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THE INFLUENCE OF PLATE CONFIGURATION AND CUO NANOFLUIDS ON HEAT TRANSFER AND PRESSURE DROP IN PLATE HEAT EXCHANGERS

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ABSTRACT

Recent studies have highlighted the impact of nanofluids in enhancing the rate of heat transfer, particularly by improving the plate heat exchangers (PHE) thermal performance. The problems of using nanofluids at high concentrations in plate heat exchangers such as sedimentation, blockage, and cost prompted researchers to try new techniques to improve the efficiency of heat exchangers by using low concentrations of nanofluids. Among these techniques is increasing the number of plates for the plate heat exchanger. Few experimental studies have been conducted in this field , the number of plates used did not exceed 16 plates. Thus, this study examines the increasing of plate numbers effect on plate heat exchangers performance with CuO nanofluids at 1%wt to avoid the problems of using high concentrations to verify the possibility of investigating whether increasing the number of plates may cause noticeable problems in pressure drop when exceeding a certain number and the possibility of finding alternative methods to achieve the best thermal performance. And achieve a balance between improving the design and physical properties of nanofluids at low concentrations. The experiments aim to determine the optimal heat exchanger configuration (plate numbers) that achieves high thermal performance while minimizing the pressure drop and pumping power.

Four different configurations (8, 12, 16, and 24 plates) were experimentally investigated. Results revealed that an increase in plate number led to directly proportional enhancements in the rate of heat transfer and the Nusselt number. In the first three configurations, the overall heat transfer coefficient improved by 10%, 17%, and 19%, respectively, with an imperceptible increase in pumping power and pressure. Effectiveness improvements of 7%, 9%, and 12% were achieved with 8, 12, and 16 plates, respectively, while using 24 plates provided the highest effectiveness improvement of approximately 24%. However, the 24-plate configuration showed a remarkable increase in the pressure drop and pumping capacity, which has an adverse effect on the overall heat exchanger performance.

KEYWORDS

Plate heat exchanger, Overall heat transfer, CuO/water nanofluid, Number of plates, Thermal conductivity enhancement.

1. INTRODUCTION

Utilization of plate heat exchangers (PHEs) has become intensely favored in many industrial applications, due to high heat transfer efficiency and compact size, exhibiting a remarkable advantage over conventional heat exchangers. The main objective of vast recent studies was looking for a modern technique to enhance the heat exchanger performance. In particular, exploiting nanotechnology becomes a major subject to improve the exchange rate in thermal devices. The nanotechnology posits that the added nanoparticles make some modifications to the base fluid's properties, thereby improving its thermal efficacy (Alasady and Maghrebi, 2022a; Alikhan et al., 2024b, 2024a; Alikhan and Maghrebi, 2022; Dhaef, 2015; H., 2015; H.Saleh and H. Dhaef, 2015; Muneer et al., 2024; Saleh and Katea, 2023). The concentration of the nanomaterials plays a crucial role in determining the extent of improvement in heat exchanger performance. Some studies track the optimum concentration over a certain range (0.5-2%) of nanofluid to obtain the best thermal convention in a tube (Akhavan-Behabadi et al., 2015). it has been Theoretically and experimentally demonstrated by (Sami Abed et al., 2023) that the physical properties improve as the concentration of Al2O3 nanoparticles increases up to 1%, beyond which (at 1.5%) significant agglomeration occurs. Furthermore, (Hussein et al., 2021) investigated the effect of TiO2 at concentrations of 0.01%, 0.03%, and 0.08% on the hardening process under different operating conditions. Their results showed the maximum impact of nanomaterials on the hardening of carbon steel was achieved at concentration of 0.03%. (Shareef & Dibs, 2021) conducted a numerical and experimental study to investigate the effect of adding Al2O3 nanoparticles at concentrations of 0.2%, 0.45%, and 0.6% to both water and ethylene glycol (EG) as a base fluid on the heat absorption in a surface plate collector. Their findings revealed the highest temperature difference was obtained using water as a base fluid with 0.6% of nanoparticles. The study (Salih & Yaseen, 2021) also examined the effect of increasing the concentration of nanoparticles beyond 5% on the heat transfer coefficient and pressure drop in a circular tube. It was found although the heat transfer coefficient improved with higher nanoparticles concentrations, the increase in concentration led to a significant rise in pressure drop, exceeding 15%. (Al-Mayahi, 2021) conducted a numerical study to investigate the effect of increasing the concentration of Cu2+ nanofluid from 0 to 0.05 in a cavity heated at a constant temperature. The study found that the Nusselt number increased with higher concentration at different Raleigh and Reynolds numbers. The investigations were conducted numerically to identify the optimum nanoparticle concentration for both turbulent and laminar flow in the tube to achieve the best thermal performance and lowest operating cost (Corcione et al., 2013, 2012a, 2012b). However, the factor of pressure drop puts in the consideration in the latest studies, and the integrity of the system derives based on balancing between pressure drop, coefficient of heat transfer, and the nanoparticles concentration parameters (Mukeshkumara et al., 2012), and (Kumar et al., 2014). They found that the Nusselt Number increased with increasing concentration of Al2O3 from 0.4-0.8 in the shell-and-tube and helically coiled tube heat exchangers. Although the nanofluids have better thermal conductivity than base fluids, their thermal efficiency differs from one nanofluid to another. For instance, CNT (carbon nano-tube) exhibits high thermal conductivity and great chemical stability over various nanomaterials (SUS Choi, 1995). A small concentration of nanoparticles added to the fluid base enhanced its thermal conductivity (Choi et al., 2001). On the other hand, both pressure drop and friction factor increased when nanofluids were added to the liquid base in multiport mini channels (Diao et al., 2017). Those increments may be attributed to the increase in viscosity that resulted from the increase in nanofluids concentration. (Oliveira et al., 2017) observed that an increase in the concentration of MWCNT resulted in a corresponding increase in viscosity and thermal conductivity. An increase in the viscosity upon increasing MWCNT concentration led to an increase in pressure and friction coefficient and also caused a decrease in the plate heat exchanger heat transfer rate (Huang et al., 2015). Whereas, (Sarafraz and Hormozi, 2016) have reached a 68% increase in the base fluid thermal conductivity when adding MWCNT to the plate heat exchanger. Additionally, the impact of increasing the plate count to 16 and employing a 1% wt hybrid nanofluid on heat transfer performance was investigated by (Gürbüz et al., 2020). It was found that heat transfer increases with increasing the number of plates with a slight increase in pressure.

Building on these findings, the present study explores the feasibility of enhancing heat transfer in a plate heat exchanger by using CuO nanofluid at a fixed concentration of 1% by adding several plates. The study aims to achieve a balance between improving heat transfer and maintaining pumping power and pressure within acceptable limits. According to the authors' information, no experimental studies have been conducted to examine the effect of increasing the number of plates on the performance of the plate heat exchanger or to determine the extent to which the number of plates can be increased without causing a significant pressure drop. Additionally, the study examined the potential benefits of combining nanofluids at specific concentrations with a certain number of plates to optimize the thermal performance for the studied cases while avoiding a significant increase in pressure drop, cost, or the size of the heat exchanger due to the added plates.

2. EXPERIMENTAL METHOD

The system includes two independent closed flow loops—cold and hot as illustrated in Fig 1.

The hot fluid which was water is heated to a desired temperature within a tank and subsequently transferred to the PHE, while the cooled fluid (CuO nanofluids) is cooled after exiting the exchanger using a refrigeration unit to maintain constant inlet temperatures for both fluids at 40°C and 26°C, respectively. Then by 0.65 kW NAVID MOTOR the two fluids, water and nanofluid, pass through the heat exchanger plates alternately between the plates to exchange heat between each two adjacent plates. Pressure, temperature, and flow sensors were installed at the inlets and outlets of the heat exchanger and connected directly to a personal PC. The data is converted into an Excel file at a rate of three readings per second. The readings were first taken using water on both the hot and cold sides at a plate count of eight, then the hot fluid was replaced with 1% nanofluid and the readings were taken using different plate counts of 12, 16, and 24. The nanofluid materials were prepared in the VCN Materials Company with precision exceeding 95%. The stability of the nanofluids was also confirmed by conducting continuous tests to examine the zeta test as shown in Fig 2, in addition to operating the device for not less than ten minutes in each test case before taking the readings, which allows time for the nanofluids to circulate in the test device and for continuous mixing of the nanoparticles within the base fluid. Four different plate configurations of the heat exchanger (8, 12, 16, and 24 plates) were tested. The PHEs are constructed using stainless steel plates with a 60° chevron angle to enhance turbulence and heat transfer. The specific design characteristics of the exchanger are summarized in Table 1.

The CuO nanofluid is widely used in various applications, thereby it was nominated with a concentration of 1% by weight of particles to be used in this study. The properties of the nanomaterial can be found in Table 2.

Table 1. Gasket plate heat exchanger design information

Components	Symbol	Value	Unit
Area of heat exchanger	A	0.352	m^2
Mean channel spacing	b	2.8	mm
diameter of Port	Dport	31	mm
Plates number	Nt	21	-
Plate width inside the gasket	Lw	91	mm
Vertical distance between centers of ports	Lv	357	mm
Horizontal distance between centers of ports	Lh	60	mm
Plate thickness	tplate	0.5	mm
Depth of corrugation	LCorrugated	2.7	mm
Hydraulic diameter	De	0.44	mm
Gasket thickness	tgasket	0.37	mm
Chevron angle	β	60	-

Table 2. Thermophysical characteristics of water and CuO

Materials	Density (kg/m3)	Specific heat (J/kg·K)	Thermal conductivity (W/m·K)
H_2O	997.2	4179	0.613
CuO	6320	531.8	76.5

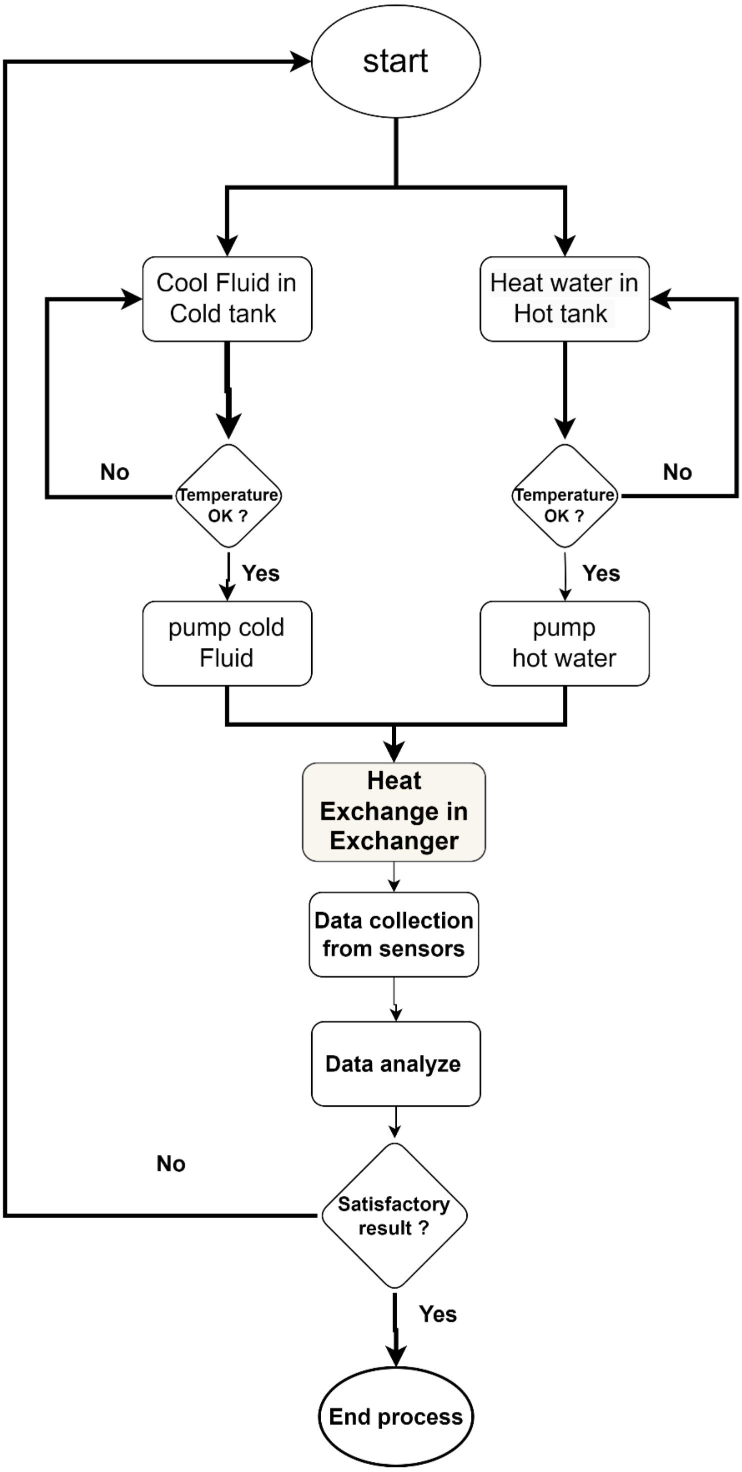

Fig. 1. Experimental Flow Chart

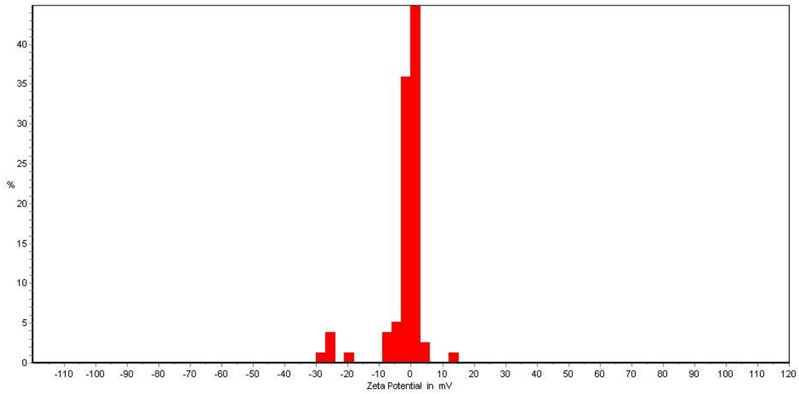

Fig. 2. Zeta potential test

3. DATA REDUCTION AND UNCERTAINTIES ANALYSIS

The thermos-physical properties of the heated and cooled fluids are determined based on the respective bulk temperatures, calculated using the following equations: (Tiwari et al., 2013):

$$T_{c,avg} = \frac{T_{c,o}+T_{c,i}}{2} \tag{1}$$

$$T_{h,avg} = \frac{T_{h,o}+T_{h,i}}{2} \tag{2}$$

$$\rho_{nf} = \varphi\rho_p+(1-\varphi)\rho_w \tag{3}$$

$$(\rho C_{p)nf} = \varphi\, (\rho C_p)_p+(1-\varphi)(\rho C_p)_w \tag{4}$$

$$\mu_{nf} = (1+2.5\varphi+6.5\varphi^2)\mu_w \tag{5}$$

$$k_{nf} = \left[\frac{k_p+2k_w-2\phi(k_w-k_p)}{k_p+2k_w+\phi(k_w-k_p)}\right]k_w \tag{6}$$

Heat quantity occupied by the nanofluids moving through the plate heat exchanger is determined using the following equations (Tiwari et al., 2013), as well as other related parameters:

$$Q = \dot{m}Cp(T_{in}-T_o) \tag{7}$$

$$Q_{avg} = \frac{Q_h+Q_c}{2} \tag{8}$$

$$U = \frac{Q_{avg}}{A\times LMTD} \tag{9}$$

The logarithmic mean temperature difference (LMTD) between the fluids, determined by the following equation (Tiwari et al., 2013):

$$LMTD = \frac{(T_{h,o}-T_{c,i})-(T_{h,i}-T_{c,o})}{ln\frac{(T_{h,o}-T_{c,i})}{T_{h,i}-T_{c,o}}} \tag{10}$$

$$f = \frac{\Delta p}{\left(\frac{Lv}{De}\right)\times\left(\frac{2G^2}{\rho}\right)} \tag{11}$$

Assuming 80% pump efficiency (Tiwari et al., 2013), the power of pump required to circulate the coolant is determined by,

$$P_{pump} = \frac{\dot{m}_{nf}*\Delta p_{nf}}{0.80*\rho_{nf}} \tag{12}$$

$$Nu = 0.348\,Re^{0.663}\,Pr^{0.33} \tag{13}$$

Table 3 presents a detailed overview of the uncertainties associated with each sensor. Based on Eq.14 from (Alasady and Maghrebi, 2022b), uncertainties in the measured data and related parameters are calculated utilizing the maximum uncertainty values of ±2% for the Nusselt number and friction factor, and ±3.7% for the Reynolds number of nanofluids. The uncertainty analysis for the function (R) is derived, where R represents a linear function of independent variables., $R = R(v_1, v_2, v_3, \dots, v_n)$.

$$\delta R = \sqrt{\left(\frac{\partial R}{\partial v_1}\delta v_1\right)^2 + \left(\frac{\partial R}{\partial v_2}\delta v_2\right)^2 + \left(\frac{\partial R}{\partial v_3}\delta v_3\right)^2 + \cdots + \left(\frac{\partial R}{\partial v_n}\delta v_n\right)^2} \tag{14}$$

Where δR, $\frac{\partial R}{\partial v_n}$, and δv_n are the function R uncertainty, the concerning partial derivative.

Table 3. The uncertainty values for used sensors

Sensor	Accuracy	Uncertainty
Temperature sensor	0.1 ºC	±0.1
Pressure sensor	0.01 mbar	±0.01
Flow meter	0.01 lit/sec	±0.01

4. RESULTS AND DISCUSSION

These experimental results were presented and discussed in this section using water and nanofluid in PHEs with varying plate numbers. The nanofluid concentration used was maintained at a fixed 1 wt% throughout the experiment. The nanofluid's higher thermal conductivity compared to water is the primary factor contributing to its enhanced thermal performance. Fig. 2 illustrates how the Nusselt number varies with mass flow rate over a range of 3 to 7 L/min in PHE with different numbers of plates. The use of CuO/water nanofluid significantly increases the Nusselt value compared to the pure water case. The percentages of enhancements for all parameters were calculated relative to the baseline case using pure water. Further, Nusselt Number improvements of 10, 15, 18, and 24% were observed as the number of plates increased from 8 to 24 respectively. The increment of both the number of plates and the flow rate achieves a proportional improvement in the Nusselt number.

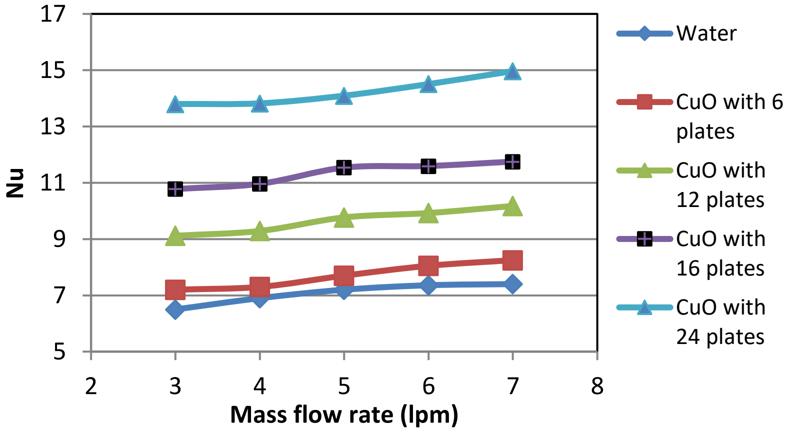

Fig. 2. Variation in Nusselt Number via mass flow rate (lpm) at different number of plates

Fig.3 depicts the heat transfer rate versus flow rate mass in PHE with varying plate numbers. Notably, the utilization of CuO/water nanofluid enhances the heat transfer significantly compared to the pure water case. Moreover, increasing the number of plates from 8 to 24 leads to improve the average heat transfer by 10, 11, 13, and 20 % compared to pure water cases. Additionally, a higher flow rate resulted in an increased heat transfer rate.

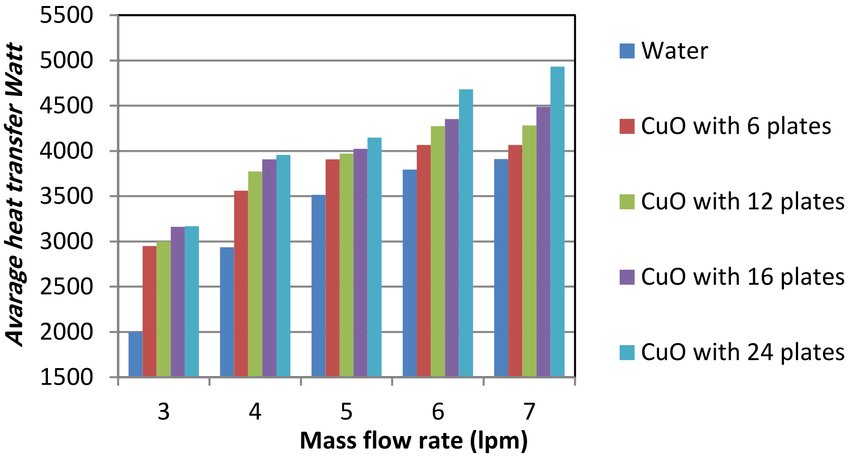

Fig. 3. Variation in average heat transfer via rate of mass flow (lpm) at different plate numbers.

Fig.4 illustrates the changes in the overall heat transfer coefficient as a function of (OHTC) with respect to the rate mass of flow through the PHE for 8, 12, 16, and 24 plates. The nanofluid utilization increases the OHTC averagely by 10 % in the HE compared to the pure water case with the same number of plates (8 plates). Similarly, using a higher number of plates achieves a further increase in the OHTC by 17% 19%, and 25 respectively. It is important to note that increasing the flow rate leads to higher Reynolds numbers, resulting in turbulent flow conditions. This enhanced turbulence contributes to an essential increase in the overall heat transfer coefficient (OHTC). The obtained results for OHTC indicate that the utilization of CuO nanofluids produces a more significant improvement in the performance of heat transfer as compared to water. This figure provides compelling evidence of the positive impact of employing the nanofluids to enhance the plate heat exchanger (PHE) performance.

Fig.5 illustrates effectiveness variation versus rate of mass flow in PHE with varying plate numbers. CuO nanofluid utilization improved the effectiveness average compared to pure water. Furthermore, the average enhancement in effectiveness achieved by employing CuO/water with 8, 12, 16, and 24 plates was obtained as 7%, 9%, 12%, and 24% respectively. It was observed that the influence of HE drops with increasing the value of the mass flow rate. It was noted that higher mass flow rates accelerate the fluid flow. Furthermore, it should be noted the working fluid heat capacity increases with the flow rate, resulting in a diminished temperature change and consequently a drop in the effectiveness of the heat exchanger (HE).

Moreover, at higher flow rates, the reduced residence time of the working fluid within the HE further contributes to a decrease in its effectiveness. The effectiveness of the PHE, as determined in this study, was found to lie within the range of 0.5 to 0.95. As Fig. 5 declares the higher performance was achieved at CuO nanofluids with 24 plates, at the expense of water and less number of plates. Also, the experimental results demonstrated that the use of CuO/water higher number of plates in PHE significantly increased thermal performance. The nanofluids utilization resulted in an enhancement of thermal performance across all heat exchangers. More increments in the perforce are achieved by increasing the number of plates in PHE.

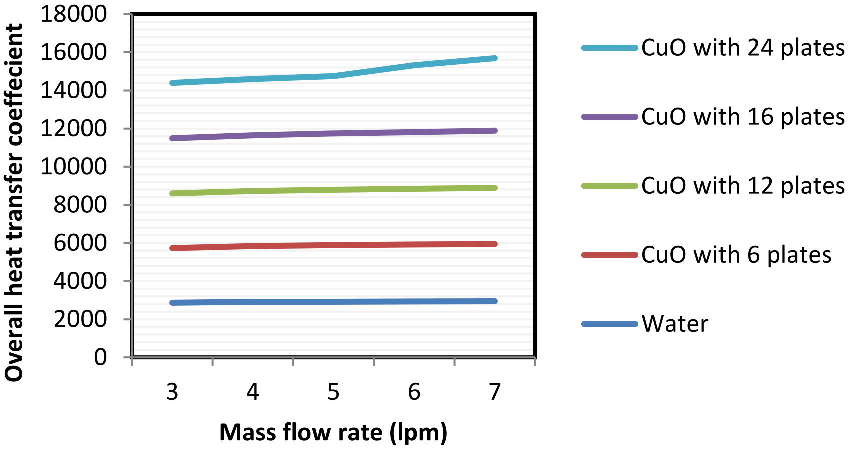

Fig. 4. Variation of OHTC with Mass Flow Rate (lpm) at different number of plates.

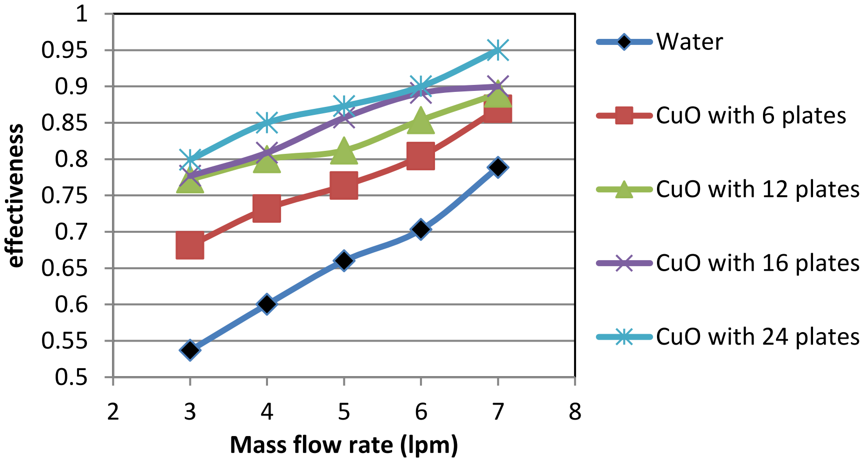

Fig.5. Variation effectiveness via mass flow rate (lpm) at different number of plates.

Fig.6 presents the average pressure drop across the plate heat exchanger (PHE) for various plate configurations. While the use of nanofluid does result in an additional pressure drop compared to water, this increase is relatively modest. Specifically, the employment of CuO nanofluid led to pressure drop increases of 9%, 11%, 15%, and 30% in PHEs by 8, 12, 16, and 24 plates, individually. Similarly, the pumping power at the 24-plate configuration increases significantly compared to the first three configurations used, which confirms the ineffectiveness of the scenario with the number of plates increasing to 24 plates in this experimental work as illustrated in Fig. 7. Hence, further improvement in the rate of heat transfer cannot be fulfilled by employing several plates scenario increases. Thereby, we recommend finding alternative solutions to enhance the heat transfer, either by adding the pulse effect to increase the flow turbulence and secondary mixing or by using hybrid nanomaterials with higher thermal properties

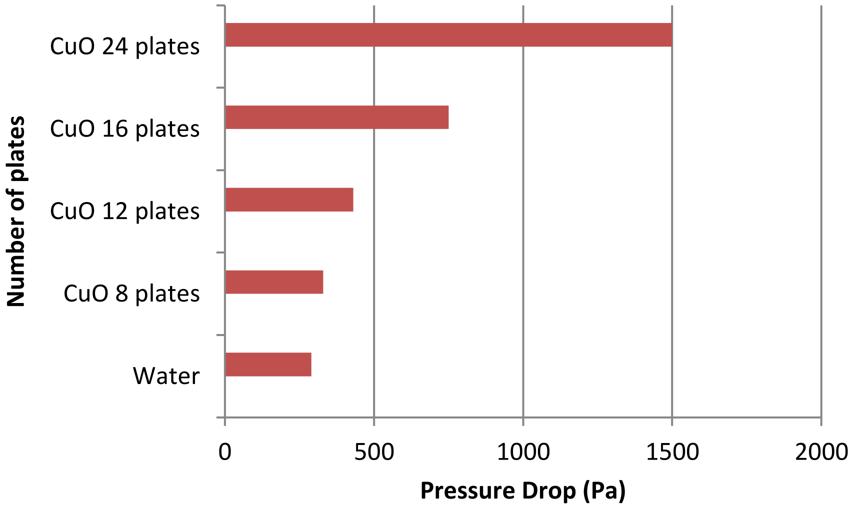

Fig. 6. Variation in pressure drop at different number of plates.

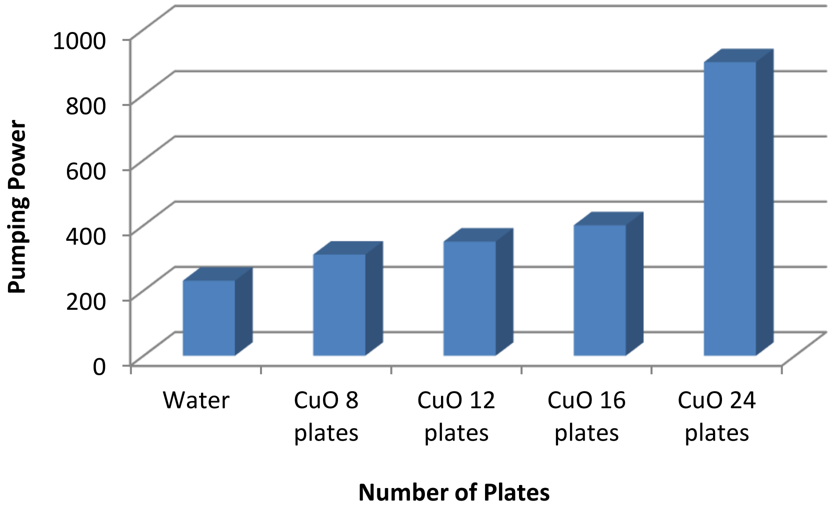

Fig.7. Variation in pumping power at different number of plates.

5. CONCLUSIONS

In this study, CuO nanofluid was utilized with configurations of 8, 12, 16, and 24 plates to examine the effect of plate number variation on PHE performance. The experimental results demonstrated that the incorporation of nanofluid of CuO/water in the PHE led to an enhancement in the thermal performance relative to pure water. This nanofluid resulted in an improvement in the thermal efficiency of the plate heat exchanger across different plate numbers. Additionally, a higher plate count resulted more essential increase in thermal efficiency when using the nanofluid. The maximum improvement in the overall heat transfer coefficient (OHTC) was observed at 10%, 17%, 19%, and 25% for PHEs with 8, 12, 16, and 24 plates, respectively. Furthermore, effectiveness improvements of 7%, 9%, and 12% were achieved with 8, 12, and 16 plates, respectively, while using 24 plates provided the highest effectiveness improvement of approximately 24%. Although the 24-plate configuration yielded the greatest improvement in effectiveness, it also led to a doubling of the pressure drop and required pumping power. This limitation introduces additional costs, making configurations beyond 16 plates less feasible for practical and economic purposes.

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