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Heat transfer and fluid flow of MgO/ethylene glycol in a corrugated heat exchanger [†]

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Abstract

The present work aims to investigate the thermo-hydraulic performance of a counter-current corrugated plate heat exchanger working with MgO/ethylene glycol nanofluid. MgO nanoparticles were dispersed in ethylene glycol at different weight (mass) concentrations of 0.1 %, 0.2 % and 0.3 % and nanofluids were introduced to a heat exchanger in form of a counter-current flow to exchange heat with water. The test rig provided conditions to measure the influence of different operating parameters such as fluid flow, mass concentration and inlet temperature of the nanofluid on heat transfer coefficient, pressure drop, and thermal performance index of the heat exchanger. Results showed that flow rate and mass concentration can intensify the convective heat transfer coefficient. However, they both increase the pressure drop of the system. The heat transfer coefficient, pressure drop was found to be enhanced by 35 % and 85 %, respectively at wt.% = 0.3. Interestingly, inlet temperature was found to only increase the heat transfer coefficient slightly (up to 9.8 % at wt.% = 0.3) and had no influence on the values of pressure drop. The presence of MgO nanoparticles was found to increase the thermo-hydraulic performance index of the heat exchanger by 34 %.

Keywords: Plate heat exchanger; Heat transfer coefficient; Pressure drop; Nanofluid; Thermo-hydraulic performance

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1. Introduction

Heat exchangers are useful heat exchanging tools providing a large heat transfer transport in a small space. Heat exchangers play a significant role in the operation of many systems such as power plants, industrial processes and heat recovery units [1, 2]. Design and development of heat exchangers, their efficiency and maintainability have always been a concern for heat transfer experts since these parameters directly influences the thermal performance of the systems. Depending on the energy demand, space available and type of the coolant, different types of heat exchangers can be used. Despite the plausible application of heat exchangers, they are limited to the thermo-physical properties of coolant used in the heat exchanger and also the operating temperature of the system. Thereby, much effort has been made to enhance the thermo-hydraulic performance of the heat exchangers using advanced engineering coolants [3-6].

Nanofluids are new generation of coolants with wide applications in the industrial and non-industrial applications [7-19]. A nanofluid is comprising of a 0-100 nm solid nanoparticles dispersed in a conventional coolant such as water. It has already been shown that the presence of the nanoparticles enhances the thermo-physical features of the base fluid including thermal conductivity, density and viscosity of nanofluid [20-23]. Hence, recent researches are directed to assess the thermal performance of single-phase and two-phase flow systems [8, 9, 12, 14, 15, 24-28]. For example, in a study conducted by Raja et al. [29], maximization of overall heat transfer coefficient (HTC) and minimization of the total pressure drop were investigated using multi-objective optimization. They considered eight different geometric designs to analyze the pressure drop and heat transfer coefficient. The results showed that 8.87 % deviation in overall heat transfer coefficient and 9.96 % deviation in total pressure drop are observed between optimization and experimental results. In another study conducted by Huang et al. [30], heat transfer characteristics together with pressure drop was assessed for a nanofluid, which consists of two different nanoparticles namely carbon nanotube and alumina. The experiments were conducted in a plate heat exchanger and it was found that the HTC for the nanofluid with two different nanoparticles was higher than that of measured for the alumina or carbon nanotube nanofluid. Smaller pressure drop was also recorded for nanofluid with two different nanoparticles. Tiwari et al. [31] conducted a set of experiments to assess a corrugated plate heat exchanger heat transfer characteristics using cesium nanofluid. They optimized the concentration of nanoparticles in order to achieve the highest enhancement in HTC. The optimized con-

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centration of nanoparticles was 0.75 vol.% for which enhancement by 39 % was achieved. They also demonstrated that the enhancement in heat transfer coefficient occurs for the case in which the temperature of nanofluid decreased. Kabeel et al. [32] implemented an experimental loop to assess the HTC and pressure drop for a heat exchanger with corrugated surface. A sensitivity analysis was performed on the volumetric concentration of nanofluid and it was found that the HTC and also the pumping power increases with an increase in the concentration of particles. An enhancement of 13 % was registered for the HTC at vol.% = 4. However, the physical mechanism for the enhancement was not revealed and the enhancement was not justified. In another study conducted by Nema [33], fluid flow and hydraulic parameters were experimentally investigated in a plate heat exchanger working with alumina nanofluid. They demonstrated that HTC is a strong function of Reynolds and Peclet numbers. Importantly, it was revealed that alumina nanoparticles can improve the rate of heat transfer in the heat exchanger. However, this enhancement is in line with an increase in pumping power of the system. Sarafraz et al. [14] conducted some tests to explore the potential application of CuO nanoparticles in a heat exchanger. They also investigated the formation of particulate fouling in the heat exchanger. Results indicated that although nanoparticle increase the HTC, they also form a scale layer inside the heat exchanger. They proposed the low-frequency vibration to remove the fouling layer and also to intensify the heat transfer within the heat exchanger. Likewise, overall thermal performance of the system is intensified in comparison with pure liquids [34-36] and when vibration is continuously applied into the heat exchanger. Abed et al. [37] studied the transport phenomena and heat transfer of nanofluids in a heat exchanger. They assessed the effects of four different nanofluids including alumina, CuO, silica, and ZnO, for various fraction of nanoparticles. Influence of different geometrical factors of the heat exchanger on HTC was examined. They demonstrated that silica nanofluid represents the largest Nusselt number in comparison with other nanofluids. Likewise, enhancement of HTC increased with an increase in the concentration of nanoparticles. However, small penalty was reported for the pressure drop due to the presence of particles. The HTC was enhanced by 35 % in comparison with water. Barzegarian et al. [38] examined the potential influence of titana-water nanosuspension on HTC and pressure drop in a heat exchanger. Titana nanoparticles were utilized for preparing nanofluids at various mass fractions of 0.3, 0.8 and 1.5 %. they reported that the HTC was enhanced by 6.6 %, 13.5 % and 23.7 % for nanoparticle fractions of 0.3 %, 0.8 % and 1.5 %, respectively. Faced with the above-reviewed literature, extensive researches have been performed to experimentally assess the plausible application of nanofluid in heat exchangers. However, still there is a question that "does a nanofluid increase the thermal performance of a plate heat exchanger?". Thereby, this is a driver for further research on the potential application of nanofluid. In the present work, MgO nanoparticles are targeted as they have plausible thermo-physical properties such as high thermal conductivity, density and viscosity of nanofluid. Using the fabricated test rig, influence of various operating parameters such as rate of fluid flow, inlet temperature to the test rig, and weight (mass) fraction of nanofluid on the HTC, value of pressure drop, and performance index of the heat exchanger.

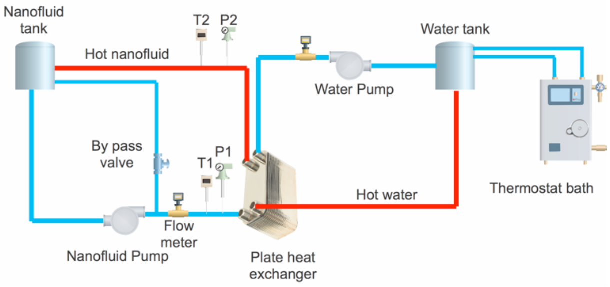


Fig. 1. A schematic diagram of the experimental setup implemented in the present work.

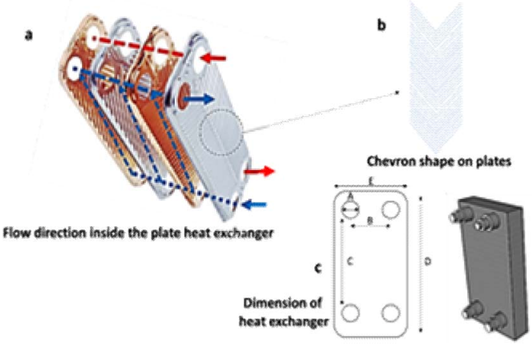


Fig. 2. Detailed specification of the internal plates of the heat exchanger.

2. Experimental

2.1 Test rig

Fig. 1 shows the test rig utilized in the present research. It consists of three main units including pumping and circulation loops, test section and measurement instruments. The circulation loops consist of a hot and a cold loop for nanofluid and water, respectively. Two tanks were employed to keep the nanofluid and water In them. Both tanks were heavily isolated. Two centrifugal pumps manufactured by DAB Company were used to pump the water and nanofluid to the heat exchanger. Temperature and pressure of each loop was measured with two RTDs thermo-meters and two pressure transmitters (both manufactured by OMEGA Company with accuracy of 1 % of reading) just before the test section and after it. The flow rate of each loop was controlled using an ultrasonic flowmeter (manufactured by Flownetix with accuracy of 0.1 % of reading). The heart of the test rig was a plate heat exchanger made by Danfus Company. Experiments were conducted three times to ensure about the repeatability and reproducibility of the data.

Table 1. Detailed specification of plates in heat exchanger.

Parameters	Value	Unit
Size	A:11.5 B:70 C:380 D:500 E:130	mm
Plate length	400	mm
Plate width	125	mm
Depth of plate	5	mm
No. of plates	36	-
Offered heat transfer area, heat transfer area/no of plates	2.9, 0.08	m^2
Fabrication	Copper-made	-
Corrugation pitch	5	mm
Corrugation angle	45	Degree

The cooling loop temperature was set at 20 °C and 1 lit/min. three times distilled water was used in the cooling cycle. All the pipes, joints, valves and sensors for hot and cooling loops were heavily insulated using glass wool to prevent from any heat loss to environment. Detailed specifications of the heat exchanger have been presented in Table 1.

2.2 Data reduction and uncertainty

To calculate the HTC for the hot loop following equation was used:

$$Q^{hot}{}_{nf} = m_{nf}.C_{p,nf}(T_{in,nf} - T_{out,nf}) . \tag{1}$$

Similar equation was used for the cold loop:

$$Q^{cold}{}_{w} = m_{w}.C_{p,w}(T_{in,w} - T_{out,w}) . \tag{2}$$

Here, Q_{nf} is the rate of heat transfer in the hot loop, m_{nf} is mass flow rate of nanofluid. Q_w is the rate of heat transfer in the cold loop, m_w is the mass flow rate in the cold loop. The mean rate of heat transfer within the heat exchanger is calculated using the following equation:

$$Q_{ave.} = \frac{Q^{hot}{}_{nf} + Q^{cold}{}_{w}}{2} . \tag{3}$$

Here, Q_{awe} is the mean heat transfer rate between the heating and cooling loops. The HTC, U, was calculated using following equation:

$$U = \frac{Q_{ave}}{A.\Delta T_{LMTD}} . \tag{4}$$

Here, ΔT_{LMTD} is referred to as log mean temperature difference, computing as follows:

$$\Delta T_{LMTD} = \frac{(T_{out,nf} - T_{in,w}) - (T_{in,nf} - T_{out,w})}{\ln(\frac{(T_{out,nf} - T_{in,w})}{(T_{in,nf} - T_{out,w})}} . \tag{5}$$

The hydraulic diameter of heat exchanger was calculated with Eq. (6) with the consideration of plate depth = 4 mm and surface enhancement coefficient = ~ 1.19:

$$D_{hydrualic} = \frac{2 \times \text{Plate depth}}{\text{Surface enhancement parameter}} \tag{6}$$

three main dimensionless numbers utilized in the present research were Nusselt and Reynolds and Prantdl numbers that can be calculated using following equations:

$$Nu = \frac{h_{nf}.D_{hydrualic}}{k_{nf}} \tag{7}$$

$$\mathrm{Re}_{nf} = \frac{\rho_{nf}.u_{nf}.D_{hydrualic}}{\mu_{nf}} \tag{8}$$

$$\mathrm{Pr} = \frac{C_{p,nf}.\mu_{nf}}{k_{nf}} . \tag{9}$$

It is worth saying that the HTC was calculated separately for cold and hot loops. To estimate the HTC for the cold loop, the correlation introduced by Huang et al. [4] was utilized:

$$\frac{h_w.D_{hydrualic}}{k_w} = 0.2302\,\mathrm{Re}^{0.745}\cdot \mathrm{Pr}^{0.4} . \tag{10}$$

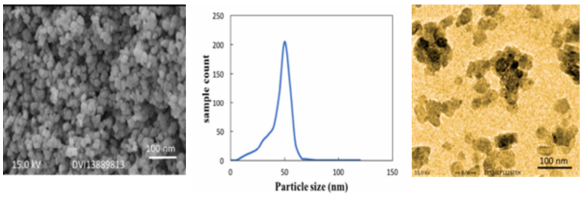
Also, for calculating the HTC in hot loop, following equation was implemented:

$$\frac{1}{U} = \frac{1}{h_{nf}} + \frac{\delta}{k_{copper}} + \frac{1}{h_w} . \tag{11}$$

Here, δ is plate thickness, k is the copper thermal conductivity as heat exchanger is copper-made, h_{nf} and h_w are convective HTC of MgO/water nano-fluid and cold water, respectively. A simple energy balance on heat loss showed that system has 9.5 % of heat loss to the environment. The energy balance equation has been represented in Eq. (12):

$$Q_{nf} = Q_w + Q_{heat\,loss} . \tag{12}$$

Here, Q_{nf} and Q_w are obtained with Eqs. (1) and (2). Importantly, reproducibility of tests was ensured with three times running the experiments, which revealed a 5.8 % deviation for three times data recording, which is reasonable. To check the uncertainty of the experiments, Kline-McKlintock [39] equation was applied and the uncertainty for the HTC was 9.8 %, and for the pressure drop it was 4.5 %. The tests were performed at three different flow rates, three different mass con-



(a) (b) (c)

Fig. 3. Characterization of nanoparticles used in the present research.

centrations, and two different inlet temperatures, which were sufficient for the sensitivity analysis.

2.3 Nanofluid preparation and characterization

To prepare nanofluids, MgO nanoparticles were purchased from USNANO and was used as purchased. Nanoparticles were uniformly distributed within the ethylene glycol using following procedure: (1) Desired weight of MgO nanoparticles were dispersed in desired weight of ethylene glycol. Then, nonyl phenol ethoxilate at 0.1 % of general volume of nanofluid was added to the base fluid to enhance the stability of nanofluid. Ultrasonic at 40 kHz and 400 W for 15 minutes was used to homogenize the nanoparticles' dispersion within the base fluid. Nanofluids were prepared at wt.% = 0.1, 0.2 and 0.3 % by weight. MgO nanoparticles were sent for scanning electron microscopy to analyze the morphology and particle size of the nanoparticle. Fig. 3(a) shows the morphology and size of the nanoparticles. As can be seen, particles are identical in terms of size and morphology. The morphology is spherical and nanoparticles are uniform in terms of size. To confirm the size of nanoparticle, the particle size count test was performed using digital scattering light device as represented in Fig. 3(b). As can be seen, the main size of the nanoparticles is 50 nm, which is in accordance with the results obtained with the scanning electron microscopic image. Fig. 3(c) shows the transmission electron microscopic image for the dispersion of nanoparticles in oil. As can be seen, the nanofluids are uniform and there is no agglomeration within the base fluid confirming the suitability of the technique used for the nanofluid preparation.

3. Results and discussion

3.1 Flow rate

Fig. 4 shows the variation of HTC with Reynolds number for various mass fractions of nanofluids and also the base fluid at inlet temperature = 50 °C. As can be seen, with increasing the flow rate of nanofluid, the HTC increases. For example, at Re = 1500 and wt.% = 0.1, the heat transfer coefficient is 1560 W/m^2. K, while it is 8970 W/m^2. K at Re = 6000. This is because at higher flow rates, more local agitations occur and free mean path of particles increases resulting in better heat transport within the base fluid. Interestingly, with an increase in the mass concentration of nanofluid, the heat transfer coefficient increases, which is discussed in the following section.

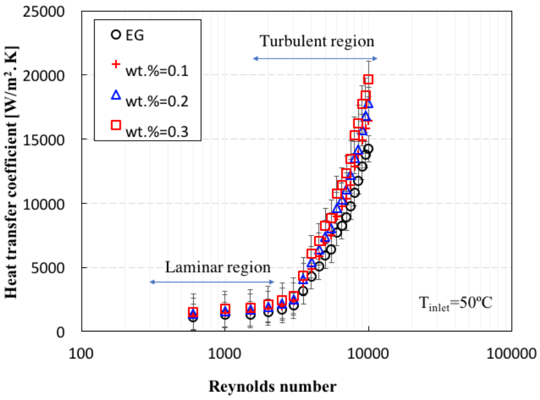


Fig. 4. Variation of HTC with nanofluid flow rate at 50 °C. Error bars show ±10 % of standard errors.

3.2 Mass concentration

In the present research, it was found that an increase in mass concentration of MgO nanoparticles increases the HTC of nanofluid. For example, for a given Reynolds number such as ~4000, at wt.% = 0.1, the HTC is 4890 W/m^2. K, while it is 9620 W/m^2. K at wt.% = 0.2 and 10790 W/m^2. K at wt.% = 0.3. This is largely due to the presence of nanoparticles within the base fluid, which not only increases the Brownian motion inside the base fluid, but also enhances the thermal conductivity of base fluid. Importantly, presence of nanoparticles results in the intensification of thermophoresis phenomena. In thermophoresis, particles migrate from a cold side and hot walls to the hot side and cold walls and also due to the creation of a micro-stream and micro-convection streams, local agitation of fluid occurs leading to the enhancement of the heat transfer coefficient. Notably, nanoparticles are energy carrier in the base fluid. They absorb thermal energy and transport it to another location using Brownian motion and bulk movement of the base fluid. The higher the Brownian motion is, the higher heat transfer can be achieved.

3.3 Inlet temperature

Fig. 5 shows the variation of HTC on fluid flow rate (Reynolds number) for two inlet temperatures of nanofluid. As can be seen, the trend shown in Fig. 4 is seen again for different inlet temperature. Interestingly, with an increase in the inlet temperature of nanofluid, the heat transfer coefficient increases. However, the influence of flow rate on the HTC is significantly larger than that of observed for the inlet temperature. Importantly, an increase in temperature of nanofluid results in the enhancement in thermo-physical properties of nanofluid such as thermal conductivity, viscosity and density. The average enhancement in heat transfer coefficient for laminar and turbulent regions at 40 °C were 4.8 % and 9.6 %, respectively. Likewise, the augmentation in HTC was 5.1 %

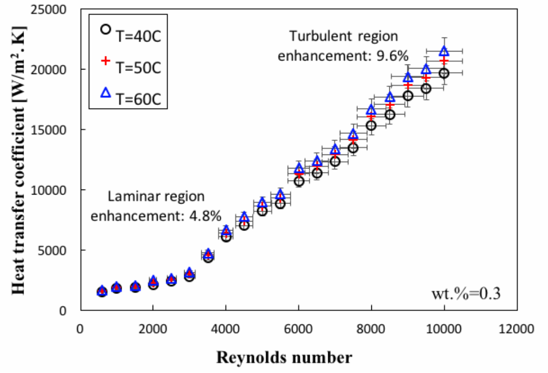


Fig. 5. Variation of HTC with the Reynolds number at various inlet temperatures of nanofluid at wt.% = 0.2. Error bars show ±10 % of standard errors.

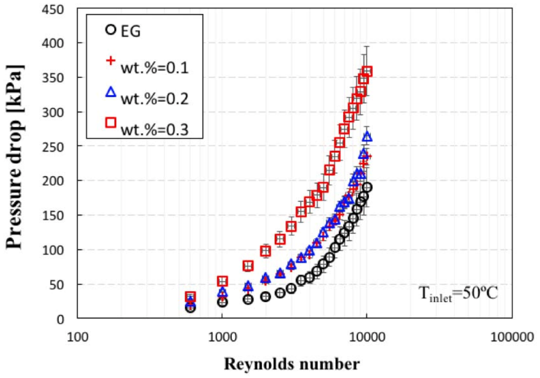


Fig. 6. Dependence of pressure drop on Reynolds number for various nanofluids and the base fluid. Error bars show ±10 % of standard errors.

and 9.8 % for inlet temperatures of 50 °C and 60 °C, respectively. Noticeably, for other mass concentrations of nanofluid, the same trend was seen.

3.4 Pressure drop

Fig. 6 shows the change of pressure drop with nanofluid flow rate for various mass fractions of nanofluid and the also the base fluid. As can be seen, increasing the Reynolds number results in the enhancement in the values of pressure drop. Importantly, the change in the values of the pressure drop with Reynolds number is almost linear and at higher Reynolds number values, higher pressure drops were recorded. Results also showed that with an increase in mass concentration of nanofluids, the value for the pressure drop increases. For example, for wt.% = 0.1, at Re = 3500, pressure drop is 89 kPa, while it is 235 kPa at Re = 10200. In fact, presence of nanoparticles results in the increase in viscosity of nanofluid. As pressure drop in tubes and pipe is a direct function of viscosity, thereby, an increase in the viscosity of nanofluid enhances the values for the pressure drop. The maximum enhancement of ~89 % for pressure drop was registered at wt.% = 0.3. Noticeably, the pressure drop registered for the nanofluids, regardless of the mass concentration of nanofluid, was higher than that of registered for the base fluid.

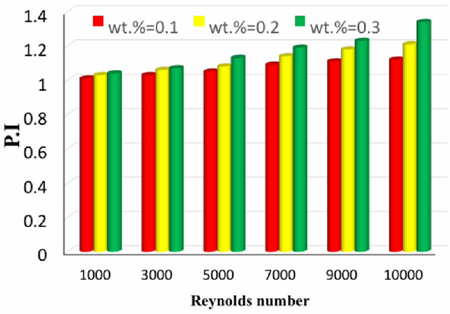


Fig. 7. Dependence of performance index on mass concentration and flow rate of nanofluid.

Noticeably, an increase in the temperature of nanofluid had no influence on the pressure drop. For example, at wt.% = 0.3, at T = 50 °C and Re = 1000, the pressure drop value was 50 kPa, while for the same conditions and at T = 70 °C, the same value of pressure drop was measured. This is because the influence of temperature on viscosity is not significant and as a result pressure drop is not a strong function of temperature.

3.5 Performance index

As shown in previous sections, an increase in mass concentration of nanofluid increases the heat transfer coefficient together with the pressure drop value. Therefore, there is a trade-off between heat transfer coefficient and pressure drop. For better evaluation, thermal performance index is defined as:

$$P.I = \frac{Nu_{nf}}{Nu_{bf}} \times \left(\frac{\Delta P_{bf}}{\Delta P_{nf}} \right)^{\frac{1}{3}}. \tag{13}$$

Here Nu is the Nusselt number that can be calculated from the following equation:

$$Nu = \frac{h \times d}{k}. \tag{14}$$

Her *h* is the HTC, *d* is the inlet diameter port of the heat exchanger, *k* is the working fluid thermal conductivity, which can be calculated for the nanofluid or the base fluid. Likewise, *nf* and *bf* stand for nanofluid and base fluid, respectively. Fig. 7 presents the performance index of the system at different mass concentration and flow rate of nanofluid.

As can be seen, the highest thermal performance index can be obtained at wt.% = 0.3, which is 34 %. Thereby, it can be concluded that although presence of nanoparticles increase the pressure drop, the amount of increase in heat transfer compensate the penalty for pressure drop resulting in the enhancement of thermal performance index. P.I was also found to be enhanced anomalously in turbulent regime rather than laminar.

This is because, in turbulent regime, Brownian motion and local agitation within the fluid intensify the energy transport by particles from one side of the base fluid to another side.

4. Conclusions

An experimental investigation was conducted on the heat transfer and fluid pressure drop in a plate heat exchanger and MgO/ethylene glycol was used as the working fluid. Following conclusions were made:

(1) Flow rate and nanofluid inlet temperature were found to increase the heat transfer coefficient of the nanofluid. The reason was attributed to the enhancement in the local agitation, Brownian motion and also enhancement in thermo-physical properties of nanofluid.

(2) Nanoparticles were found to increase the pressure drop over the base fluid. The maximum enhancement in pressure drop was found at wt.% = 0.3 by ~89 %.

(3) Performance index was found to be largely increased in turbulent regime rather than laminar. Also, it was understood that although the addition of MgO nanoparticles increases the value of pressure drop, the rate of enhancement for heat transfer coefficient is higher than pressure drop. As a result, higher performance index was seen. Overall, MgO nanofluid shows a promising future for cooling applications. However, more evaluations are still required for other systems and heat exchangers to draw a final conclusion and a general trend for MgO/EG nanofluid.

(4) Investigations on the potential fouling formation of MgO nanoparticles within the heat exchanger showed that after 500 minutes of operation, no layer of fouling was seen within the heat exchanger, which was attributed to the high stability of MgO in ethylene glycol. However, further investigations on the fouling of MgO nanofluid is highly recommended.

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References

[1] G. Huminic and A. Huminic, Application of nanofluids in heat exchangers: A review, *Renewable and Sustainable Energy Reviews*, 16 (2012) 5625-5638.

[2] C. T'Joen, Y. Park, Q. Wang, A. Sommers, X. Han and A. Jacobi, A review on polymer heat exchangers for HVAC&R applications, *International Journal of Refrigeration*, 32 (2009) 763-779.

[3] Q. Li, G. Flamant, X. Yuan, P. Neveu and L. Luo, Compact heat exchangers: A review and future applications for a new generation of high temperature solar receivers, *Renewable and Sustainable Energy Reviews*, 15 (2011) 4855-4875.

[4] E. Salari, S. M. Peyghambarzadeh, M. M. Sarafraz and F. Hormozi, Boiling thermal performance of TiO_2 aqueous nanofluids as a coolant on a disc copper block, *Periodica Polytechnica. Chemical Engineering*, 60 (2016) 106.

[5] M. Kamalgharibi, F. Hormozi, S. A. H. Zamzamian and M. Sarafraz, Experimental studies on the stability of CuO nanoparticles dispersed in different base fluids: Influence of stirring, sonication and surface active agents, *Heat and Mass Transfer*, 52 (2016) 55-62.

[6] M. Sarafraz, S. Peyghambarzadeh and S. Alavifazel, Enhancement of nucleate pool boiling heat transfer to dilute binary mixtures using endothermic chemical reactions around the smoothed horizontal cylinder, *Heat and Mass Transfer*, 48 (2012) 1755-1765.

[7] A. Arya, M. Sarafraz, S. Shahmiri, S. Madani, V. Nikkhah and S. Nakhjavani, Thermal performance analysis of a flat heat pipe working with carbon nanotube-water nanofluid for cooling of a high heat flux heater, *Heat and Mass Transfer* (2017) 1-13.

[8] A. Arya, S. Shahmiry, V. Nikkhah and M. M. Sarafraz, Cooling of high heat flux flat surface with nanofluid assisted convective loop: Experimental assessment, *Archive of Mechanical Engineering*, 64 (2017) 519-531.

[9] M. Nakhjavani, V. Nikkhah, M. Sarafraz, S. Shoja and M. Sarafraz, Green synthesis of silver nanoparticles using green tea leaves: Experimental study on the morphological, rheological and antibacterial behaviour, *Heat and Mass Transfer*, 53 (2017) 3201-3209.

[10] E. Salari, M. Peyghambarzadeh, M. M. Sarafraz and F. Hormozi, Boiling heat transfer of alumina nano-fluids: Role of nanoparticle deposition on the boiling heat transfer coefficient, *Periodica Polytechnica. Chemical Engineering*, 60 (2016) 252.

[11] E. Salari, S. Peyghambarzadeh, M. Sarafraz, F. Hormozi and V. Nikkhah, Thermal behavior of aqueous iron oxide nanofluid as a coolant on a flat disc heater under the pool boiling condition, *Heat and Mass Transfer*, 53 (2017) 265-275.

[12] M. Sarafraz, A. Arya, V. Nikkhah and F. Hormozi, Thermal performance and viscosity of biologically produced silver/coconut oil nanofluids, *Chemical and Biochemical Engineering Quarterly*, 30 (2017) 489-500.

[13] M. Sarafraz and F. Hormozi, Qualitative investigation of the convective boiling heat transfer of dilute Al_2O_3-water/glycerol solution inside the vertical annuli, *Bulg Chem Commun*, 46 (2014) 645-651.

[14] M. Sarafraz, V. Nikkhah, S. Madani, M. Jafarian and F. Hormozi, Low-frequency vibration for fouling mitigation and intensification of thermal performance of a plate heat exchanger working with CuO/water nanofluid, *Applied Thermal Engineering*, 121 (2017) 388-399.

[15] M. Sarafraz, V. Nikkhah, M. Nakhjavani and A. Arya, Thermal performance of a heat sink microchannel working with biologically produced silver-water nanofluid: Experimental assessment, *Experimental Thermal and Fluid*

Science, 91 (2018) 509-519.

[16] M. Sarafraz, S. Peyghambarzadeh, F. Hormozi and N. Vaelim, Experimental studies on the pward convective boiling flow to DI-water and CuO nanofluids inside the annulus, *Journal of Applied Fluid Mechanics*, 9 (2014).

[17] M. M. Sarafraz, S. Peyghambarzadeh and A. S. Fazel, Experimental studies on nucleate pool boiling heat transfer to ethanol/MEG/DEG ternary mixture as a new coolant, *Chemical Industry and Chemical Engineering Quarterly*, 18 (2012) 577-586.

[18] O. Pourmehran, T. B. Gorji and M. Gorji-Bandpy, Magnetic drug targeting through a realistic model of human tracheobronchial airways using computational fluid and particle dynamics, *Biomechanics and Modeling in Mechanobiology*, 15 (2016) 1355-1374.

[19] M. Yousefi, O. Pourmehran, M. Gorji-Bandpy, K. Inthavong, L. Yeo and J. Tu, CFD simulation of aerosol delivery to a human lung via surface acoustic wave nebulization, *Biomechanics and Modeling in Mechanobiology*, 16 (2017) 2035-2050.

[20] A. Amrollahi, A. Hamidi and A. Rashidi, The effects of temperature, volume fraction and vibration time on the thermo-physical properties of a carbon nanotube suspension (carbon nanofluid), *Nanotechnology*, 19 (2008) 315701.

[21] M. Biglarian, M. R. Gorji, O. Pourmehran and G. Domairry, H2O based different nanofluids with unsteady condition and an external magnetic field on permeable channel heat transfer, *International Journal of Hydrogen Energy*, 42 (2017) 22005-22014.

[22] R. Tabassum, R. Mehmood, O. Pourmehran, N. Akbar and M. Gorji-Bandpy, Impact of viscosity variation on oblique flow of Cu–H_2O nanofluid, *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering* (2017) 0954408917732759.

[23] M. Sarafraz, V. Nikkhah, M. Nakhjavani and A. Arya, Fouling formation and thermal performance of aqueous carbon nanotube nanofluid in a heat sink with rectangular parallel microchannel, *Applied Thermal Engineering*, 123 (2017) 29-39.

[24] M. Sarafraz, A. Arya, F. Hormozi and V. Nikkhah, On the convective thermal performance of a CPU cooler working with liquid gallium and CuO/water nanofluid: A comparative study, *Applied Thermal Engineering*, 112 (2017) 1373-1381.

[25] M. Sarafraz and F. Hormozi, Intensification of forced convection heat transfer using biological nanofluid in a double-pipe heat exchanger, *Experimental Thermal and Fluid Science*, 66 (2015) 279-289.

[26] M. Sarafraz and F. Hormozi, Heat transfer, pressure drop and fouling studies of multi-walled carbon nanotube nanofluids inside a plate heat exchanger, *Experimental Thermal and Fluid Science*, 72 (2016) 1-11.

[27] M. Sarafraz, F. Hormozi and M. Kamalgharibi, Sedimentation and convective boiling heat transfer of CuO-water/ethylene glycol nanofluids, *Heat* and *Mass Transfer*, 50 (2014) 1237-1249.

[28] M. M. Sarafraz and F. Hormozi, Forced convective and nucleate flow boiling heat transfer to alumnia nanofluids, *Periodica Polytechnica. Chemical Engineering*, 58 (2014) 37.

[29] B. D. Raja, R. Jhala and V. Patel, Thermal-hydraulic optimization of plate heat exchanger: A multi-objective approach, *International Journal of Thermal Sciences*, 124 (2018) 522-535.

[30] D. Huang, Z. Wu and B. Sunden, Effects of hybrid nanofluid mixture in plate heat exchangers, *Experimental Thermal and Fluid Science*, 72 (2016) 190-196.

[31] A. K. Tiwari, P. Ghosh and J. Sarkar, Heat transfer and pressure drop characteristics of CeO_2/*water* nanofluid in plate heat exchanger, *Applied Thermal Engineering*, 57 (2013) 24-32.

[32] A. Kabeel, T. A. El Maaty and Y. El Samadony, The effect of using nano-particles on *corrugated* plate heat exchanger performance, *Applied Thermal Engineering*, 52 (2013) 221-229.

[33] S. D. Pandey and V. Nema, Experimental analysis of heat transfer and friction factor of nanofluid as a coolant in a corrugated plate heat exchanger, *Experimental Thermal and Fluid Science*, 38 (2012) 248-256.

[34] M. Sarafraz, Experimental investigation on pool boiling heat transfer to formic acid, propanol and 2-butanol pure liquids under the atmospheric pressure, *Journal of Applied Fluid Mechanics*, 6 (2013).

[35] V. Nikkhah, M. Sarafraz and F. Hormozi, Application of spherical copper oxide (II) water nano-fluid as a potential coolant in a boiling annular heat exchanger, *Chemical and Biochemical Engineering Quarterly*, 29 (2015) 405-415.

[36] M. Sarafraz, F. Hormozi, S. Peyghambarzadeh and N. Vaeli, Upward flow boiling to DI-water and Cuo nanofluids inside the concentric annuli, *Journal of Applied Fluid Mechanics*, 8 (2015).

[37] A. M. Abed, M. Alghoul, K. Sopian, H. Mohammed and A. N. Al-Shamani, Design characteristics of corrugated trapezoidal plate heat exchangers using nanofluids, *Chemical Engineering and Processing: Process Intensification*, 87 (2015) 88-103.

[38] R. Barzegarian, M. K. Moraveji and A. Aloueyan, Experimental investigation on heat transfer characteristics and pressure drop of BPHE (brazed plate heat exchanger) using TiO2–water nanofluid, *Experimental Thermal and Fluid Science*, 74 (2016) 11-18.

[39] S. A. Kline and A. F. McClintock, Describing uncertainties in single-sample experiments, *ASME Mech. Eng.*, 75 (1953) 3-8.

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