 magnetic nanofluid showed a 34% thermal conductivity enhancement with a 1 vol% of nanoparticles [30].

A study on a shell and tube heat exchanger by the Fe_2O_3/EG and Fe_2O_3/water nanofluids reports an increase in the base fluid's thermal conductivity with the hot fluid's temperature [31]. A compact air-cooled heat exchanger with water-based iron oxide nanofluid under laminar flow conditions reports a 13% and 11.5% increase in the overall heat transfer coefficient and rate of heat transfer, respectively, at the concentration of 0.65 vol. % [32]. Studies on thermal conductivity analysis for the nanofluid consisting of Fe_2O_3/Al_2O_3 nanoparticle suspension in engine oil reported that even a small amount of nanoparticle addition improved the thermal properties of the nano-lubricant and concluded a 33% improvement of the heat transfer coefficient at a mass fraction of 4% [33]. Mixing engine oil with different nanoparticles, such as diamond, copper oxide, and titanium oxide (TiO_2), showed that the nanoparticle addition to oil significantly contributes to the reduction of abrasion and friction and improves oil properties [34].

From the beginning of the nanofluid applications in different sectors, many works explored these novel fluids' distinctive properties and capabilities. Iron oxide (Fe_2O_3) is a non-toxic and cost-effective nanomaterial with good thermophysical and heat transfer properties. Many researchers on this topic are focusing only on thermal conductivity studies. However, it will be possible to explore its heat transfer properties in real-time heat exchangers. Nanofluid offers many advantages. However, certain disadvantages are found in real applications, such as fouling, surface erosion, and instability. Engine oil offers a solution to reduce fouling. Literature also supports that miniature plate heat exchangers are efficient with better performance for nanofluids. Hence, a compact plate heat exchanger was used in our study. Also, to the best of the author's knowledge, the heat transfer performance of a nanofluid mixture of Fe_2O_3-W-EO has not been investigated in a plate heat Exchanger in the literature. In this work, experiments were conducted in a plate-type compact heat exchanger by mixing homogenized Fe_2O_3 nanoparticles in a base fluid of two different mixed base fluids, a W-EO mixture of volume fractions (5%EO + 95%W) and (10%EO +90%W).

MATERIALS AND METHODS

Preparation of Fe_2O_3-water-engine oil nanofluid

In this study, the Fe_2O_3 nanoparticles were suspended in a W-EO mixture with a two steps (sol-gel) method with a Fe_2O_3 nanoparticle size of 45 nm. Two types of mixed base fluids with volume fractions (5%EO + 95%W) and (10%EO +90%W were prepared by the amount calculated by Eq. (1).

$$\varphi = \frac{(m/\rho)_{Fe_2O_3}}{(m/\rho)_{Fe_2O_3} + (m/\rho)_{W:EO}} \qquad (1)$$

To assure the stability of the prepared nanofluid, a high-pressure homogenizer was applied, and the prepared nanofluid was used in the plate heat exchanger as cold fluid. The SEM image of the Fe_2O_3 nanoparticle and the preparation method are shown in Figures 1 and 2, respectively. The prepared nanofluid was homogeneously suspended throughout the base fluid because of the high-pressure homogenizer.

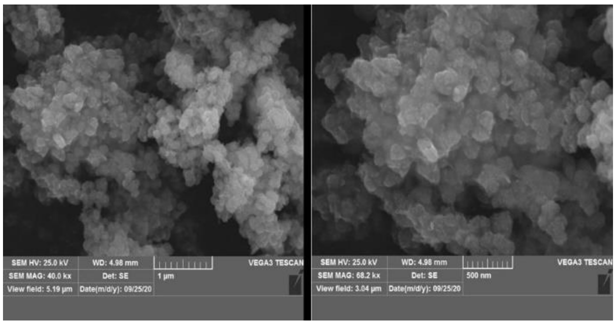

Figure 1. SEM image of Fe_2O_3 nanoparticle.

Figure 2. Preparation of the Fe_2O_3-W-EO nanofluid.

Experimental set-up

Studies were conducted in a plate-type heat exchanger, where the hot and cold fluids flow in a counter-current pattern. Figure 3 presents the experimental set up with a plate heat exchanger and two containers (for cold and hot side fluid), a temperature controller, flow meters for flow measurement and control, and two fluid pumps. The plate heat exchanger consists of 13 stainless steel corrugated plates (Alfa Laval, India), providing seven and six flow channels for the hot and cold fluids, respectively. The plate length and thickness are 0.154 m and 0.25 mm, respectively.

Figure 3. Photographic view of the experimental set-up.

First, the cold fluid (Fe_2O_3-W-EO) was pumped to the heat exchanger through a rotameter and returned to the cold fluid reservoir. Next, the hot fluid (water) passed counter-currently through a control valve and entered the heat exchanger. The flow rate readings were measured and controlled by the flow meter. Finally, the hot and cold fluid's inlet and outlet temperature readings were altered with four K-type thermocouples inserted with the heat exchanger.

Determination of thermophysical properties of Fe_2O_3-W-EO nanofluid

Thermal conductivity was measured using a thermal conductivity analyzer (Scientico, India), and viscosity was measured with a redwood viscometer for all the concentrations of the Fe_2O_3-W-EO nanofluid, as shown in Figure 4.

Figure 4. Measurement of thermal conductivity and viscosity of the Fe_2O_3-W-EO nanofluid.

The density and specific heat capacity of the nanofluid were calculated by Eqs. (2) and (3) [26,27]:

$$\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_p \quad , \tag{2}$$

$$Cpnf = ((1-\varphi)\rho_f C_{pf} + \varphi\rho_p C_{pp}) / (\rho_{nf}) \tag{3}$$

The obtained results of the thermophysical properties were used for calculating different dimensionless numbers (Reynolds, Prandtl, and Nusselt numbers) applied in this study.

Determination of Nusselt number and heat transfer coefficient of Fe_2O_3-water-engine oil nanofluid

Eqs. (4) and (59 were used to determine the Nusselt number [21] (Kim model) and the heat transfer coefficient of the nanofluid:

$$Nu = 0.295(N\mathrm{Re})^{0.64}(N\mathrm{Pr})^{0.32}\left(\left(\frac{\Pi}{2}-\beta\right)\right) \tag{4}$$

$$h = \frac{NuD_H}{K} \tag{5}$$

RESULTS AND DISCUSSION

To assess the heat transfer characteristics of Fe_2O_3 nanoparticle addition in the base W-EO fluid, the convective heat transfer coefficient (*h*) and dimensionless numbers, such as Reynolds, Prandtl, and Nusselt numbers, were calculated at different nanoparticle volume fractions (from 0.3% to 1.5%) and hot fluid temperatures (from 55 °C to 75 °C) for the EO-W base fluid volume fractions of (5:95 and 10:90).

Impact of Fe_2O_3 nanoparticle addition on Reynolds and Prandtl number for base fluid of (5 % EO + 95%W) at various hot fluid inlet temperatures

The Reynolds number is the inertia and viscous force ratio, while the Prandtl number provides a relation between a flowing fluid's momentum and thermal transport. Figure 5 shows the effects of Fe_2O_3 nanoparticle volume fraction on the Reynolds and Prandtl numbers.

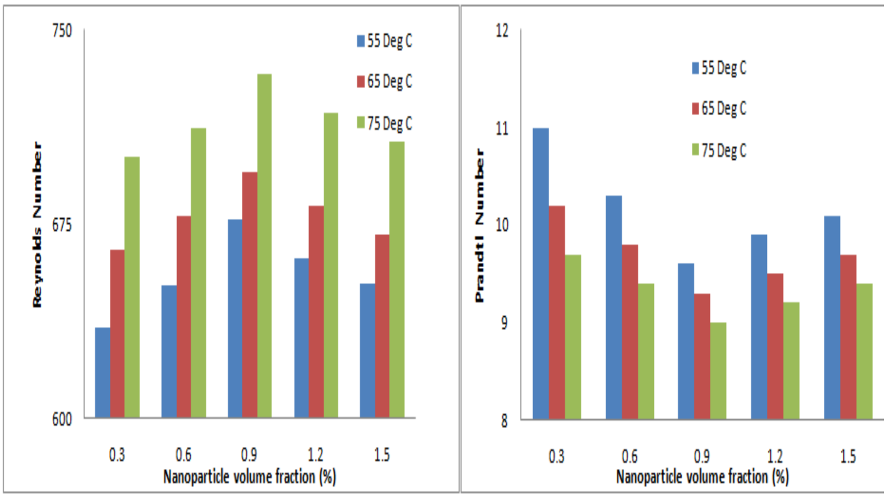

Figure 5. Effect of Fe_2O_3 nanoparticle volume fraction on the Reynolds and Prandtl numbers for a base fluid (5 % EO + 95%W) at various hot fluid inlet temperatures.

Figure 5 shows that the Reynolds number increases moderately with adding the nanoparticles. However, at a lower temperature, there is a significant increment in the Reynolds number because of the incremental effect in density concerning the viscosity of a nanofluid. Because of the Reynolds number increment and thermal capacity, the heat transfer rate increases significantly. Due to the incremental effect on the thermal conductivity of nanofluids, heat transport dominates over momentum transport. Hence, the Prandtl number decreases at all the volume fractions of nanofluid (Figure.5).

Impact of Fe_2O_3 nanoparticle addition on Nusselt number and heat transfer coefficient for a base fluid of (5 % EO + 95%W) at various hot fluid inlet temperatures

The Nusselt number and convective heat transfer coefficient were calculated to assess the heat transfer characteristics of the prepared nanofluid. Experimental results of Nusselt number and heat transfer coefficient was presented in Figure 6 by observing the impact on different hot fluid inlet temperature (55 °C, 65 °C, and 75 °C) and nanoparticle volume fraction (0.3–1.5%) of a base fluid volume fraction of 5:95.

Based on the experimental results at the hot fluid inlet temperature of 55° C, the Nussult number and convective heat transfer coefficient increase with the nanoparticle volume fraction. However, the optimum enhancement was obtained at the nanoparticle volume fraction of 0.9%. After this concentration, the enhancement decreases due to the decrease in fluid thermal boundary layer thickness (viscosity decreases near the wall). Concerning the convective heat transfer coefficient, a similar pattern (heat transfer increases with nanoparticle volume fraction) was observed since, at the higher nanoparticle concentration, the thermal conductivity and Brownian motion play a significant role in enhancing the rate of heat transfer. It is also confirmed from Figure 6 that the Nusselt number enhancement is directly proportional to nanoparticle concentration and hot fluid temperature; however, the maximum enhancement was noted at 0.9 volume% of nanoparticle volume fraction.

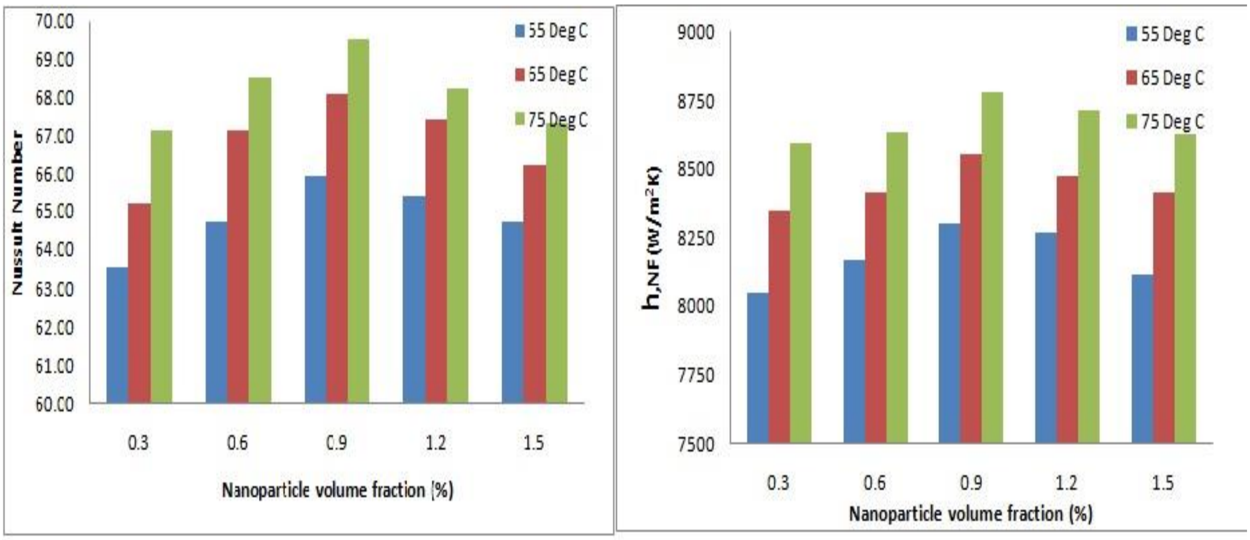

Figure 6. Effect of Fe_2O_3 nanoparticle volume fraction on the Nusselt number and the heat transfer coefficient for a base fluid (5 % EO + 95%W) at various hot fluid inlet temperatures.

Impact of Fe_2O_3 nanoparticle addition on Reynolds number and Prandtl number for a base fluid of (10 % EO + 90%W) at various hot fluid inlet temperatures

Figure 7 presents the effect of Fe_2O_3 nanoparticle addition on the Reynolds and Prandtl numbers for a base fluid of (10% EO + 90% W) for changes in the inlet temperature of the hot fluid.

Figure 7 shows a similar impact, i.e., the addition of nanoparticles increases the Reynolds number and observes the maximum Reynolds number of 647 for the nanoparticle concentration of 0.9 (volume%) and hot fluid temperatures. Figure 7 also depicts the variations in the Prandtl number under the same operating conditions. Again, it can be seen that the Prandtl number decreases with an enhancement of the nanoparticle volume fractions, and the maximum decrease was observed at 0.9 (volume%) with a value of 10.2, 9.8, and 9.4. This effect on the Reynolds and Prandtl numbers can be related to the effect on the density and viscosity of the nanofluid compared with the base fluid (W-EO).

Impact of Fe_2O_3 nanoparticle addition on Nusselt number and heat transfer coefficient for a base fluid of (10 % EO + 90%W) at various hot fluid inlet temperatures

Figure 8 plots the changes in Nusselt number and heat transfer coefficient for the base fluid ratio of 5:95%

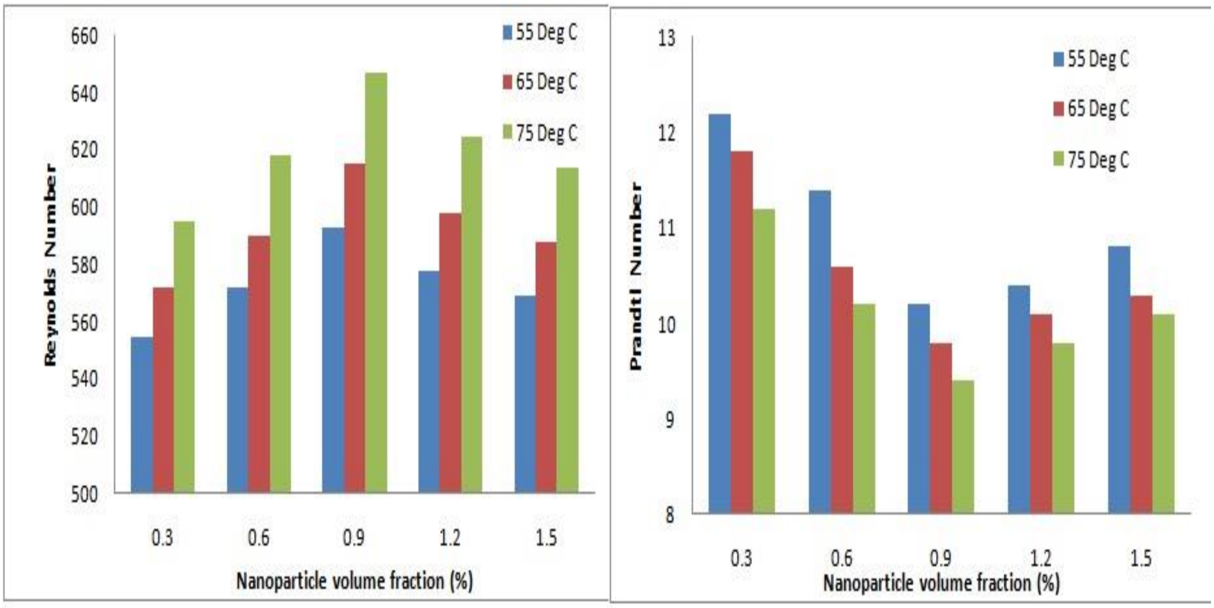

Figure 7. Effect of Fe_2O_3 nanoparticle volume fraction on the Reynolds and Prandtl numbers for a base fluid (10 % EO + 90%W) at various hot fluid inlet temperatures.

and 10:90% (EO: W) to show the impact of the nanoparticle addition of 0.3 vol.% to 1.5 vol.% at different hot fluid inlet temperatures. Increasing the nanoparticle volume fraction in all samples augments the Nusselt number and the heat transfer coefficient. These changes are linear at all the temperatures, however different ranges based on the temperature inlets. This Nusselt number improvement is due to the rate of increase of heat transfer by the Fe_2O_3 nanoparticle addition, which not only improves the thermal conductivity of the base fluid but also incurs a thermal dispersion in the flow, a novel way of improving heat transfer processes. At a low nanoparticle volume fraction of (0.3%), as can be seen in Figure 7, the enhancement of the Nusselt number is low, and it increases slowly with increasing the nanoparticle volume fraction up to 0.9 vol.%; after that, the enhancement decreases, and the optimum enhancement is observed at the 0.9 vol.% Fe_2O_3 nanoparticle volume fraction. Figure 8 also shows that up to 0.9 vol.% of nanoparticles, the heat transfer coefficient increment was high; after that, it slowly decreases, and the heat transfer coefficient values are 7325 W/m^{2}K at 55 °C and 7975 W/m^{2}K at 75 °C.

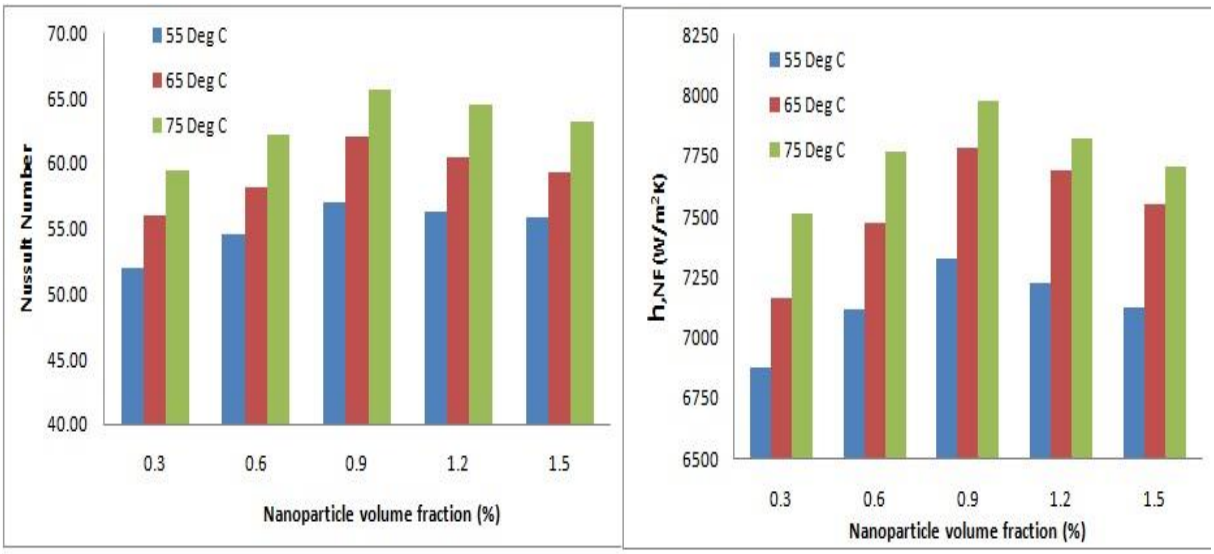

Figure 8. Effect of Fe_2O_3 nanoparticle volume fraction on the Nusselt number and the heat transfer coefficient for a base fluid (10 % EO + 90%W) at various hot fluid inlet temperatures.

CONCLUSION

A high-pressure homogenizer was used for the nanofluid preparation in the form of a uniform suspension throughout the study. The study shows that the heat transfer coefficient and Nusselt number of the W-EO mixture increase significantly by adding Fe_2O_3 nanoparticles. This addition not only improves the thermal conductivity of the base fluid but also incurs a thermal dispersion in the flow, which is a novel way of improving heat transfer processes. The results indicate that the Reynolds number increases moderately while the Prandtl number decreases proportionately at all the nanoparticle concentrations. However, the nanoparticle volume fraction significantly affects the Reynolds and Prandtl numbers at lower temperatures. For a given set of operating parameters, an optimum enhancement in heat transfer coefficient was observed at 0.9 vol.% of Fe_2O_3 nanoparticle for both base fluid fractions. The study reveals that heat transfer enhancement is high at all nanofluid concentrations at a higher hot fluid temperature (75 °C). Because of the heat transfer properties improvement, the Fe_2O_3-W-EO can be used as an alternate fluid in engines and other heat transfer applications.

It is suggested to study the heat transfer performance of the heat exchanger by considering the effect of experimental time on the results since the nanofluid properties are affected by the running time in the system (mainly stability). Furthermore, further heat transfer studies may be performed by combining different metal/metal oxide nanoparticle suspensions with different base fluids. In the future, studies with hybrid nanofluid (mixing different nanoparticles in the base fluid) can be explored and scaled up for industrial heat exchangers.

ACKNOWLEDGEMENT

The authors are grateful for the financial contribution of the Students Project Grand by TNSCST and SEED Grand provided by the management of the Kongu Engineering College and Department of Chemical Engineering for the facility.

NOMENCLATURE

W	Water
EO	Engine oil
D_H	Hydraulic diameter, m
ΔT_{LMTD}	Logarithmic mean temperature difference
ø	Nanoparticle volume fraction, dimensionless
m	Mass, kg
U	Overall heat transfer coefficient, W/m^2 K
N_{Nu}	Nusselt number, dimensionless
N_{Pr}	Prandtl Number, dimensionless
N_{Re}	Reynolds number, dimensionless
V	Volumetric flow rate, liter/min
N	Number of channels, dimensionless
b	Plate depth, m
Cp	Specific heat capacity, J/(kg K)
Lw	Plate width, m
PHE	Plate heat exchanger
Pr	Prandtl number, dimensionless
h	Heat transfer coefficient, W/m^2 K
vol. %	Volume %
Greek symbols	
β	corrugation angle, °
ρ	density, kg/m^3
µ	dynamic viscosity, Pa s
ø	nanoparticle volume fraction, dimensionless
k	thermal conductivity, W/(m K)
Subscripts	
$T_{b,c}$	cold fluid bulk temperature
T_h	temperature of hot fluid, °C
T_c	temperature of cold fluid, °C
H	hot fluid
C	cold fluid
in	inlet
out	outlet
nf	nanofluid
f	base fluid
p	Particle

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NAUČNI RAD

ISTRAŽIVANJA PRENOSA TOPLOTE U PLOČASTOM RAZMJENJUĆU TOPLOTE KORISTEĆI NANOFLUID FE_2O_3-VODA-MOTORNO ULJE

Poboljšanje performansi prenosa toplote konvencionalnog fluida stvara značajne uštede energije u procesnim industrijama. Sa ovog aspekta, sprovedena je eksperimentalna studija za procenu performansi prenosa toplote nanofluida Fe_2O_3-voda-motorno ulje pri različitim koncentracijama i ulaznim temperaturama toplijeg fluida u pločasti razmenjivač toplote. Eksperimenti su sprovedeni mešanjem nanočestica Fe_2O_3 (45 nm) u baznom fluidu mešavine voda-motorno sa zapreminskim udelom od 5% motornog ulja + 95% vode i 10% motornog ulja +90% vode. Glavni cilj ove studije bio je da se procene uticaji zapreminskog udela nanočestica i varijacija temperature na ulazu toplijeg fluida na performanse prenosa toplote pripremljenog nanofluida. Na osnovu eksperimentalnih rezultata određeni su koeficijent konvektivnog prolaza toplote, Rejnoldsov, Prandtlov i Nuseltov broj. Rezultat pokazuje da su pri ulaznoj temperaturi toplijeg fluida od 75 °C, optimalno povećanje Nuseltovog broja i koeficijenta konvektivnog prenosa toplote pri 0,9 vol.% nanočestica za obe smeše baznih tečnosti. Povećanje koeficijenta prenosa toplote je zbog efekta Braunovog kretanja (povećanje toplotne provodljivosti), kretanja izazvanog temperaturnim gradijentom (termoforetski) i kretanja usled gradijenta koncentracije (osmoforetski). Ako se zapreminski udeo nanočestice poveća, onda je porast Rejnoldsovog broja veći od promene Prandtlovog broja, što povećava Nuseltov broj i koeficijent konvektivnog prenosa toplote.

Ključne reči: motorno ulje, Fe_2O_3, prenos toplote, nanofluid, pločasti razmenjivač toplote, voda.