Journal of the Brazilian Society of Mechanical Sciences and Engineering (2020) 42:524
https://doi.org/10.1007/s40430-020-02601-1

TECHNICAL PAPER

A comparative study on utilizing hybrid-type nanofluid in plate heat exchangers with different number of plates

Emine Yağız Gürbüz[1,2] · **Adnan Sözen**[3] · **Halil İbrahim Variyenli**[3] · **Ataollah Khanlari**[4] · **Azim Doğuş Tuncer**[2,5]

Received: 31 March 2020 / Accepted: 3 September 2020 / Published online: 17 September 2020

Abstract

Different methods have been utilized to enhance the thermal efficiency of the heat exchangers (HEs). A widely used method to upgrade the thermal efficiency of HEs is upgrading the thermal properties of working fluid by utilizing nanoparticles. In this study, Al_2O_3 and CuO have been utilized to prepare Al_2O_3–CuO/water hybrid nanofluid. Accordingly, Al_2O_3 and CuO nanoparticles have been mixed into the water with 1% (50:50) weight concentration. The main objective of this work is testing the prepared hybrid nanofluid in plate-type HEs (PHEs) with 8, 12 and 16 plates to determine the influence of number of plates on heat transfer improvement by hybrid nanofluid. Experimental findings of the present study demonstrated that utilizing Al_2O_3–CuO/water hybrid-type nanofluid in the PHE enhanced thermal efficiency notably in comparison with single-type nanofluids. Using this hybrid nanofluid increased the thermal performance in all PHEs with different number of plates. However, it is observed that increasing number of plates led to more increment in thermal performance by utilizing hybrid nanofluid. The highest increment in overall heat transfer coefficient was obtained as 12%, 19% and 20% in PHEs with eight, 12 and 16 plates, respectively. In addition, the highest enhancement in effectiveness was achieved as 10%, 11.7% and 16% in PHEs with eight, 12 and 16 plates, respectively.

Keywords Plate heat exchanger · Hybrid nanofluid · Al_2O_3–CuO/water · Performance

List of symbols

A	Total heat transfer area (m^2)
C	Heat capacity rate (W/K)
c_p	Specific heat capacity (J/kg K)
D_h	Hydraulic diameter (m)
f	Friction factor
G	Mass velocity (kg/m^2 s)
h	Heat transfer coefficient (W/m^2 K)
H	Depth of corrugation (m)
k	Thermal conductivity (W/mK)
L	Length of channel (m)
LMTD	Log mean temperature difference (K)
$\dot{m}$	Mass flow rate (m/s)
Nu	Nusselt number
P_c	Pumping power (W)
Pe	Peclet number
PHE	Plate heat exchanger
Pr	Prandtl number
Re	Reynolds number
T	Temperature (°C)
$\dot{Q}$	Heat transfer rate (W)
U	Overall heat transfer coefficient
u	Velocity (m/s)
W	Channel width (m)
W_R	Total uncertainty (%)
w_1, w_2, w_n	The uncertainties in the independent variables

Greek letters

Δx	Plate thickness (m)
ε	Effectiveness

Technical Editor: Ahmad Arabkoohsar.

This article has been selected for a Topical Issue of this journal on Nanoparticles and Passive-Enhancement Methods in Energy.

✉ Ataollah Khanlari
ata_khanlari@yahoo.com; akhanlari@thk.edu.tr

1 Energy Systems Engineering, Muğla Sıtkı Koçman University, Muğla, Turkey

2 Natural and Applied Science Institute, Gazi University, Ankara, Turkey

3 Energy Systems Engineering, Gazi University, Ankara, Turkey

4 Mechanical Engineering, University of Turkish Aeronautical Association, Ankara, Turkey

5 Energy Systems Engineering, Burdur Mehmet Akif Ersoy University, Burdur, Turkey

ρ	Density (kg/m^3)
μ	Dynamic viscosity (kg/m s)
φ	Volume fraction of nanoparticles
α	Thermal diffusivity (m^2/s)

Subscripts

av	Average
bf	Base fluid
cl	Cold loop
hl	Hot loop
hnf	Hybrid nanofluid
hnp	Hybrid nanoparticle
in	Inlet
out	Outlet
p	Plate

1 Introduction

One of the most significant issues in energy conversion systems is efficient heat transfer that is investigated by many researchers. Heat exchangers (HEs) are apparatuses which are generally utilized to transfer thermal energy between two fluids. Various types of HEs are utilized in many applications. Plate heat exchangers (PHEs) are compact-type HE that are utilized in many applications such as food industry, chemical industry, cooling and heating, because of their high thermal efficiency. Plate shape, plate thickness and channel geometry are the major parameters that affect the efficiency of PHE [1]. There are lots of studies available that analyzed the effects of various factors on thermal behavior of PHE [2–5].

In addition, different methods have been utilized to raise the thermal performance of the HEs [6, 7]. Integrating extended surface areas like fins and baffles is a widely used method to improve heat transfer in HEs, while adding fins and baffles could raise pressure drop in HEs. Another method to raise the thermal performance of HEs is upgrading the thermal properties of working fluid by utilizing nanoparticles. The obtained fluids are called nanofluids, which are suspensions of nanoparticles in main working fluids. Using nanofluids can eliminate disadvantages of conventional fluids because of their superior thermal conductivity in comparison with common fluids [8–12]. Particle ratio, particle size, particle shape and base fluid properties are the major parameters that affect nanofluid thermal behavior [13–16]. Many researchers have investigated utilization of various types of nanofluids in PHE. Tiwari et al. [17] studied various nanoparticles and different volume fractions of them including CeO_2/water, SiO_2/water, TiO_2/water and Al_2O_3/water. They aimed to find maximum values of the thermal performances in a commercial PHE. Their results revealed that optimum volume concentrations vary for each nanoparticle. In a similar study, Sun et al. [18] experimentally analyzed the various mass volume ratios of different nanoparticles including Cu, Fe_2O_3 and Al_2O_3 in water as base fluid with the aim of increasing heat transfer properties of PHE. Their obtained findings demonstrate that the overall heat transfer coefficient (OHTC) and also resistance coefficient were meaningfully increased.

In addition, lots of nanoparticles have been investigated in many base fluids by many researchers. Their obtained outcomes revealed that mixing nanoparticles to the base working fluid generally has positive impact on the performance of HE [19–24]. Recently, hybrid nanofluid solutions have become a popular research area because of their advantages such as improved thermal properties and heat transfer performance. Han et al. [25] investigated hybrid-type nanofluid's thermal behavior including carbon nanotube particles. They stated that adding carbon nanotubes has an important effect on improving the thermal performance. Suresh et al. [26] prepared Al_2O_3–Cu/water hybrid nanofluid with a concentration of 0.1%. The results showed that using this nanofluid increased Nusselt number as 13.56%. In another experimental research performed by Huang et al. [27], the effect of utilization of a nanofluid consisting of carbon nanotubes–Al_2O_3 on heat transfer characteristics of PHE was investigated. They reported that by using hybrid nanofluid, the heat transfer rate increased compared to Al_2O_3/water nanofluid and water. Kumar et al. [28] analyzed the impact of spacing between the plates in PHE and utilization of different nanofluids including TiO_2, graphene nanoplate, MWCNT, Al_2O_3, ZnO, CeO_2 and hybrid CuO/Al_2O_3. The results indicated that 5 mm spacing exhibited the best thermal performance. Moreover, it found that using the MWCNT/water nanofluid in PHE gave the highest heat transfer coefficient (HTC) which was almost 53% higher than the water. In another study, Kumar et al. [29] experimentally tested thermal behavior of utilizing TiO_2 + MWCNT/water, CeO_2 + MWCNT/water, Al_2O_3 + MWCNT/water and ZnO + MWCNT/water, hybrid nanofluids in PHE. Their findings showed that CeO_2 + MWCNT/water nanofluid led to maximum performance improvement in PHE. Bhattad et al. [30] experimentally analyzed AL_2O_3/multiwalled carbon nanotube (MWCNT) hybrid nanofluid usage in different concentrations in PHE. Their results showed a maximum increment of 15.2% in HTC.

Al_2O_3 and CuO are widely used as nanoparticles in different base fluids to upgrade the thermal performance. Analyzing available works in the literature showed the ability of Al_2O_3/water and CuO/water nanofluids in enhancing thermal performance of different types of HEs. Also, some researchers showed the advantages of using hybrid nanofluids in comparison with single nanofluids [31, 32]. The main aim of using hybrid nanofluids is utilizing physical and chemical properties of two or more various types of nanoparticles that can better impact on the thermophysical and rheological properties of nanofluids. Therefore, in this study, Al_2O_3 and

CuO have been utilized to prepare Al_2O_3–CuO/water hybrid nanofluid. Accordingly, Al_2O_3 and CuO nanoparticles have been mixed into the water with 1% (50:50) weight concentration. In addition, Al_2O_3/water and CuO/water nanofluids have been prepared at the same concentration to compare with hybrid nanofluid. The main objective of this research is testing the prepared hybrid nanofluid in PHEs with eight, 12 and 16 plates to determine the influence of number of plates on heat transfer improvement by hybrid nanofluid. It should be stated that there is not any study in the literature which investigates the influence of number of plates on heat transfer characteristics of nanofluids. Figure 1 shows main steps of this work.

2 Materials and methods

In this section, test setup, preparation of CuO/water, Al_2O_3/water and Al_2O_3–CuO hybrid nanofluids and also experimental steps have been explained.

2.1 Test setup

The schematic diagram of utilized test rig is presented in Fig. 2. The setup contains seven main parts: PHE, circulation pump, *K*-type thermocouples, coiled heat exchanger, heater, and two flow meters. Two circuits are available in the experimental apparatus: cold and hot circuits (Fig. 2). Hot fluid circuit is closed, and hot fluid is heated up in coiled HE and transferred to the PHE. Nevertheless, the cold fluid circuit is open and heated water in the cold side of PHE is drained from the system. It is better to state that to achieve accurate temperature values, thermocouples have been submerged in the outlet and inlet of the PHE in the experimental apparatus. In this study, three PHEs with same plate corrugation design and various plate numbers have been tested. The plate heat exchangers are made from stainless-steel plates with 60° chevron angle and have 8, 12 and 16 plates. A view of utilized plate-type heat exchangers is shown in Fig. 3. Plate length and plate width are 208 mm and 76 mm, respectively. Port-to-port distance and port-to-port width are 172 mm and 42 mm, respectively. In addition, plate thickness is 0.4 mm.

2.2 Preparation of nanofluid

Al_2O_3 and CuO nanoparticles are widely used in various applications. In many researches, Al_2O_3 and CuO including single nanofluids were experimentally and numerically analyzed. Also, in the recent years, hybrid nanofluids are utilized to obtain higher thermal performance. In this study, Al_2O_3 and CuO have been utilized to prepare Al_2O_3/water and CuO/water and Al_2O_3–CuO/water hybrid nanofluids. In this regard, ball milling process has been used to attain homogeneous nanoparticles and also to decrease the nanoparticle size. Then, to obtain hybrid nanofluid, CuO and Al_2O_3 nanoparticles were mixed by using a mechanical mixer with 1% weight concentration. Al_2O_3–CuO/water

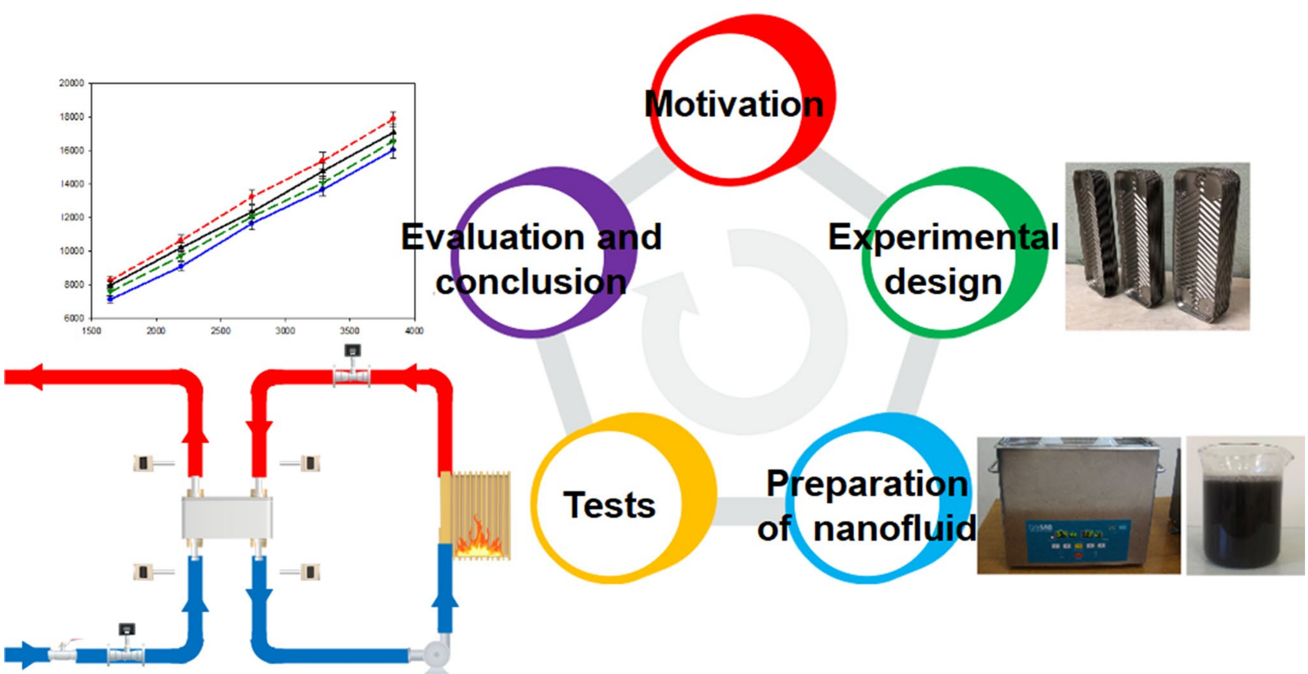

Fig. 1 Main steps of this work

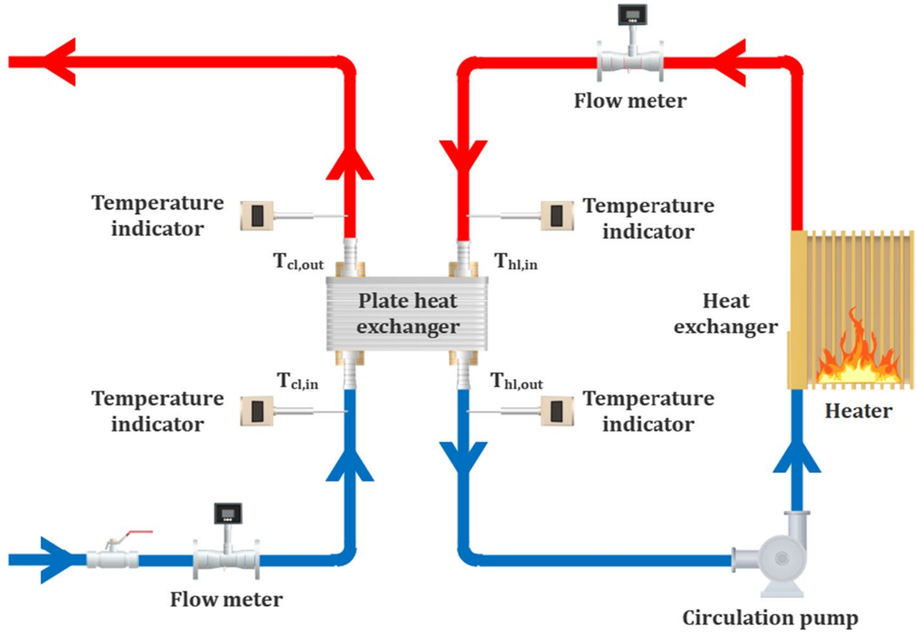

Fig. 2 Schematic view of test rig

Fig. 3 A view of utilized plate-type heat exchangers

nanofluid was prepared with 1% (50:50) particle weight concentration. Also, CuO/water and Al_2O_3/water single-type nanofluids have been prepared in order to compare with hybrid nanofluid. The obtained nanoparticles were added into the water and mechanically mixed. There are various techniques to prevent sedimentation and aggregation problems. In this study, Triton X-100 surface-active agent was mixed into the prepared nanofluid solutions. Adding surface-active agent enhances wetting ability and reduces surface tension and consequently leads to achieve stable nanofluid. In addition to using surface-active agent, ultrasonication process has been utilized to enhance the stability of prepared single and hybrid nanofluids.

Determining thermophysical properties of the utilized nanofluids is another important issue. Densities of Al_2O_3/water, CuO/water and Al_2O_3–CuO/water nanofluids have been determined by taking weight of a specified volume of solutions by utilizing an analytical balance. Using nanoparticles improves heat transfer by upgrading thermal conductivity of base fluid. But, adding nanoparticles increases the viscosity of base fluid which can increase pressure drop. The viscosity of prepared nanofluids has been achieved by using AND SV-10 viscometer device. In the present work, heat capacity of the working fluid has been attained with differential scanning calorimetry (DSC) technique. Accordingly, Perkin Elmer Diamond DSC device has been used in obtaining heat capacity of single and hybrid nanofluids. Finally, thermal conductivity of prepared nanofluid samples has been determined by utilizing TPS 500S thermal conductivity measuring device which uses hot-disk method.

2.3 Test procedure

The performance tests of single and hybrid nanofluids have been done utilizing three different PHEs with eight, 12 and 16 plates. The tests have been performed in various configurations to specify the thermal behavior of the nanofluid in PHEs. In this context, the performance tests have been done in five various flow rates in the range of 3–7 lpm. The experiments have been conducted by using water, CuO/water, Al_2O_3/water and Al_2O_3–CuO/water hybrid nanofluids with the aim of specifying the effect of using single and hybrid nanofluids on the efficiency. Moreover, all experiments were repeated three times to achieve reliable results.

As mentioned above, the experiments have been conducted at five different flow rates. Before starting each experiment, flow rate and outlet temperature were adjusted to the set values. Then, the experiment started and system worked until it reached steady-state conditions. The temperature values at inlet and outlet of two fluid loops were recorded when steady-state conditions were obtained. It should be stated that pressure drop in the HE was not obtained experimentally.

3 Theoretical analysis

The heat transfer in PHE can be expressed as the detracted energy in hot loop ($\dot{Q}_{\mathrm{hl}}$) or as the gained energy by the cold loop ($\dot{Q}_{\mathrm{cl}}$) and found by utilizing the following equations:

$$\dot{Q}_{\mathrm{hl}} = \dot{m}_{\mathrm{hl}} \times c_{p,\mathrm{hl}} \times \left(T_{\mathrm{hl,in}} - T_{\mathrm{hl,out}}\right) \tag{1}$$

$$\dot{Q}_{\mathrm{cl}} = \dot{m}_{\mathrm{cl}} \times c_{p,\mathrm{cl}} \times \left(T_{\mathrm{cl,out}} - T_{\mathrm{cl,in}}\right) \tag{2}$$

Mean value of the detracted and gained heat can be found as follows:

$$\dot{Q}_{\mathrm{av}} = \frac{\left(\dot{Q}_{\mathrm{hl}} + \dot{Q}_{\mathrm{cl}}\right)}{2}. \tag{3}$$

The effectiveness of the PHE can be defined by Eq. (4):

$$\varepsilon_{\mathrm{PHE}} = \frac{C_{\mathrm{hl}} \times \left(T_{\mathrm{hl,in}} - T_{\mathrm{hl,out}}\right)}{C_{\mathrm{min}} \times \left(T_{\mathrm{hl,in}} - T_{\mathrm{hl,out}}\right)} = \frac{C_{\mathrm{cl}} \times \left(T_{\mathrm{cl,out}} - T_{\mathrm{cl,in}}\right)}{C_{\mathrm{min}} \times \left(T_{\mathrm{hl,in}} - T_{\mathrm{hl,out}}\right)} \tag{4}$$

Heat capacity rate of hot fluid (C_{hl}) can be calculated as follows:

$$C_{\mathrm{hl}} = \dot{m}_{\mathrm{hl}} \times c_{p,\mathrm{hl}}. \tag{5}$$

Heat capacity rate of cold fluid (C_{cl}) can be found as follows:

$$C_{\mathrm{cl}} = \dot{m}_{\mathrm{cl}} \times c_{c,\mathrm{hl}}. \tag{6}$$

Heat transfer coefficient can be found by utilizing Nusselt number [33]:

$$\mathrm{Nu} = \frac{h \times D_{\mathrm{h}}}{k} \tag{7}$$

There are different correlations available for Nusselt number in PHE [34]:

$$\mathrm{Nu} = 0.348 \times \mathrm{Re}^{0.663} \times \mathrm{Pr}^{0.33} \tag{8a}$$

$$\mathrm{Nu} = 0.471 \times \mathrm{Re}^{0.5} \times \overset{0.33}{\mathrm{Pr}} \tag{8b}$$

where Reynolds number and Prandtl number can be found by utilizing Eq. (9) and Eq. (10), respectively:

$$\mathrm{Re} = \frac{G \times D_{\mathrm{h}}}{\mu} \tag{9}$$

$$\mathrm{Pr} = \frac{\mu \times c_p}{k}. \tag{10}$$

OHTC can be found by utilizing Eq. (11):

$$U = \frac{\dot{Q}_{\mathrm{av}}}{A \times \mathrm{LMTD}}. \tag{11}$$

Logarithmic mean temperature difference can be defined by the following expression:

$$\mathrm{LMTD} = \left[\left(T_{\mathrm{hl,in}} - T_{\mathrm{cl,out}}\right) - \left(T_{\mathrm{hl,out}} - T_{\mathrm{cl,in}}\right)\right] \Big/ \ln\left(\frac{T_{\mathrm{hl,in}} - T_{\mathrm{cl,out}}}{T_{\mathrm{hl,out}} - T_{\mathrm{cl,in}}}\right). \tag{12}$$

The HTC of nanofluid can be found by Eq. 13:

$$U = \frac{1}{\left(1/h_{\mathrm{hl}}\right) + \left(1/h_{\mathrm{cl}}\right) + \left(\Delta x/k_{\mathrm{p}}\right)}. \tag{13}$$

Each channel has an equivalent flow area. The following formulas are used for calculation of a wetted perimeter:

$$A_0 = HW \tag{14}$$

$$P = 2(W + H) \tag{15}$$

The hydraulic diameter of the channel can be obtained by utilizing Eq. (16) [35]:

$$D_{\mathrm{h}} = \frac{4A_0}{P} \tag{16}$$

Thermal diffusivity and specific flow rates for fluids can be estimated utilizing Eqs. (17)–(18), respectively:

$$\alpha = \frac{k}{\rho c_p} \tag{17}$$

$$G = \frac{m}{A_0} \tag{18}$$

The Peclet number can be estimated as follows:

$$\mathrm{Pe} = \frac{u D_{\mathrm{h}}}{\alpha} \tag{19}$$

The friction factor in PHE is obtained from Eq. (20) [36]:

$$f = \left(2.9 + 5.6\emptyset + 0.12\emptyset^2\right)\mathrm{Pe}^{-0.13} \quad (20)$$

Pressure drop value of a PHE can be calculated by utilizing the friction factor in Eq. (21) [36]:

$$\Delta p = f\left[\frac{LG^2}{2D_{\mathrm{h}}\rho g_c}\right] \quad (21)$$

Pumping power can be estimated from the following formula:

$$P_c = \frac{\dot{m}\Delta p}{\rho}. \quad (22)$$

Experimental uncertainty can be calculated as follows [37, 38]:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1}w_1\right)^2 + \left(\frac{\partial R}{\partial x_2}w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n}w_n\right)^2\right]^{1/2}. \quad (23)$$

4 Experimental findings

In this part, the experimental outcomes of utilizing water, single and hybrid nanofluids in three PHEs with different number of plates are presented and concluded.

Single and hybrid nanofluids have been tested with 1% weight concentration. It must be indicated that prepared CuO and Al_2O_3 nanoparticle sizes are 77 nm and 78 nm, respectively, with purity of 99.5%. In the first step of the experiments, water has been used in hot fluid loop of PHE. In the second stage of the experiments, single and hybrid nanofluids have been used as working fluid and the obtained results have been compared to the deionized water. The obtained thermophysical properties of single and hybrid nanofluids are presented in Table 1. As it is seen, thermal conductivity of nanofluids is higher in comparison with the water, which is the main reason for upgrading the thermal performance of nanofluids.

Figure 4 presents heat transfer rate via Reynolds number in PHE with eight plates. As it is seen in Fig. 4, utilizing Al_2O_3–CuO/water nanofluid enhanced the heat transfer

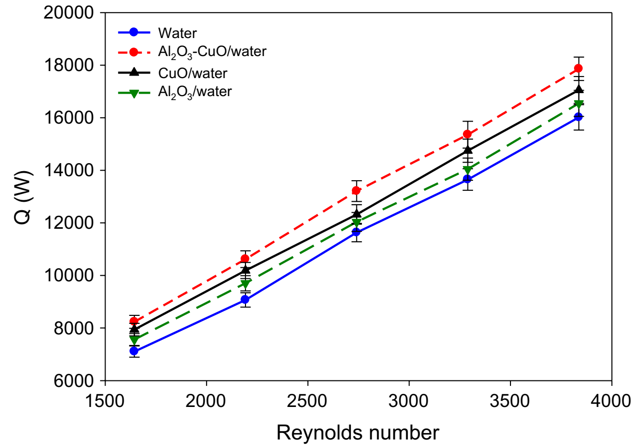

Fig. 4 Heat transfer rate via Reynolds number (eight plates)

notably in comparison with water, CuO/water and Al_2O_3/water. A mean enhancement of 9.5% in the heat transfer was achieved by utilizing hybrid-type nanofluid. Also, average improvement in the heat transfer by using Al_2O_3/water and CuO/water was obtained as 4.6% and 8.9%, respectively. It is better to state that increasing Reynolds number which is directly related to flow rate led to improvement in heat transfer as seen in Fig. 4.

Figure 5 illustrates transferred heat via Reynolds number in PHE with 12 plates. Utilizing Al_2O_3–CuO/water in this HE improved the heat transfer rate averagely as 11.4%. Also, average increment in the heat transfer by using CuO/water and Al_2O_3/water was obtained as 10.5% and 4.9%, respectively.

Figure 6 shows transferred heat via Reynolds number in PHE with 16 plates. Using hybrid nanofluid in this HE increased transferred heat averagely as 13.1%. Also, average increment in the transferred heat by utilizing CuO/water and Al_2O_3/water was obtained as 11.3% and 5.2%, respectively. It is clearly seen that increasing the number of plates in PHE led to higher enhancement in heat transfer rate by utilizing nanofluid. The obtained results for heat transfer clearly show that utilizing hybrid-type nanofluid caused more enhancement in comparison with single-type nanofluids.

Obtained heat transfer rate in this research varied in the range of 7102–19.532 W. In a study done by Ozdemir

Table 1 Thermophysical properties of single and hybrid nanofluids at 40 °C

Fluid	Viscosity (mPa s)	Density (kg/m^3)	Heat capacity (J/kg K)	Thermal conductivity (W/m K)
Water	0.62	998	4180	0.61
Al_2O_3/water	0.77	1012	4090	0.65
CuO/water	0.73	1044	3950	0.69
Al_2O_3–CuO/water	0.74	1031	4020	0.72

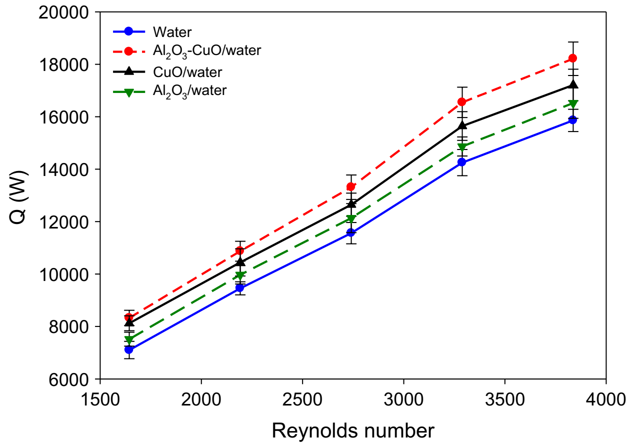

Fig. 5 Heat transfer rate via Reynolds number (12 plates)

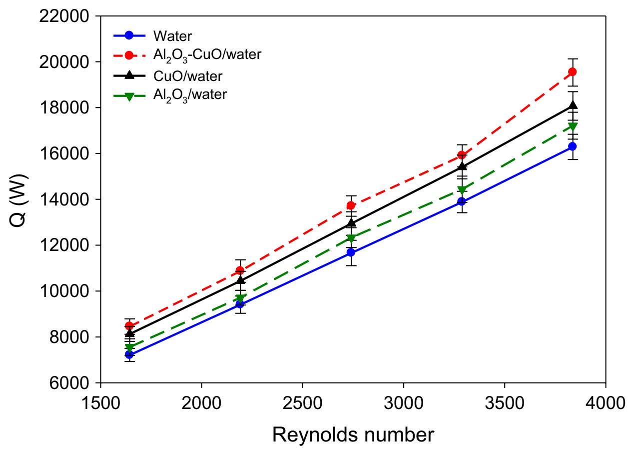

Fig. 6 Heat transfer rate via Reynolds number (16 plates)

and Ergun [5], Al_2O_3/water nanofluid was experimentally tested in PHE with 16 plates and achieved heat transfer rate between 3000 and 14,000 W. In another study conducted by Variyenli [3], the performance of using fly ash nanofluid in PHE with 16 plates was analyzed and heat transfer rate obtained was 2500–10,800 W. Also, Khanlari et al. [2] experimentally tested TiO_2/water and Kaolin/water nanofluids in PHE and found heat transfer rate in the range of 5000–20,000 W.

Figure 7 demonstrates the variation in OHTC with respect to Reynolds number in PHE with eight plates. Hybrid nanofluid utilization in this HE increased the OHTC averagely as 10.5%. Also, average increase in the OHTC by using CuO/water and Al_2O_3/water was obtained as 6.6% and 3.2%, respectively.

Figure 8 demonstrates the change in OHTC with respect to Reynolds in PHE with 12 plates. Hybrid nanofluid utilization improved the OHTC averagely as 17%. Also,

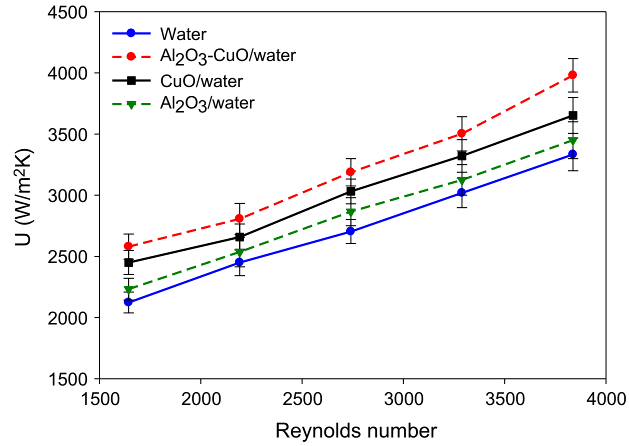

Fig. 7 Change in OHTC with Reynolds number (eight plates)

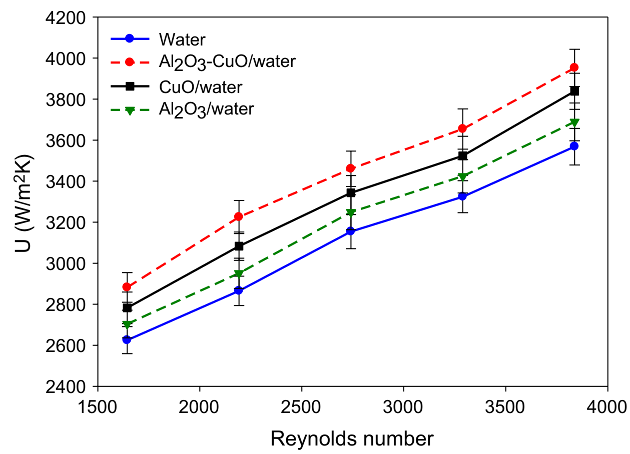

Fig. 8 Change in OHTC with Reynolds number (12 plates)

average increase in the OHTC by using CuO/water and Al_2O_3/water was obtained as 11.2% and 4.3%, respectively.

Figure 9 demonstrates the change in OHTC via Reynolds number in PHE with 16 plates. Hybrid nanofluid utilization improved the OHTC averagely as 18.6%. Also, average increment in the OHTC by using CuO/water and Al_2O_3/water was obtained as 11.8% and 4.9%, respectively. Utilization of Al_2O_3–CuO/water hybrid nanofluid enhanced the OHTC significantly. Moreover, increasing the number of plates in PHE caused higher increase in OHTC by using this hybrid nanofluid. It should be indicated that higher flow rates lead to higher Reynolds numbers and consequently turbulent flows, which increases OHTC. The achieved results for OHTC clearly present that utilizing hybrid nanofluid caused more improvement in comparison with single-type nanofluids.

Obtained OHTC in this study varied in the range of 2123–4503 W/m^2 K. In a research done by Sarafraz et al. [39], CuO/water nanofluid was tested in PHE with 36 plates

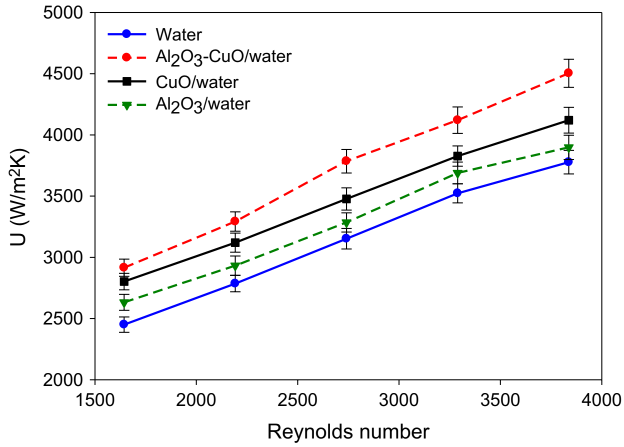

Fig. 9 Change in OHTC with Reynolds number (16 plates)

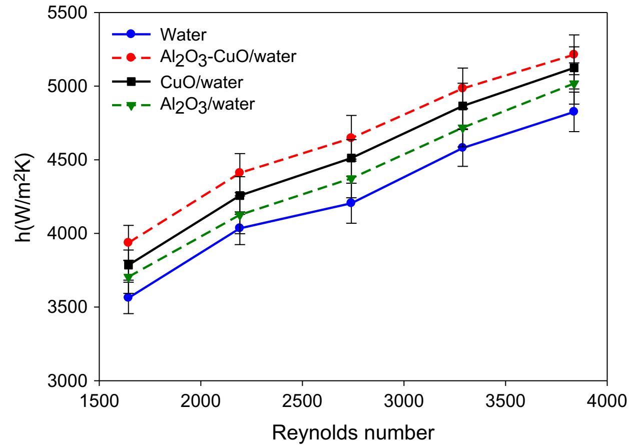

Fig. 11 HTC variation with Reynolds number (12 plates)

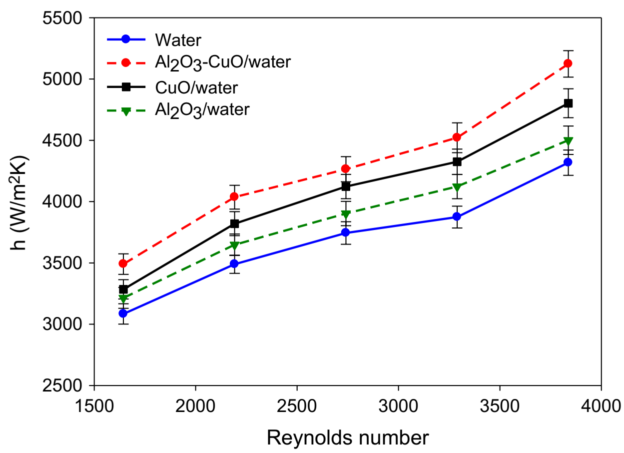

Fig. 10 HTC variation with Reynolds number (eight plates)

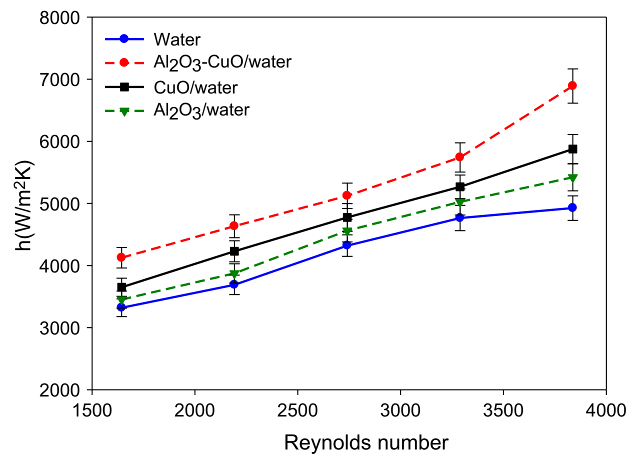

Fig. 12 HTC variation with Reynolds number (16 plates)

and OHTC was obtained up to 12,000 W/m^2 K. In another work conducted by Variyenli [3], the performance of using fly ash nanofluid in PHE with 16 plates was analyzed and OHTC was obtained between 1400 and 2600 W/m^2 K. Teng et al. [40] investigated the utilization of carbon-based nanofluid in PHE and found OHTC in the range of 2700–3300.

Figure 10 shows HTC variation with Reynolds number in PHE with eight plates. It is observed that utilizing Al_2O_3–CuO/water nanofluid improved heat transfer coefficient in all Reynolds numbers significantly. Average improvement of 8.2% in HTC was achieved by utilizing hybrid-type nanofluid. In addition, average increment in the HTC by utilizing CuO/water and Al_2O_3/water was obtained as 6.2% and 3.4%, respectively.

Figure 11 illustrates HTC variation with Reynolds number in PHE with 12 plates. Hybrid-type nanofluid utilization enhanced the HTC averagely as 14.9%. In addition, average improvement in the HTC by using CuO/water and Al_2O_3/water was obtained as 9.7% and 4.7%, respectively.

Figure 12 shows HTC change with Reynolds number in PHE with 16 plates. Average improvement of 19% in HTC was achieved by using hybrid-type nanofluid. Also, average enhancement in the HTC by using CuO/water and Al_2O_3/water was achieved as 12.9% and 6%, respectively. Experimental results showed that increasing number plates led to more increment in HTC by using hybrid-type nanofluid because it increases the presence time of fluid inside the HE. The achieved results for HTC present that utilizing hybrid nanofluid led to more enhancement in comparison with single-type nanofluids.

Obtained HTC in this study varied in the range of 3084–6890 W/m^2 K. In a work conducted by Huang et al. [27], multiwalled carbon nanotubes and Al_2O_3-based hybrid nanofluids were tested in PHE and HTC was obtained in the range of 2500–10,000 W/m^2 K. In another study done by Variyenli [3], fly ash containing nanofluid was tested in PHE and HTC was achieved in the range of 1600–3000 W/m^2 K. Also, Sun et al. [18] analyzed the performance of Cu/

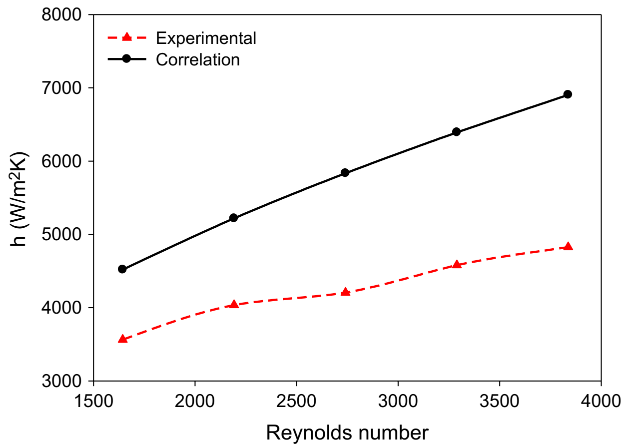

Fig. 13 HTC variation of water with Reynolds number (eight plates)

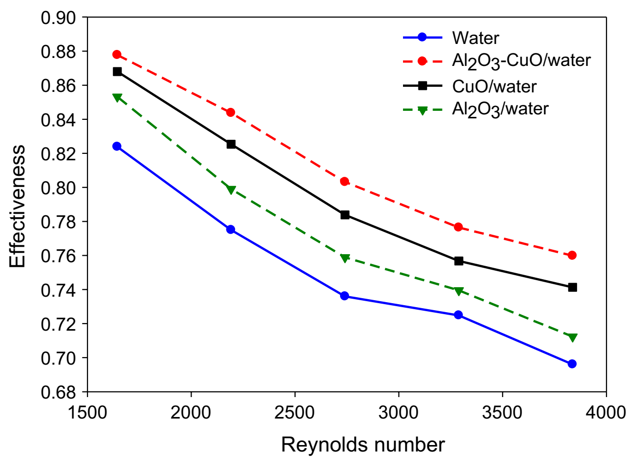

Fig. 14 Change in the effectiveness of PHE with respect to Reynolds number (eight plates)

water, Fe_2O_3/water and Al_2O_3/water nanofluids in PHE and obtained HTC between 300 and 2000 W/m^2 K. Shirzad et al. [41] tested Al_2O_3/water, CuO/water and TiO_2/water nanofluids in PHE and found HTC in the range of 3000–28,000. However, it should be stated that mentioned studies were done in various Reynolds numbers which makes it hard to make an accurate comparison.

There are some correlations available in the literature which are proposed to obtain Nusselt number and consequently HTC. Figure 13 presents a comparison between experimentally obtained HTC and the obtained HTC by using a correlation suggested by Kakaç and Liu [34]. As it can be seen, experimentally obtained HTC values for water are lower than those obtained by using correlation.

Figure 14 shows HE effectiveness variation with Reynolds number in PHE with eight plates. It is clear that utilizing CuO/water, Al_2O_3/water and Al_2O_3–CuO/water hybrid nanofluid improved effectiveness in all Reynolds

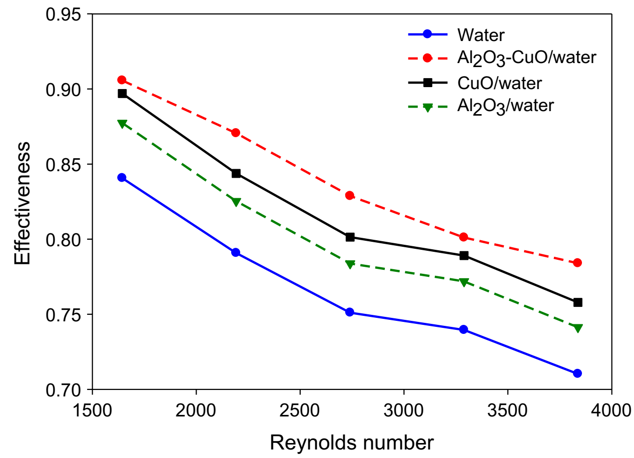

Fig. 15 Change in the effectiveness of PHE with respect to Reynolds number (12 plates)

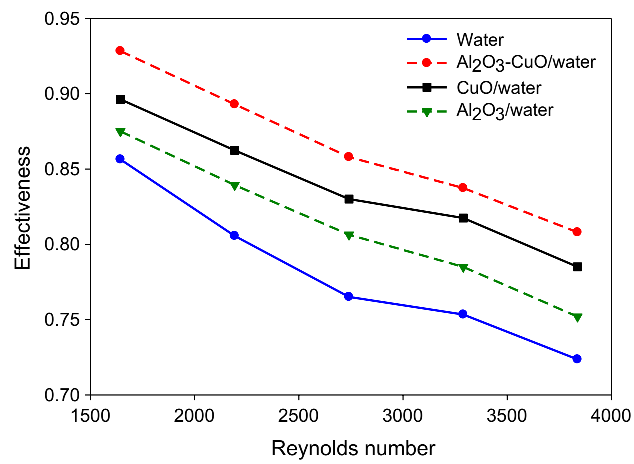

Fig. 16 Change in the effectiveness of PHE with respect to Reynolds number (16 plates)

numbers. Average enhancement of 8.1% in effectiveness was obtained by using hybrid-type nanofluid. Moreover, average increment in the effectiveness by using CuO/water and Al_2O_3/water was obtained as 5.8% and 3%, respectively.

Figure 15 illustrates effectiveness variation with Reynolds number in PHE with 12 plates. Hybrid nanofluid utilization improved the effectiveness averagely as 9.3%. In addition, average enhancement in the effectiveness by utilizing CuO/water and Al_2O_3/water was obtained as 6.7% and 4.3%, respectively.

Figure 16 shows effectiveness change with Reynolds number in PHE with 16 plates. Average improvement of 10.8% in effectiveness was achieved by using hybrid-type nanofluid. Also, mean increment in the effectiveness by using Al_2O_3/water and CuO/water was obtained as 4.1% and 7.4%, respectively.

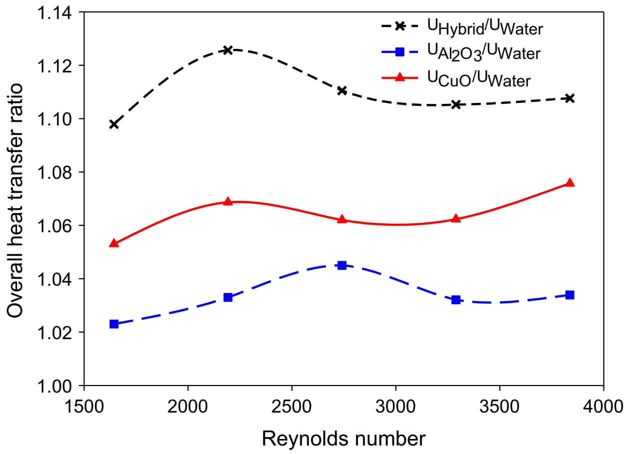

Fig. 17 Variation in OHTC ratio via Reynolds number (eight plates)

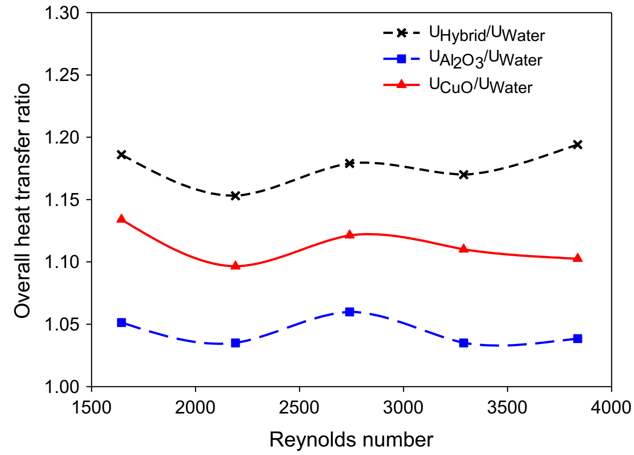

Fig. 18 Variation in OHTC ratio via Reynolds number (12 plates)

It was observed that effectiveness of HE was reduced by raising Reynolds number value. It should be said that Reynolds number rises by increasing flowing fluid flow rate. In addition, it must be said that heat capacity rate of working fluid improves by rising flow rate and consequently temperature change in working fluid reduces, which lead to fall in effectiveness of HE. Moreover, in higher fluid flow rates, temperature change will be lesser because working fluid's presence period is limited in the HE and leads to reduction in the effectiveness of HE.

The obtained effectiveness of PHE in this study varied in the range of 0.69–0.92. Khanlari et al. [2] experimentally tested TiO_2/water and kaolin/water nanofluids and found effectiveness between 0.7 and 0.91. Bhattad et al. [30] conducted a study on a PHE with Al_2O_3 + MWCNT/water and obtained effectiveness between 0.45 and 0.75.

The variation in the OHTC ratio ($U_{\text{nanofluid}}/U_{\text{water}}$) via Reynolds number in PHE with eight plates is presented in Fig. 17. This figure shows the positive impact of utilizing nanofluid on the performance enhancement of PHE. OHTC ratio varied between 1.025 and 1.125 in various Reynolds numbers. Figure 18 presents the variation in the OHTC ratio via Reynolds number in PHE with 12 plates. OHTC ratio varied between 1.04 and 1.19 in different Reynolds numbers. The variation in the OHTC ratio with Reynolds number in PHE with 16 plates is shown in Fig. 19. OHTC ratio varied between 1.04 and 1.20 in different Reynolds numbers in PHE with 16 plates. As it can be seen in Figs. 16, 17 and 18, higher performance enhancement was achieved by using hybrid nanofluids in comparison with single-type nanofluids.

Experimental findings of the present study demonstrated that utilizing Al_2O_3–CuO/water hybrid nanofluid in the PHE increased thermal performance notably. Using this hybrid nanofluid increased the thermal performance in all PHEs with different number of plates. However, it is observed that increasing number of plates led to more increment in the performance by using hybrid nanofluid.

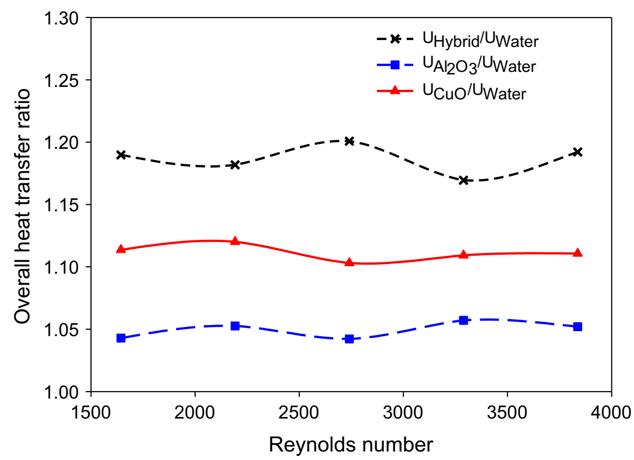

Fig. 19 Variation in OHTC ratio via Reynolds number (16 plates)

Table 2 Uncertainty values of some parameters

Parameter	Unit	Uncertainty
Temperature	°C	± 0.53
Flow rate	lpm	± 5.24%
Transferred heat	W	± 8.2%

Uncertainty values of some parameters are given in Table 2. Obtained values are in a good agreement with the similar studies in the literature [2, 3, 45]. In a research conducted by Tu et al. [46], uncertainty value for transferred heat was found as ± 10.4%. Also, Afshari et al. [47] obtained uncertainty value for temperature as 1.2%.

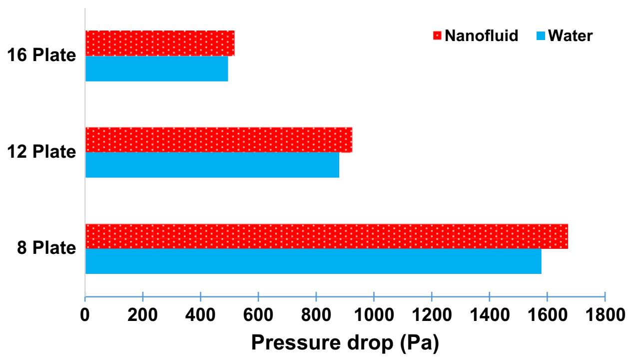

Fig. 20 Average pressure drop in PHE with different number of plates

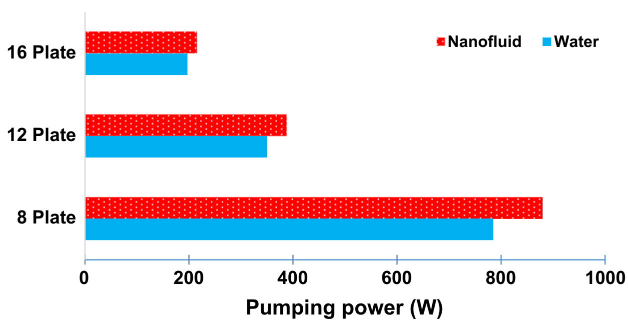

Fig. 21 Average pumping in PHE with different number of plates

Figure 20 presents average pressure drop in PHE with different number of plates. It is better to state that pressure drop in the HE was not obtained experimentally. The pressure drop in this work was achieved by utilizing a widely used correlation. As it can be seen in Fig. 20, using nanofluid led to an extra pressure drop in PHE. However, the difference between pressure drops of water and nanofluid is not high. Using hybrid nanofluid increased the pressure drop as 6%, 5% and 4.3% in PHEs with eight, 12 and 16 plates, respectively. A research done by Kabeel et al. [42] used Al_2O_3 nanofluid with different volume concentrations (1–4%) in PHE and obtained pressure drop between 1200 and 1800 Pa. Tiwari et al. [17] experimentally analyzed thermal performance of Al_2O_3/water in PHE and obtained pressure drop in the range of 30–520 Pa. Also, Sun et al. [18] analyzed the performance of Cu/water, Fe_2O_3/water and Al_2O_3/water nanofluids in PHE and obtained pressure drop between 30 and 160 Pa. Behrangzade et al. [43] utilized Ag–water nanofluid as the working fluid in PHE and achieved pressure drop of 400–1800 Pa. Kwon et al. [44] studied ZnO and Al_2O_3 nanofluids in a PHE and found pressure drop between 250 and 2500 Pa.

In addition, Fig. 21 presents average pumping in PHE with different number of plates. As it is seen in Fig. 21, using nanofluid led to an increase in pumping power in PHE. However, the difference in pumping of water and nanofluid is not high. Utilizing hybrid nanofluid increased the pumping as 12%, 10.5% and 9% in PHEs with eight, 12 and 16 plates, respectively.

Table 3 shows summary of studies about CuO/water and Al_2O_3/water nanofluids utilization in various types of HEs. As it is clear, utilizing Al_2O_3/water and CuO/water nanofluids separately enhanced the efficiency. In the present research, the thermal performance of PHE improved by utilizing CuO–Al_2O_3/water hybrid nanofluid because single nanoparticle cannot supply all intended properties. The obtained results in the present study show successful utilization of hybrid-type nanofluid. However, it is better to state that in studies given in Table 3, nanoparticle concentration is not the same in all studies.

Table 3 Summary of studies about Al_2O_3/water and CuO/water nanofluids usage in various types of HEs

References	Nanoparticles	Type of study	HE	Results
Bahmani et al. [48]	Al_2O_3	Numerical	Tubular type	30% maximum improvement in the efficiency
Chun et al. [49]	Al_2O_3	Experimental	Tubular type	HTC enhanced 13% in comparison with the base fluid by 0.5% particle ratio
Sözen et al. [50]	Al_2O_3	Experimental	Tubular type	5.1% improvement in the thermal performance
Srinivas and Venu Vinod [51]	CuO, Al_2O_3	Experimental	Shell and helically Coiled	CuO/water and Al_2O_3/water enhanced HTC as 32.7% and 30.37%, respectively
Pandey and Nema [31]	Al_2O_3	Experimental	Plate type	Increase in the heat exchanger performance between 4.6 and 10%
Kabeel et al. [42]	Al_2O_3	Experimental	Plate type	13% improvement in thermal performance
Kumar et al. [52]	CuO	Experimental	Shell and tube	Transferred heat raised by increasing nanoparticle concentration
Sarafraz et al. [39]	CuO	Experimental	Plate type	OHTC increased between 3.4 and 8.6%
This study	Al_2O_3–CuO	Experimental	Plate type	Highest enhancement in effectiveness achieved as 10%, 11.7% and 16% in PHEs with eight, 12 and 16 plates, respectively

5 Conclusions

In the present work, Al_2O_3 and CuO have been utilized to prepare Al_2O_3–CuO/water hybrid nanofluid. Accordingly, Al_2O_3 and CuO nanoparticles have been added to the water with 1% (50:50) weight concentration. The prepared single and hybrid nanofluids have been tested PHEs with eight, 12 and 16 plates to determine the influence of number of plates on heat transfer improvement by hybrid-type nanofluid. Experimental outcomes of the present work demonstrated that utilizing Al_2O_3–CuO/water nanofluid in the PHE enhanced thermal performance notably. Using this hybrid nanofluid increased the thermal performance in all PHEs with different number of plates. However, it is observed that increasing number of plates caused more increment in thermal efficiency by using hybrid nanofluid. Maximum increment in OHTC was obtained as 12%, 19% and 20% in PHEs with eight, 12 and 16 plates, respectively. In addition, the highest enhancement in effectiveness was achieved as 10%, 11.7% and 16% in PHEs with eight, 12 and 16 plates, respectively.

References

1. Khanlari A, Sözen A, Variyenli Hİ (2019) Simulation and experimental analysis of heat transfer characteristics in the plate type heat exchangers using TiO_2/water nanofluid. Int J Numer Methods Heat Fluid Flow 29:1343–1362
2. Khanlari A, Sözen A, Variyenli Hİ, Gürü M (2019) Comparison between heat transfer characteristics of TiO_2/deionized water and kaolin/deionized water nanofluids in the plate heat exchanger. Heat Transf Res 50:435–450
3. Variyenli Hİ (2019) Experimental and numerical investigation of heat transfer enhancement in a plate heat exchanger using a fly ash nanofluid. Heat Transf Res 50:1477–1494
4. Barzegarian R, Keshavarz Moraveji M, Aloueyan A (2016) Experimental investigation on heat transfer characteristics and pressure drop of BPHE (brazed plate heat exchanger) using TiO_2–water nanofluid. Exp Therm Fluid Sci 74:11–18
5. Ozdemir MB, Ergun ME (2019) Experimental and numerical investigations of thermal performance of Al_2O_3/water nanofluid for a combi boiler with double heat exchangers. Int J Numer Methods Heat Fluid Flow 20:1300–1321
6. Karagoz S, Afshari F, Yildirim O, Comakli O (2017) Experimental and numerical investigation of the cylindrical blade tube inserts effect on the heat transfer enhancement in the horizontal pipe exchangers. Heat Mass Transf 53:2769–2784
7. Afshari F, Zavaragh HG, Sahin B, Grifoni RC, Corvaro F, Marchetti B, Polonara F (2018) On numerical methods; optimization of CFD solution to evaluate fluid flow around a sample object at low Re numbers. Math Comput Simul 152:51–68
8. Avramenko AA, Shevchuk IV, Moskalenko AA, Lohvynenko PN, Kovetska YY (2018) Instability of a vapor layer on a vertical surface at presence of nanoparticles. Appl Therm Eng 139:87–98
9. Moreira TA, Moreira DC, Ribatski G (2018) Nanofluids for heat transfer applications: a review. J Braz Soc Mech Sci Eng 40:303
10. Nair V, Parekh AD, Tailor PR (2018) Water-based Al_2O_3, CuO and TiO_2 nanofluids as secondary fluids for refrigeration systems: a thermal conductivity study. J Braz Soc Mech Sci Eng 40:262
11. Badali Y, Azizian-Kalandaragh Y, Akhlaghi EA, Altindal S (2020) Ultrasound assisted method for preparation of Ag_2S nanostructures: fabrication of Au/Ag_2S–PVA/n–Si schottky barrier diode and exploring their electrical properties. J Electron Mater 49:444–453
12. Badali Y, Koçyiğit S, Aytimur A, Altindal Ş, Uslu I (2019) Synthesis of boron and rare earth stabilized graphene doped polyvinylidene fluoride (PVDF) nanocomposite piezoelectric materials. Polym Compos 40:3623–3633
13. Avramenko AA, Shevchuk IV, Tyrinov AI, Blinov DG (2014) Heat transfer at film condensation of stationary vapor with nanoparticles near a vertical plate. Appl Therm Eng 73:389–396
14. Gürbüz EY, Variyenli Hİ, Sözen A, Khanlari A, Ökten M (2020) Experimental and numerical analysis on using CuO–Al_2O_3/water hybrid nanofluid in a U-type tubular heat exchanger. Int J Numer Methods Heat Fluid Flow. https://doi.org/10.1108/HFF-04-2020-0195
15. Asadi A, Pourfattah F, Szilágyi IM, Afrand M, Żyła G, Ahn HS, Wongwises S, Nguyen HM, Arabkoohsar A, Mahian O (2019) Effect of sonication characteristics on stability, thermophysical properties, and heat transfer of nanofluids: a comprehensive review. Ultrason Sonochem 58:104701
16. Deymi-Dashtebayaz M, Akhoundi M, Arabkoohsar A, Ebrahimi-Moghadam A, Jabari Moghadam A, Farzaneh-Gord M (2020) Thermo-hydraulic analysis and optimization of CuO/water nanofluid inside helically dimpled heat exchangers. J Therm Anal Calorim. https://doi.org/10.1007/s10973-020-09398-0
17. Tiwari AK, Ghosh P, Sarkar J (2015) Particle concentration levels of various nanofluids in plate heat exchanger for best performance. Int J Heat Mass Transf 89:1110–1118
18. Sun B, Peng C, Zuo R, Yang D, Li H (2016) Investigation on the flow and convective heat transfer characteristics of nanofluids in the plate heat exchange. Exp Therm Fluid Sci 76:75–86
19. Taghizadeh-Tabari Z, Heris SZ, Moradi M, Kahani M (2016) The study on application of TiO_2/water nanofluid in plate heat exchanger of milk pasteurization industries. Renew Sustain Energy Rev 58:1318–1326
20. Javadi FS, Sadeghipour S, Saidur R, BoroumandJazi G, Rahmati B, Elias MM, Sohel MR (2013) The effects of nanofluid on thermophysical properties and heat transfer characteristics of a plate heat exchanger. Int Commun Heat Mass Transf 44:58–63
21. Zhao Q, Xu H, Tao L (2020) Flow and heat transfer of nanofluid through a horizontal microchannel with magnetic field and interfacial electrokinetic effects. Eur J Mech B/Fluids 80:72–79
22. Zheng M, Han D, Asif F, Si Z (2019) Effect of Al_2O_3/water nanofluid on heat transfer of turbulent flow in the inner pipe of a double-pipe heat exchanger. Heat Mass Transf. https://doi.org/10.1007/s00231-019-02774-z
23. Ağbulut Ü, Sarıdemir S (2018) A general view to converting fossil fuels to cleaner energy source by adding nanoparticles. Int J Ambient Energy. https://doi.org/10.1080/01430750.2018.1563822
24. Ağbulut Ü, Karagöz M, Sarıdemir S, Öztürk A (2020) Impact of various metal-oxide based nanoparticles and biodiesel blends on the combustion, performance, emission, vibration and noise characteristics of a CI engine. Fuel 270:117521
25. Han ZH, Yang B, Kim SH, Zachariah MR (2007) Application of hybrid sphere/carbon nanotube particles in nanofluids. Nanotechnology 18:105701
26. Suresh S, Venkitaraj KP, Selvakumar P, Chandrasekar M (2012) Effect of Al_2O_3–Cu/water hybrid nanofluid in heat transfer. Exp Therm Fluid Sci 38:54–60

27. Huang D, Wu Z, Sunden B (2016) Effects of hybrid nanofluid mixture in plate heat exchangers. Exp Therm Fluid Sci 72:190–196
28. Kumar V, Kumar Tiwari A, Kumar Ghosh S (2016) Effect of variable spacing on performance of plate heat exchanger using nanofluids. Energy 114:1107–1119
29. Kumar V, Kumar Tiwari A, Kumar Ghosh S (2018) Exergy analysis of hybrid nanofluids with optimum concentration in a plate heat exchanger. Mater Res Express 5:065022
30. Bhattad A, Sarkar J, Ghosh P (2019) Experimentation on effect of particle ratio on hydrothermal performance of plate heat exchanger using hybrid nanofluid. Appl Therm Eng 162:114309
31. Babar H, Ali HM (2019) Towards hybrid nanofluids: preparation, thermophysical properties, applications, and challenges. J Mol Liq 281:598–633
32. Mehryan SAM, Farshad MK, Mohammad G, Chamkha AJ (2017) Free convection of hybrid Al_2O_3/Cu water nanofluid in a differentially heated porous cavity. Adv Powder Technol 28:2295–2305
33. Gherasim I, Roy G, Nguyen CT, Vo-Ngoc D (2009) Experimental investigation of nanofluids in confined laminar radial flows. Int J Therm Sci 48(8):1486–1493
34. Kakaç S, Liu H (2002) Heat exchangers: selection, rating and thermal design, 2nd edn. CRC Press LLC, Florida
35. Khairul MA, Alim MA, Mahbubul IM, Hepbasli A, Hossain A (2014) Heat transfer performance and exergy analyses of a corrugated plate heat exchanger using metal oxide nanofluids. Int Commun Heat Mass Transf 50:8–14
36. Pandey SD, Nema VK (2012) Experimental analysis of heat transfer and friction factor of nanofluid as a coolant in a corrugated plate heat exchanger. Exp Therm Fluid Sci 38:248–256
37. Khanlari A, Sözen A, Şirin C, Tuncer AD, Gungor A (2020) Performance enhancement of a greenhouse dryer: analysis of a cost-effective alternative solar air heater. J Clean Prod 251:119672
38. Ağbulut Ü, Gürel AE, Ergün A, Ceylan İ (2020) Performance assessment of a V-Trough photovoltaic system and prediction of power output with different machine learning algorithms. J Clean Prod 268:122269
39. Sarafraz MM, Nikkhah V, Madani SA, Jafarian M, Hormozi F (2017) Low-frequency vibration for fouling mitigation and intensification of thermal performance of a plate heat exchanger working with CuO/water nanofluid. Appl Therm Eng 1215:388–399
40. Teng TP, Hsiao TC, Chung CC (2019) Characteristics of carbon-based nanofluids and their application in a brazed plate heat exchanger under laminar flow. Appl Therm Eng 146:160–168
41. Shirzad M, Ajarostaghi SSM, Delavar MA, Sedighi K (2019) Improve the thermal performance of the pillow plate heat exchanger by using nanofluid: numerical simulation. Adv Powder Technol 30:1356–1365
42. Kabeel AE, El Maaty TA, El-Samadony Y (2013) The effect of using nano-particles on corrugated plate heat exchanger performance. Appl Therm Eng 52:221–229
43. Behrangzade A, Heyhat MM (2016) The effect of using nano-silver dispersed water based nanofluid as a passive method for energy efficiency enhancement in a plate heat exchanger. Appl Therm Eng 102:311–317
44. Kwon YH, Kim D, Li CG, Lee JK, Hong DS, Lee JG, Lee SH, Cho YH, Kim SH (2011) Heat transfer and pressure drop characteristics of nanofluids in a plate heat exchanger. J Nanosci Nanotechnol 11:5769–5774
45. Khanlari A (2020) The effect of utilizing Al_2O_3–SiO_2/deionized water hybrid nanofluid in a tube-type heat exchanger. Heat Transf Res. https://doi.org/10.1615/HeatTransRes.2020034103
46. Tu YD, Wang RZ, Ge TS (2018) New concept of desiccant enhanced heat pump. Energy Convers Manag 156:568–574
47. Afshari F, Karagoz S, Comakli O, Ghasemi Zavaragh H (2019) Thermodynamic analysis of a system converted from heat pump to refrigeration device. Heat Mass Transf 55(2):281–291
48. Bahmani MH, Sheikhzadeh G, Zarringhalam M, Akbari OA, Alrashed AAAA, Shabani GAS, Goodarzi M (2018) Investigation of turbulent heat transfer and nanofluid flow in a double pipe heat exchanger. Adv Powder Technol 29:273–282
49. Chun BH, Kang HU, Kim SH (2008) Effect of alumina nanoparticles in the fluid on heat transfer in double-pipe heat exchanger system. Korean J Chem Eng 25(5):966–971
50. Sözen A, Variyenli Hİ, Özdemir MB, Gürü M, Aytaç I (2016) Heat transfer enhancement using alumina and fly ash nanofluids in parallel and cross-flow concentric tube heat exchangers. J Energy Inst 89:414–424
51. Srinivas T, Venu Vinod A (2016) Heat transfer intensification in a shell and helical coil heat exchanger using water-based nanofluids. Chem Eng Process 102:1–8
52. Kumar N, Sonawane SS (2016) Experimental study of thermal conductivity and convective heat transfer enhancement using CuO and TiO_2 nanoparticles. Int Commun Heat Mass Transf 76:98–107