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Upgrading the performance of shell and helically coiled heat exchangers with new flow path by using TiO_2/water and CuO–TiO_2/water nanofluids

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A R T I C L E I N F O

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A B S T R A C T

Along with the developing technologies, the need for energy has increased day by day and negative environmental effects of fossil energy based systems increased the importance of efficient energy systems. In the recent years, shell and helically coiled type heat exchangers (SHCHEs) are extensively used in various applications because of their superior specifications in comparison with other heat exchangers. In the present work, it is targeted to raise the thermal performance of recently developed shell and helically coiled heat exchangers using single and hybrid type nanofluids. The main aim of this research is specifying the impact of hybrid CuO–TiO_2/water nanofluid in comparison with single TiO_2/water nanofluid. Also, the effect of adding fins as turbulators on performance enhancement of nanofluids was analyzed. In this regard, TiO_2/water and CuO–TiO_2/water nanofluids with 1% (wt./wt.) concentration was prepared and circulated in the hot side of both heat exchangers. TiO_2/water working nanofluid application in finless and finned SHCHEs averagely upgraded overall heat transfer coefficient as 7.5% and 8.6%, respectively. CuO–TiO_2/water working nanofluid application in finless and finned SHCHEs averagely upgraded overall heat transfer coefficient as 10.8% and 12%, respectively. Generally, it was observed that utilizing TiO_2/water and CuO–TiO_2/water nanofluid in unmodified and modified SHCHEs importantly raised the thermal performance. However, utilization of hybrid type nanofluid presented better performance than single nanofluid in both SHCHEs. Moreover, the outcomes exhibited further positive impacts of integrating fins on performance enhancement of both single and hybrid nanofluids.

1. Introduction

Due to the excessive increase in the unit costs of energy, the correct management of energy consumption and energy efficiency are gaining importance gradually. Heat exchangers play a crucial role because they influence the overall effectiveness of the energy conversion systems. This is because of the vital role that heat exchangers play in heat transfer between two fluids in the energy systems. In the heat exchanger market, shell and helically coiled heat exchangers (SHCHE) have the largest market share among all types of heat exchangers with approximately 40% [1]. Therefore, studies on improving the performance of shell and helically coiled heat exchangers have an important place in the literature [2–4]. In SHCHE, fluid passing through the helically coiled tubes that leads to produce a centrifugal force. The generated centrifugal force has a significant impact on flow behavior in the SHCHE. Therefore, the SHCHE allows a higher heat transfer rate with minimum pressure loss by making centrifugal effect over the flow in the helically coiled tube [5,6]. In some works, it is stated that parameters such as inlet velocity, coil diameter and coil pitch are the major parameters that affects heat transfer in the SHCHE [7,8].

Different types of SHCHEs have been analyzed by researchers from various aspects of view. In a study, Alimoradi [9] applied exergy approach in order to determine the overall flow and thermal behavior of SHCHEs. In another academic research, Alimoradi [10] numerically and empirically investigated thermal effectiveness of SHCHEs and its main relation with NTU. Miansari et al. [11] used numerical method in order to analyze grooves impacts on the total efficiency of a new SHCHE.

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Nomenclature

A	heat transfer area (m^2)
c_p	specific heat capacity ($kJ.kg^{-1}.K^{-1}$)
C	heat capacity rate ($W{\cdot}K^{-1}$)
d	coiled tube diameter (m)
De	Dean Number
D_h	hydraulic diameter (m)
h	heat transfer coefficient ($W.m^{-2}.K^{-1}$)
HE	heat exchanger
$\dot{m}$	mass flow rate ($kg.s^{-1}$)
Nu	Nusselt number
$OHTC$	overall heat transfer coefficient ($W.m^{-2}.K^{-1}$)
Pr	Prandtl Number
Re	Reynolds Number
T	temperature (K)
$SHCHE$	shell and helically coiled heat exchanger
w_1, w_2, w_n	the uncertainties in the independent variables
W_R	the overall uncertainty (%)

Greek letters

ΔT_{LMTD}	logarithmic mean temperature difference (K)
ε	effectiveness
μ	dynamic viscosity (Pa.s)
ρ	density ($kg.m^{-3}$)

Subscripts

cld	cold
cldfld	cold fluid
ht	hot
htfld	hot fluid
i	inlet
in	inner
o	outlet

Abu-Hamdeh et al. [12] simulated helically coiled tube type heat exchangers by applying exergy approach to determine its thermal and flow characteristics. Etghani and Hosseini Baboli [13] developed a new model in order to analyze the influence of some factors such as coil pitch and its diameter on heat and fluid flow characteristics of a SHCHE. Andrzejczyk and Muszynski [14] developed and used various types of turbulators in order to raise the thermal effectiveness of a SHCHE. Andrzejczyk and Muszynski [15] experimentally surveyed the thermal efficiency improvement potential of a SHCHE utilizing continuous core-baffle.

Two different thermal improvement approaches including active and passive methods are extensively used to increase heat transfer rate in heat exchangers [16,17]. In the passive method, changes are often applied to the surfaces and geometry of heat exchangers. These changes are often preferred in academic studies such as the addition of baffles, microchannels and fins in the design of heat exchangers [18,19]. Conventional working fluids such as water and oil cause some limitations in heat transfer rates due to their low thermal conductivity values [20–23]. In the active method, the working fluid in the energy system is changed, and heat transfer rate is increased by supplying the fluid with superior thermophysical specifications [24–27]. The concept of replacing the working fluid was first introduced to the literature in 1995 with the term "nanofluid" by Choi and Eastman [28]. There are some other outstanding studies are available that indicated high thermal performance can be achieved by using metal nanoparticles in the main fluid [29–31]. The thermal behavior of nanofluids depends on many factors that should be considered to obtain high thermal performance. Fig. 1 briefly represents the base parameters that influence the characteristics of nanofluids. Particle size, particle shape, particle ratio, and also base fluid's properties are the most important factors which affect the thermal and flow behavior of nanofluid [32,33].

CuO and TiO_2 nanoparticles are widely utilized to prepare nanofluids because of their good thermal specifications [34–36]. In a study conducted by Fule et al. [37], CuO/water single nanofluid was studied in two different particle ratios at Reynolds numbers between 812 and 1895 in a SHCHE in order to enhance its thermal effectiveness. Bazdidi-Tehrani et al. [38] numerically investigated the behavior of TiO_2/water working fluid in a ribbed type flat solar heater. Ali et al. [39] investigated different preparation techniques for TiO_2 based nanofluids and suggested some methods for improving physical properties and

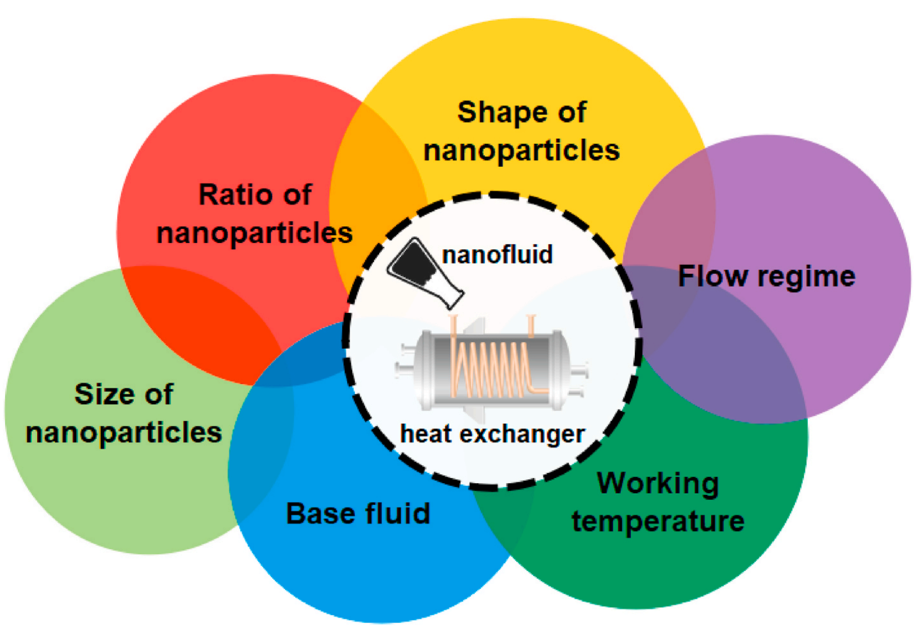

Fig. 1. The main parameters that influence the characteristics of nanofluids.

stability of the mixture. He et al. [40] analyzed the convective heat transfer of TiO_2 including nanofluid in a tube utilizing the Euler-Lagrange method and particle volume fraction, Reynolds number and particle size parameters were analyzed as variables within the scope of the study. Rao and Sankar [41] investigated heat transfer increment potential in a double tube heat exchanger utilizing CuO including nanofluid. Elmnefi and Abdullah [42] utilized TiO_2 and Al_2O_3 containing water based nanofluids in order to upgrade the thermal efficiency of a shell and tube heat exchanger.

The overall performance of nanofluids as working fluids could be enhanced by utilizing two or more various nano-sized particles that are commonly called as hybrid type nanofluids. As it is known, single nanoparticles are not able to cover all intended specifications. Therefore, hybrid type nanofluids are good candidates to be utilized in heat exchangers because they could supply enhanced thermal characteristics due to synergetic influence [43–45]. There are some researchers exhibited that hybrid type nanofluids present good thermal efficiency than that of single [46–49].

Investigating available studies in the literature exhibited that different nanofluids have been tested in many energy systems. Also, many types of academic works have been performed on utilization of various types of nanofluids in SHCHEs. But, various nanofluids show varying behavior in different types of heat exchangers. Therefore, it is crucial to evaluate the thermal characteristics of various nanofluids in different heat exchangers. Previously Tuncer et al. [50] designed a new type of SHCHE by applying a basic and efficient change. In another survey, Tuncer et al. [51] added fins over the coiled tube of the SHCHE with the aim of increasing the effectiveness. In this work, it is targeted to raise the thermal effectiveness of both finless and finned SHCHEs by utilizing CuO–TiO_2/water and TiO_2/water nanofluids in the hot side of the system. In this context, single and hybrid nanofluids including TiO_2/water and CuO–TiO_2/water have been prepared and empirically tested at varying Reynolds numbers to specify their influence over the thermal characteristics of newly developed SHCHEs. Fig. 2 is presented in order to summarize the main steps of the present work.

2. Material and method

2.1. Experimental setup

In this stage of the study, different working fluids have been examined in two different types of SHCHEs. As working fluids, base fluid (pure water), TiO_2/water, and hybrid CuO–TiO_2/water (at percent mass ratio of 50:50) have been used in the experiments. Besides the comparison of TiO_2 nanofluid with pure water, it was compared with hybrid CuO–TiO_2/water. The purpose of the study is to reveal the differences between the utilization of single and hybrid types nanofluids in two different SHCHEs. The schematic image of test rig used in the current work is provided in Fig. 3. Nanofluid flows on the hot side of the shell and helically coiled heat exchanger while cold fluid (water) flows in the shell side and leaves the system after gaining energy from hot side. Accordingly, flow meters with accuracy of ±5% as well as thermocouples with 0.5 °C accuracy were used for measurements in the experimental setup. Considering the geometric dimensions of the shell and helically coiled heat exchangers, the main shell's height is 375 mm, diameter of shell is 140 mm, coiled tube's inner diameter is 6 mm, coiled tube's outer diameter is 8 mm, coil diameter is 100 mm, coil pitch is 16 mm, and the total number of rotations is 18. The overall dimensions of both SHCHEs are the same in order to be able to conduct a reliable comparison between the heat exchangers. However, in one SHCHE, longitudinal fins have been integrated over the inner tubes as turbulators with the aim of increasing turbulence inside the heat exchanger. The main difference between this study and other studies in the literature is that a secondary internal tube is included to regulate the fluid flow on the shell side and consequently to increase the efficiency. It must be noted that the production of shell and helically coiled heat exchangers was carried out by taking into account previous literature studies. The major structure of SHCHEs used in the experiments and the production stages during manufacturing are given in detail in Fig. 4 and Fig. 5, respectively. In other words, Fig. 4 represents the main structure of the SHCHEs used in the experiments and the behavior of the flow during the experiments. The inner tube and shell part of the shell and helically coiled heat exchangers have been made of stainless steel material. Also, thermal insulation was applied for the necessary parts of the experimental set to minimize heat losses. As stated before, two SHCHEs used in the experiments including heat exchangers with fins and without fins. As seen in Fig. 4, unlike other shell and helically coiled heat exchangers in the literature, it was equipped with an extra tube in the shell section. Modified SHCHE has been obtained by adding fins to the helical tube in order to achieve turbulent flow. An increase of 635 cm^2 in surface area has been obtained in the SHCHE design with fin addition. Thus, it could be said that the heat transfer can raise with the produced new system. The flow is provided horizontally in both designs. In addition, cold fluid enters the system from the inner tube to the shell side. Nanofluids containing TiO_2/water and hybrid CuO–TiO_2/water are circulated in the coil side of the heat exchangers in the system.

2.2. Preparation of working fluid

As stated in the previous section, three different working fluids containing pure water, TiO_2/water, and CuO–TiO_2/water have been used in two different SHCHEs. For this purpose, the two-step method,

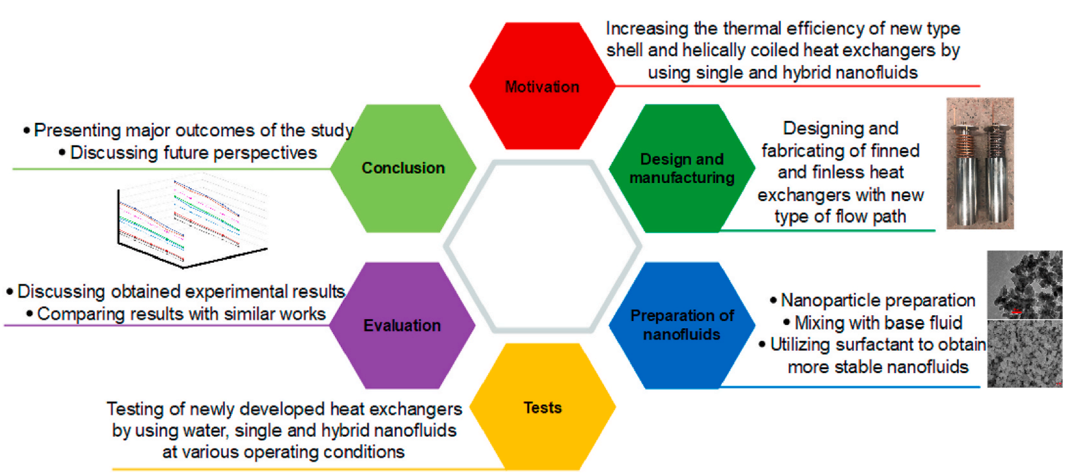

Fig. 2. The major steps of the present study.

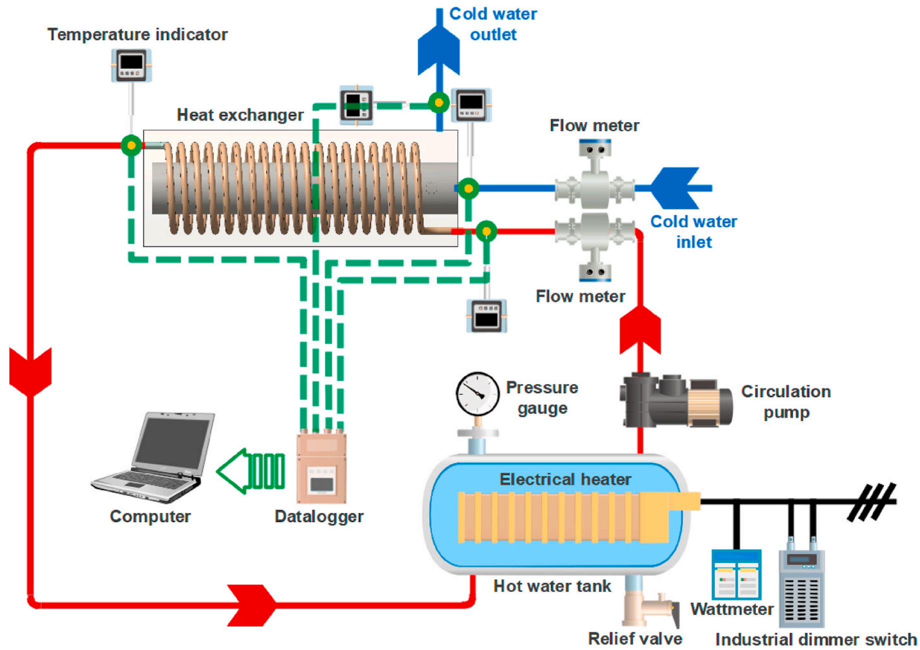

Fig. 3. Schematic image of the test setup.

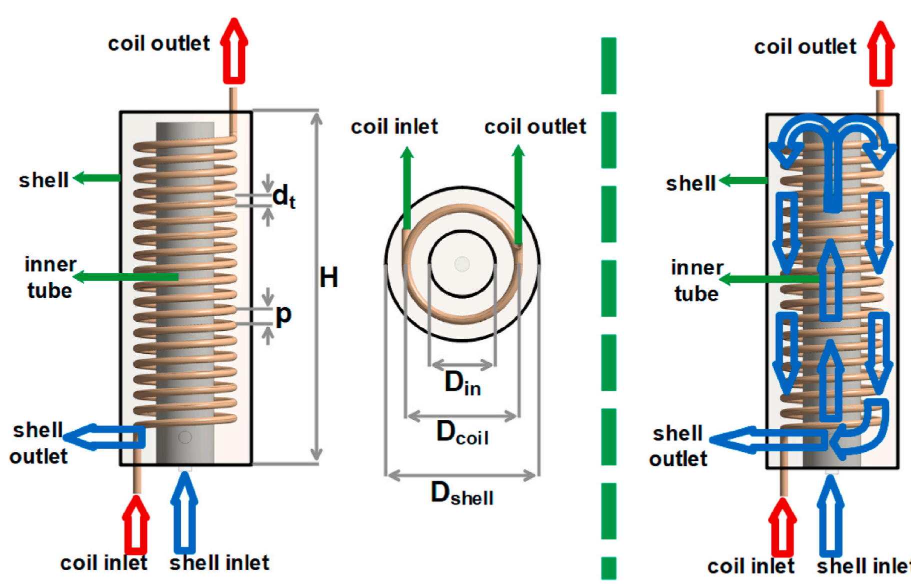

Fig. 4. Major structure of SHCHEs and flow pattern.

which is frequently used in the literature, has been applied in the preparation of nanofluids in this study. In the first step, dry powder nanoparticles have been prepared by applying ball milling process four 8 h [52]. In this context, Spex-8000 device has been used to decrease the size of particles and also to obtain homogeneous nanoparticles. SEM image of prepared nanoparticles including Ti_2O and CuO are provided in Fig. 6. The obtained CuO and TiO_2 nanoparticles' mean size are 38 nm and 18 nm, respectively. CuO and TiO_2 nanoparticles have purity values of 99.90% and 99.55%, respectively. In addition, CuO and TiO_2 nanoparticles' colors are black and white, respectively. In the second step, nanoparticles has been mixed with the base liquid (pure water) in the desired ratio (1% wt./wt.) by measuring with a precision balance. In this regard, a mechanical mixer has been used. Both single and hybrid nanofluids have been prepared at particle ratio of 1% (wt./wt.). It must be said that CuO–TiO_2/water hybrid type nanofluid has been obtained at percent mass ratio of 50:50 (CuO–TiO_2). In this method, a certain proportion of surfactant (Triton X-100, 0.2% wt./wt.) has been added to the solution because van der Waals forces and surface area sizes between nanoparticles cause aggregation. Utilizing surfactant improves wetting capability of the prepared nanofluid solution and decreases surface tension. There is also an ultrasonication bath stage to raise the stability of the nanofluids. Applying ultrasonication is one of the widely utilized methods for enhancing the stability of nanofluids which its effect presented in previous researches [53,54]. Prepared CuO–TiO_2/water and TiO_2/water nanofluids has been exposed to the continuous pulsing by utilizing an ultrasonic bath for 5 h [55–57]. Fig. 7 represents a schematic diagram of preparation stages of utilized nanofluids.

Besides ensuring the stability of the working fluid, it is very important to accurately determine the thermophysical properties of TiO_2/water and CuO–TiO_2/water nanofluids used in the experimental part. In this context, the densities of used nanofluids has been determined by measuring weight of a certain volume of nanofluids with a precision

Fig. 5. Inner view of the manufactured SHCHEs.

balance (accuracy: ±0.01 g). Viscosity measurements of TiO_2/water and $CuO–TiO_2$/water nanofluids have been carried out with the aid of AND SV-10 viscometer device (accuracy: ±1%). The specific heat capacities of prepared TiO_2/water and $CuO–TiO_2$/water solutions have been obtained using Differential Scanning Calorimetry (DSC) technique. In this regard, PerkinElmer Diamond DSC device (accuracy: ±1%) has been used in order to obtain heat capacities of TiO_2/water and $CuO–TiO_2$/water fluids. Moreover, thermal conductivities of prepared single and hybrid nanofluids have been achieved by using TPS 500S thermal conductivity measuring device (accuracy: 5%) that applies hot disk technique. Table 1 illustrates thermophysical properties of water, TiO_2/water and $CuO–TiO_2$/water at 40 °C.

The experiments have been conducted at 5 hot side's inlet temperature containing 45 °C, 50 °C, 55 °C, 60 °C, and 65 °C. Also, the experiments have been performed at three different cold side's flow rate (correspond to Reynold numbers of 630, 800 and 1100) and three hot side's flow rates (correspond to Reynold numbers of 6600, 11,000 and 16,000). Moreover, the values of the Dean number ranged from 1616 to 3920. All tests have been conducted three times to ensure the reliability of the data as much as possible.

The method of preparing the nanofluid has a significant influence on its stability. Homogeneous distribution and clustering in the working fluid are the main parameters that determine stability. Zeta potential measurement provides detailed information about dispersion or aggregation in suspension. Dynamic light scattering (DLS) method, which is a non-destructive physical method that works based on the interactions between light and particles to maintain the stability and homogeneity of the nanofluid, was used to investigate the particle size distribution. Samples were tested in DLS after ultrasonication. DLS results are shown in terms of Z-average size (d.nm) and width parameter (PdI Polydispersity index) [58]. PdI is calculated by dividing the mass-weighted average particle diameter by the number-weighted average particle diameter. According to the graph, larger sized particles diffract more intensely. The size distribution by density shown in Fig. 8 was obtained for all suspensions at room temperature using Zetasizer Malvern. The spectrum stretches from 0.1 to 10,000 nm on the logarithmic scale. It can be seen that the overall trend is the same for all the structures

Table 1
Thermophysical properties of water, TiO_2/water and $CuO–TiO_2$/water 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
TiO_2/water	0.72	1020	4070	0.64
$CuO–TiO_2$/water	0.74	1033	4045	0.70

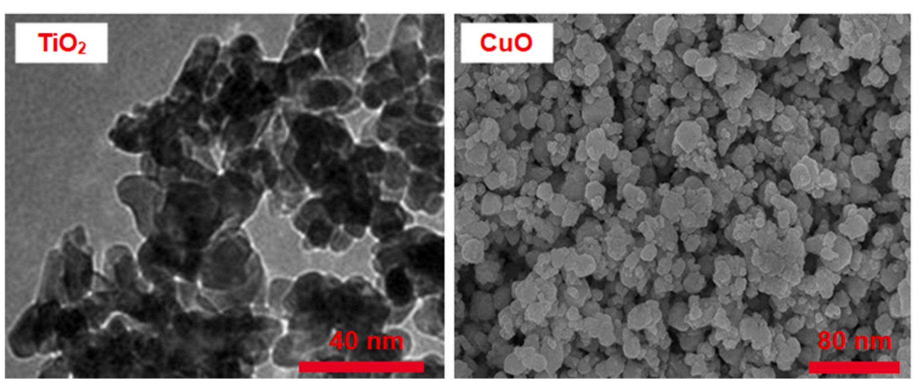

Fig. 6. SEM image of prepared nanoparticles.

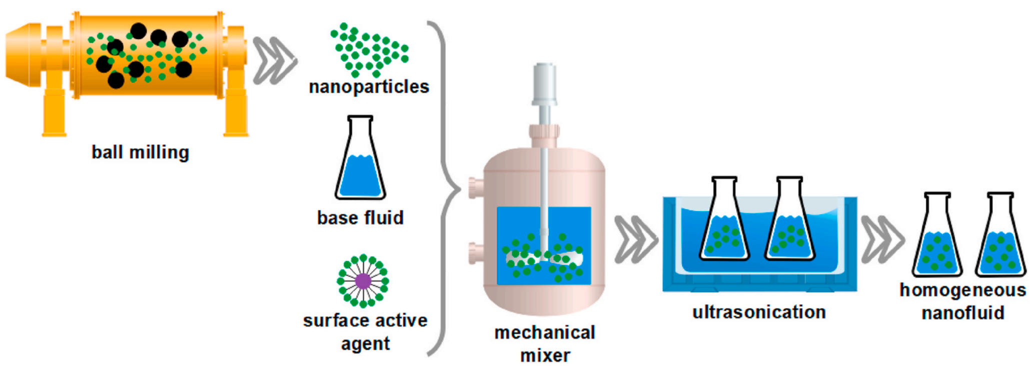

Fig. 7. Schematic diagram of preparation stages of utilized nanofluids.

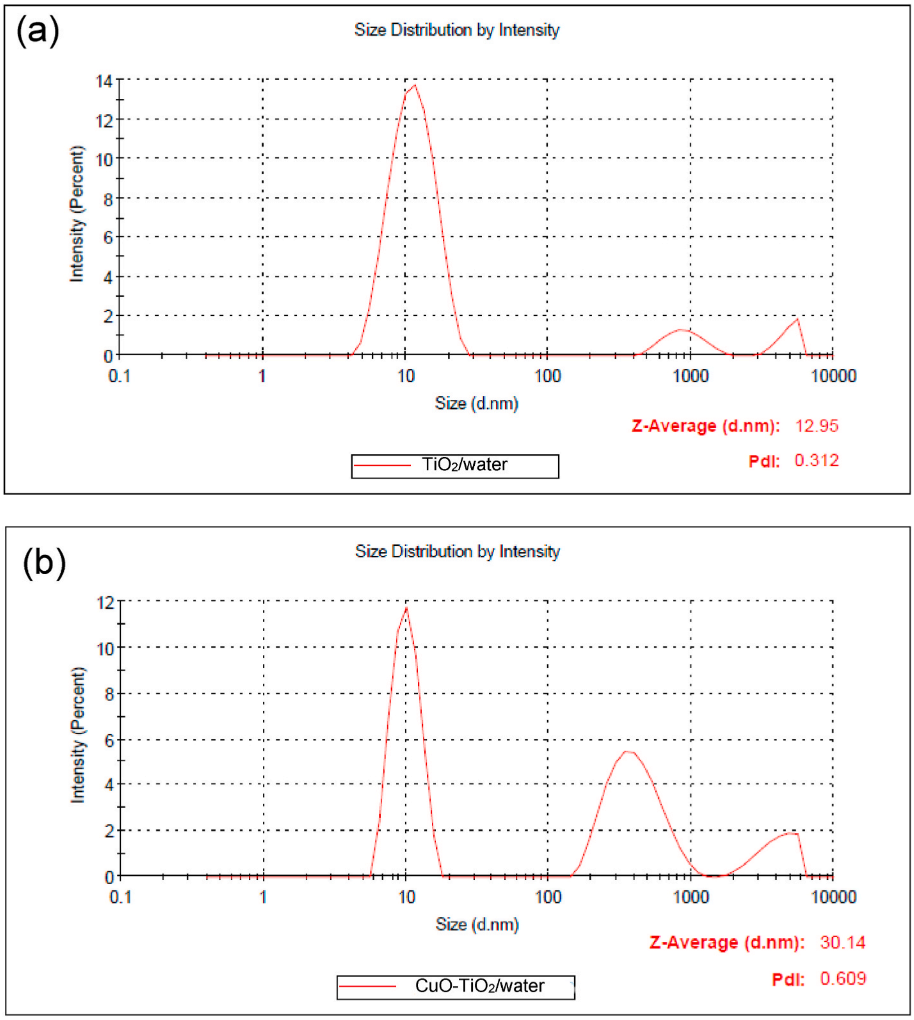

Fig. 8. The DLS particle size analysis of the a) TiO_2/water and b) CuO–TiO_2/water nanofluids.

shown. According to ISO guidelines [59], a PdI value of less than 0.7 should be preferred to ensure even distribution. PdI values greater than 0.7 indicate that the nanoparticles have a wide and unsteady distribution. In the figure, the PdI values are between 0.1 and 0.7, so it can be said that the particle distribution in the study is uniform and appropriate. The highest mean diameter of TiO_2 and CuO–TiO_2 hybrid particles is about 13 nm and 30 nm, respectively. According to the test results, agglomeration phenomenon did not occur in both nanofluids. The findings also confirmed that the CuO and TiO_2 nanoparticles were evenly dispersed, forming a uniform layered CuO–TiO_2 hybrid nanofluid.

The fluid in contact with the solid surface forms an angle called the contact angle. The contact angle depends on the surface energy and characterizes the degree of wetting of the surface. This angle changes depending on the solid and contact fluid being contacted. A contact angle of 0° represents a perfect wetting condition and 180° represents a completely non-wetting condition. As a general rule, if the contact angle is less than 90°, the fluid wets the solid surface, the fluid becomes hydrophilic; if it is greater than 90°, the solid surface is not wetted by the fluid and it can be said that the surface is hydrophobic [60]. The use of surfactants helps to reduce the solid-liquid surface tension and contact angle on the surface. Using the same droplet volume, contact angle measurements for distilled water and prepared nanofluids were made using Krüss DSA100 goniometer at room temperature. The contact angle of pure water was obtained as 58°. The contact angle was measured as 38° for TiO_2/water nanofluid, while it was 42° for CuO–TiO_2/water (see Fig. 9). The outcomes demonstrate the solid–liquid contact angles of all the samples are hydrophilic in nature since the contact angle is less than 90°. This causes the fluid to spread across the surface better, increasing the wetting of the surface.

3. Theoretical calculations

The equations used to calculate parameters like efficiencies and overall heat transfer coefficients of the shell and helically coiled heat exchangers have been given in this part of the study. The amounts of heat transferred in the hot side and the cold side can be found by utilizing Eq. (1) and Eq. (2), respectively. The specific heat capacity values for Eq. (1) and Eq. (2) were accepted as average values.

$$\dot{Q}_{ht} = \dot{m}_{ht}.c_{p,ht}.\left(T_{ht,i} - T_{ht,o}\right) \tag{1}$$

$$\dot{Q}_{cld} = \dot{m}_{cld}.c_{p,cld}.\left(T_{cld,o} - T_{ht,i}\right) \tag{2}$$

In the shell and helically coiled heat exchangers, it is clear that there will be a certain loss in heat transfers between hot and cold regions. As stated in the previous section, thermal insulation has been applied in order to reduce thermal losses. Therefore, the losses between the two regions are neglected in Eq. (3) to simplify the equations.

$$\dot{Q}_{ht} = \dot{Q}_{cld} \tag{3}$$

As in all thermal systems, the effectiveness (ε) is the most important term in the studies with shell and helically coiled HEs. In this study, Eq. (4) gives the expression of the effectiveness (ε). Heat capacity ratios for

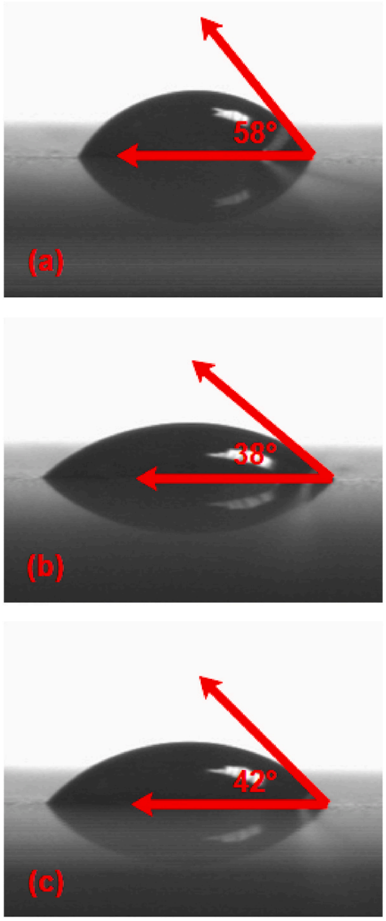

Fig. 9. Droplet contact angle of: (a) water, (b) TiO_2/water and (c) CuO–TiO_2/water.

hot working fluid (C_{htfld}) and cold working fluid (C_{cldfld}) used in Eq. (4) are given in Eq. (5) and Eq. (6), respectively.

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{maximum}} = \frac{C_{htfld}\left(T_{ht,i} - T_{ht,o}\right)}{C_{minimum}\left(T_{ht,i} - T_{cld,i}\right)} = \frac{C_{cldfld}\left(T_{cld,o} - T_{cld,i}\right)}{C_{minimum}\left(T_{ht,i} - T_{cld,i}\right)} \tag{4}$$

$$C_{htfld} = \dot{m}_{ht}.c_{p,ht} \tag{5}$$

$$C_{cldfld} = \dot{m}_{cld}.c_{p,cld} \tag{6}$$

Another important term to be calculated in the evaluation of the shell and helically coiled heat exchanger is the overall heat transfer coefficient (OHTC). The logarithmic mean temperature difference (ΔT_{LMTD}) is used in the calculation of the OHTC. Eq. (7) and Eq. (8) represent (ΔT_{LMTD})and the OHTC, respectively.

$$\Delta T_{LMTD} = \frac{\Delta T_i - \Delta T_o}{\ln\left(\frac{\Delta T_i}{\Delta T_o}\right)} \tag{7}$$

$$OHTC = \frac{\dot{Q}}{A(\Delta T_{LMTD})} \tag{8}$$

In order to determine the flow regime on the coil side of the SHCHE, the Re number must be calculated. General form of Reynolds number could be expressed as:

$$Re = \frac{\rho V D_h}{\mu} \tag{9}$$

Also, Reynolds number for shell and coil sides of SHCHE can be rewritten as given in Eq. (10) and Eq. (11), respectively:

$$Re_{shell} = \frac{4\ \dot{m}_{shell}}{\pi D_{h,shell}\ \mu} \tag{10}$$

$$Re_{coil} = \frac{4\ \dot{m}_{coil}}{\pi D_{h,coil}\ \mu} \tag{11}$$

Moreover, critical Reynolds number for coil side could be expressed as [61,62]:

$$Re_{coil,critical} = 2100\left[1 + 12\left(\frac{d_{in}}{D_{coil}}\right)^{1/2}\right] \tag{12}$$

Dean number is another dimensionless number that used in analyzing flow in helically coiled tube. In order to gain Dean number, Eq. (13) can be used [63]:

$$De = Re_{coil}\left(\frac{d_{in}}{D_{coil}}\right)^{0.5} \tag{13}$$

Another important dimensionless number that is generally used in thermal analysis is Nusselt number. General equations for Nusselt numbers of coil and shell sides. *Nu* number in shell and coil sides can be expressed by using Eq. (14) and Eq. (15), respectively. Also, in gaining the *Nu* number on the shell or coil side of the SHCHE, correct determination of the hydraulic diameter ($D_{h,shell}$) is important. Eq. (16) can be used in the hydraulic diameter calculation for the shell side of the SHCHE.

$$Nu_{shell} = \frac{h_{shell} D_{h,shell}}{k} \tag{14}$$

$$Nu_{coil} = \frac{h_{in} d_{in}}{k} \tag{15}$$

$$D_{h,shell} = \frac{4\ x\ volume\ of\ shell\ side}{Contact\ surface\ with\ fluid} \tag{16}$$

The overall empirical uncertainty expression can be given using Eq. (17) [64]. Also, uncertainty for heat transfer rate, *OHTC*, ΔT_{LMTD} and *HTC* can be given by Eqs. (18)-(21).

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{1/2} \tag{17}$$

$$W_Q = \left[\left(\frac{\partial Q}{\partial Q_{cld}} w_{Q_{cld}}\right)^2 + \left(\frac{\partial Q}{\partial Q_{ht}} w_{Q_{ht}}\right)^2\right]^{1/2} \tag{18}$$

$$W_{OHTC} = \left[\left(\frac{\partial OHTC}{\partial Q} w_Q\right)^2 + \left(\frac{\partial OHTC}{\partial \Delta T_{LMTD}} w_{\Delta T_{LMTD}}\right)^2\right]^{1/2} \tag{19}$$

$$W_{\Delta T_{LMTD}} = \left[\left(\frac{\partial \Delta T_{LMTD}}{\partial T_{cld,i}} w_{T_{cld,i}}\right)^2 + \left(\frac{\partial \Delta T_{LMTD}}{\partial T_{cld,o}} w_{T_{cld,o}}\right)^2 + \left(\frac{\partial \Delta T_{LMTD}}{\partial T_{ht,in}} w_{T_{ht,i}}\right)^2 + \left(\frac{\partial \Delta T_{LMTD}}{\partial T_{ht,o}} w_{T_{ht,o}}\right)^2\right]^{1/2} \tag{20}$$

$$W_{HTC_{cld}} = \left[\left(\frac{\partial HTC_{cld}}{\partial OHTC} w_{OHTC} \right)^2 + \left(\frac{\partial HTC_{cld}}{\partial HTC_{ht}} w_{HTC_{ht}} \right)^2 \right]^{1/2} \tag{21}$$

Obtained uncertainties for temperature, flow rate, heat transfer rate, HTC and effectiveness are ±0.60 °C, ±5.18%, ±5.42%, ±6.54% and ±7.54%, respectively. Elshazly et al. [65] found uncertainty for HTC between the range of 4.7–7.0% in a SHCHE. In another research, Panahi and Zamzamian [66] obtained uncertainties for HTC and effectiveness parameters approximately as ±9% and ±10%, respectively in a similar SHCHE. It can be said that obtained uncertainties in the present research are in good line with similar surveys that analyzed SHCHEs in the scientific literature.

4. Results and discussion

In the present part of this paper, the major outputs of the experimental tests of two SHCHEs by using water, TiO_2/water and CuO–TiO_2/water are illustrated and explained in detail. In the experimental tests of analysis of both SHCHEs, the hot loop's inlet temperature was specified at a given temperature containing 45 °C, 50 °C, 55 °C, 60 °C, 65 °C according to the previous studies [50,51] and necessary values were recorded when steady-state conditions were achieved. The performance tests have been conducted at flow rates between 1.5 and 3.5 lpm. These flow rates have been selected according to the similar previous studies that investigated related SHCHEs [66–69].

Fig. 10 illustrates average heat transfer in two SHCHEs using three working fluids in hot side at different temperatures and varying

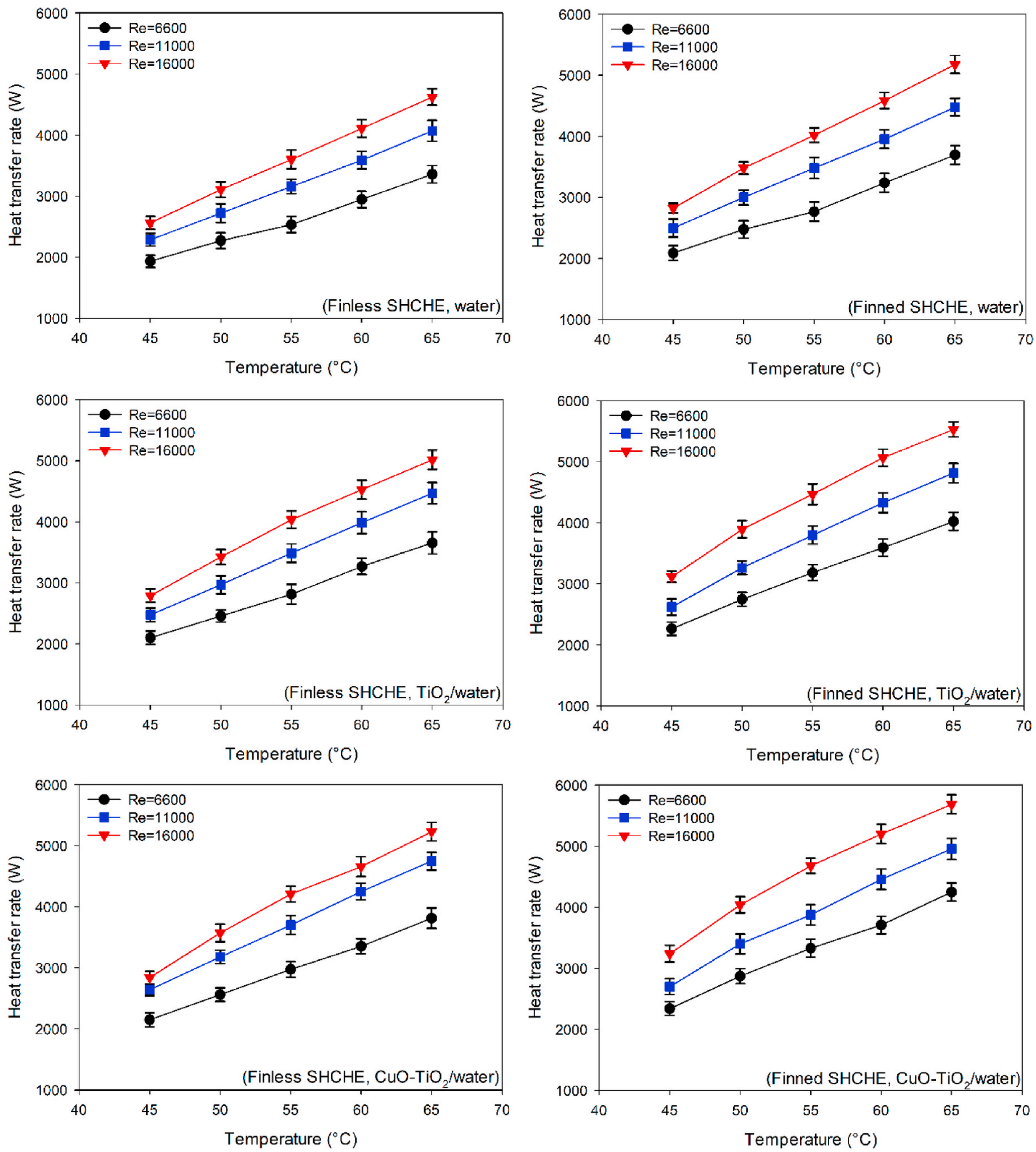

Fig. 10. Average transferred heat in both SHCHEs with different nanofluids.

Reynolds numbers of coil side. As it can be obviously seen in Fig. 10, transferred thermal energy in the SHCHEs improved with increasing hot loop inlet temperature at all experimented Reynolds numbers. Also, positive impact of adding turbulators in the SHCHEs could be obviously seen by comparing transferred energy at same Reynolds number and temperature. Employing TiO_2/water and CuO–TiO_2/water nanofluids as circulating fluids in the hot loop of both SHCHEs led to upgrade the transferred heat of the system. High thermal conductivity of utilized nanoparticles led to increase in thermal conductivity of the working fluid which consequently improved heat transfer in the system. In general, it is observed that the gained increment in heat transfer improved with raising Reynolds number parameter. In other words, it could be concluded that the impact of using TiO_2/water single and CuO–TiO_2/water nanofluids in high Reynolds numbers is relatively high when compared to low Reynolds numbers. By increasing Reynolds number, turbulence intensity raises which leads to achieve more improvement in heat transfer rate. Outcomes of this study, indicated that using nanofluids in high Reynolds number can leads to achieve more thermal improvement in comparison with lower Reynolds numbers. Moreover, utilizing CuO–TiO_2/water hybrid nanofluid illustrated a better performance than single nanofluid. The obtained results for heat transfer rate indicated that using hybrid nanofluid can provides better heat transfer which arise from higher thermal conductivity of hybrid type. Utilizing TiO_2/water and CuO–TiO_2/water nanofluids as circulating fluids in finless SHCHE led to average improvement in heat transfer as 9% and 13%, respectively. While, using TiO_2/water and CuO–TiO_2/water nanofluids in modified SHCHE averagely improved heat transfer as 9.6% and 13.8%, respectively. In a research done by Afshari et al. [36], TiO_2–Al_2O_3/water hybrid and TiO_2/water single nanofluids examined in brazed plate heat exchangers with varying number of plates in Reynolds numbers among 1600–3800 and transferred heat averagely increased in the range of 4–12.3%. Also, Khanlari et al. [70] empirically investigated TiO_2/water single nanofluid in a brazed type plate heat exchanger. Their main outcomes exhibited that utilizing TiO_2/water nanofluid averagely raised heat transfer as 6.5%. Srinivas and Vinod [71] experimentally tested CuO/water nanofluid in a SHCHE at different particle concentrations and obtained heat transfer rate approximately between 500 and 6000 W. They stated that a maximum improvement of 32.7% was obtained by using CuO/water nanofluid.

OHTC is another important parameter which could be helpful in evaluating heat exchangers like SHCHEs. Fig. 11 shows variation of OHTC parameter in both modified and unmodified SHCHEs using TiO_2/water and CuO–TiO_2/water at varying Reynolds numbers of coil side and different temperatures. Fig. 11 represents that using both TiO_2/water and CuO–TiO_2/water in hot loop of modified and unmodified SHCHEs importantly enhanced OHTC parameter in test conditions. TiO_2/water working nanofluid application in finless and finned SHCHEs averagely upgraded OHTC as 7.5% and 8.6%, respectively. CuO–TiO_2/water working nanofluid application in finless and finned SHCHEs averagely upgraded OHTC as 10.8% and 12%, respectively. Also, TiO_2/water nanofluid in finless and finned SHCHEs caused to highest increment in OHTC parameter as 10.2% and 11.5%, respectively. In addition, CuO–TiO_2/water nanofluid in finless and finned SHCHEs caused to highest increment in OHTC parameter as 14.3% and 15%, respectively. It must be said that improvement in OHTC values in SHCHEs in Reynolds numbers of 11,000 and 16,000 were higher when compared to Reynolds number of 6600. Moreover, as obviously seen in Fig. 11, utilization of CuO–TiO_2/water nanofluid led to obtain more increment which clearly exhibited the positive effect of adding CuO to achieve hybrid type nanofluid. The obtained outcomes for OHTC once again exhibited the good influence of adding fins over the coiled tube on heat transfer improvement by using single and hybrid nanofluids. Adding fins over the coiled tube led to raise turbulence intensity and consequently enhanced the fluid velocity in the zones adjacent to the coiled tube which could be illustrated as the main factor for increasing the heat transfer in the finned SHCHE especially by using nanofluids. In a study, Afshari et al. [36] empirically investigated TiO_2/water single and TiO_2–Al_2O_3/water hybrid nanofluids in brazed plate heat exchangers in Reynolds numbers among 1600–3800 and stated that TiO_2/water and TiO_2–Al_2O_3/water nanofluids utilization improved OHTC in the ranges of 4.3–6% and 8–14.5%, respectively. In another work by Khanlari et al. [70], TiO_2/water nanofluid utilized in a brazed plate type heat exchanger and gained a mean improvement of 6% in OHTC. In addition, Naik and Vinod [72] tested CuO including nanofluid and stated that utilizing CuO nanoparticles at 1% (wt./wt.) concentration increased OHTC of a SHCHE as 29%. They utilized a stirrer in order to avoid sedimentation and obtaining homogeneous flowing fluid. But, this could increase energy consumption and should be considered in initial calculations.

Another significant parameter is HTC which generally utilized in order to examine the thermal performance of heat exchangers. Fig. 12 represents variation of HTC parameter in hot side of SHCHEs at three Reynolds numbers of coil side and varying temperature. As can be seen in Fig. 12, HTC exhibits a similar trend with OHTC in both modified and unmodified SHCHEs. Using TiO_2/water single type nanofluid in the coil side of unmodified and modified SHCHEs averagely upgraded HTC parameter as 9.2% and 14%, respectively. However, TiO_2/water single nanofluid utilization in hot loop of finless and finned SHCHEs led to

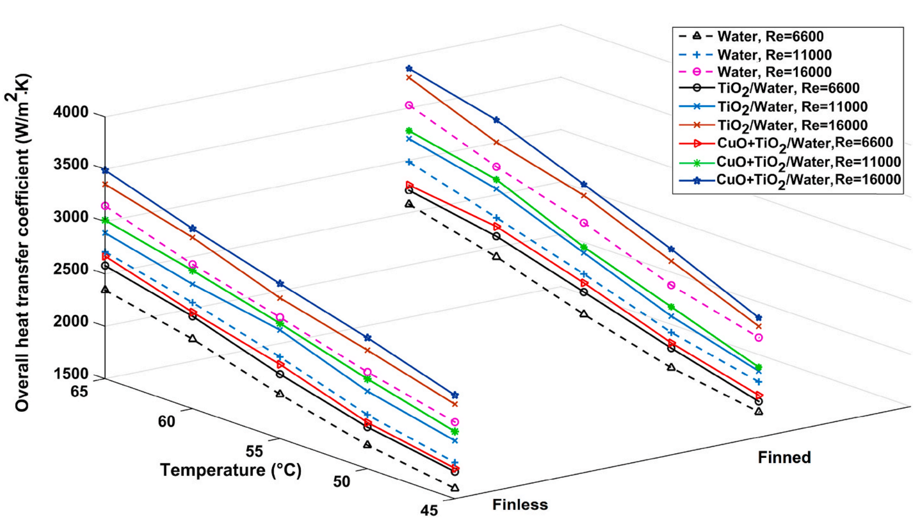

Fig. 11. Variation of OHTC in both SHCHEs with different nanofluids.

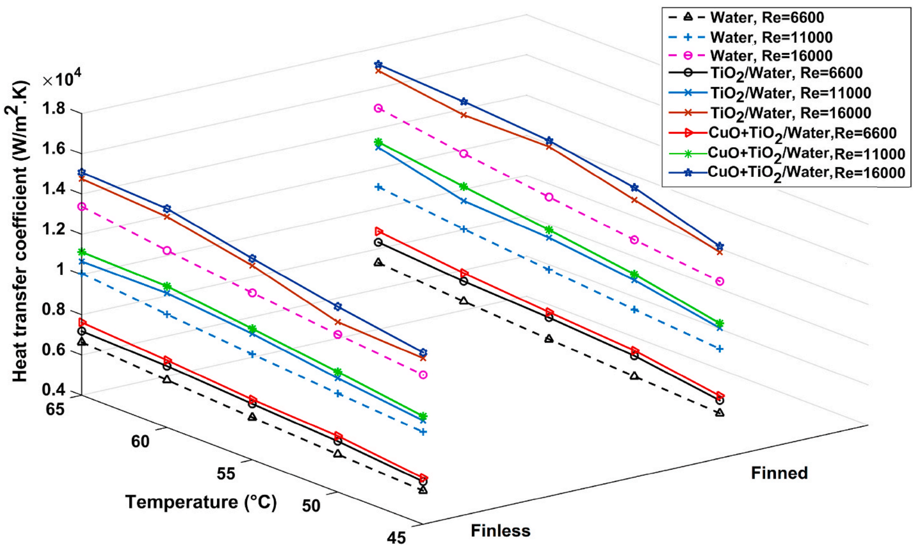

Fig. 12. Variation of HTC of hot side in both SHCHEs using water and nanofluids.

maximum increase in HTC as 11% and 18.2%, respectively. Circulating of CuO–TiO_2/water hybrid type nanofluid in the coil side of finless and finned SHCHEs averagely increased HTC parameter as 13% and 18.1%, respectively. In addition, CuO–TiO_2/water hybrid nanofluid application in hot loop of finless and finned SHCHEs led to maximum increase in HTC as 16% and 20%, respectively. Similar to the behavior of OHTC, increment in HTC parameter values in Reynolds numbers of 11,000 and 16,000 were higher compared to the Reynolds number of 6600. Moreover, the achieved HTC values clearly presented the significant impact of applying fins in the SHCHE over the heat transfer coefficient enhancement by utilizing CuO–TiO_2/water and TiO_2/water nanofluids. In the present study, HTC values of hot side by using CuO–TiO_2/water, TiO_2/water and water were gained in the range of 5668–17158 W/m^2.K. Palanisamy and Mukesh Kumar [73] designed a similar SHCHE and obtained HTC between the range of 3800–6800 W/m^2K utilizing water and carbon nanotubes/water as working fluids. In another survey conducted by Bahrehmand and Abbassi [74] a SHCHE experimentally tested and HTC in coil side gained between 5000 and 25000 W/m^2K utilizing Al_2O_3/water as main fluid of hot loop. Niwalkar et al. [75] calculated HTC between the range of 2000–14000 W/m^2K in a SHCHE by testing water and SiO_2/water as working fluids. Kulkarni et al. [76] utilized biosynthesized zinc nanofluid in the shell side of a SHCHE at different working conditions and HTC obtained approximately between the range of 1200–13000. Also, their results indicated positive impact of using zinc nanofluid.

Fig. 13 illustrates HTC change of shell side (cold side) in modified and unmodified SHCHEs with Reynolds number of shell side at different temperatures by using CuO–TiO_2/water and TiO_2/water nanofluids. It is better to state that in Fig. 13, shell side's HTC variation is given with respect to shell side's Reynolds number at different temperatures. Utilizing TiO_2/water single nanofluid in the finless and finned SHCHEs averagely increased HTC parameter of the shell side as 5.7% and 7.5%, respectively. Also, using CuO–TiO_2/water hybrid nanofluid in the finless and finned SHCHEs averagely increased HTC parameter of the shell side as 7.9% and 10.5%, respectively. The obtained increments for shell side's HTC are relatively low by comparing them with mean increments for HTC of coil side of SHCHEs. This phenomenon again exhibits the crucial impact of circulating TiO_2/water and CuO–TiO_2/water fluids in

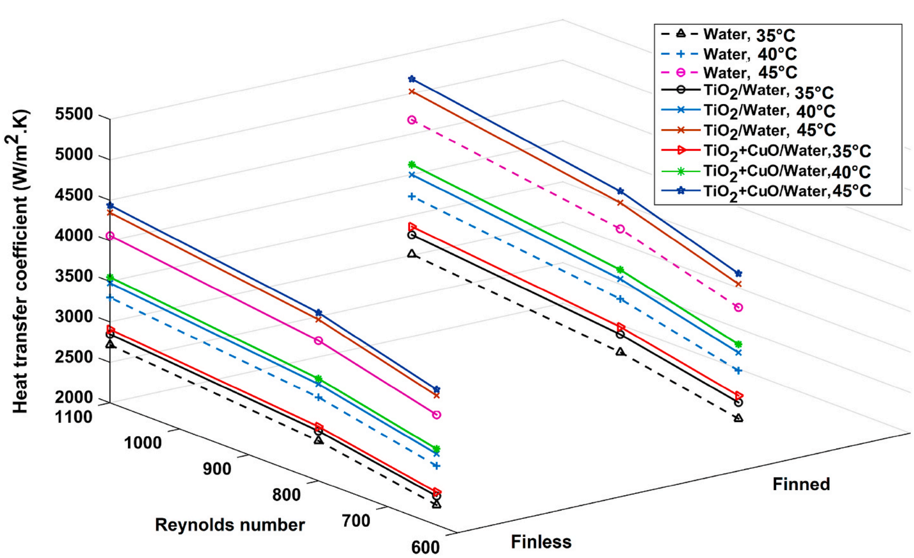

Fig. 13. Variation of HTC of cold side in both SHCHEs using water and nanofluids.

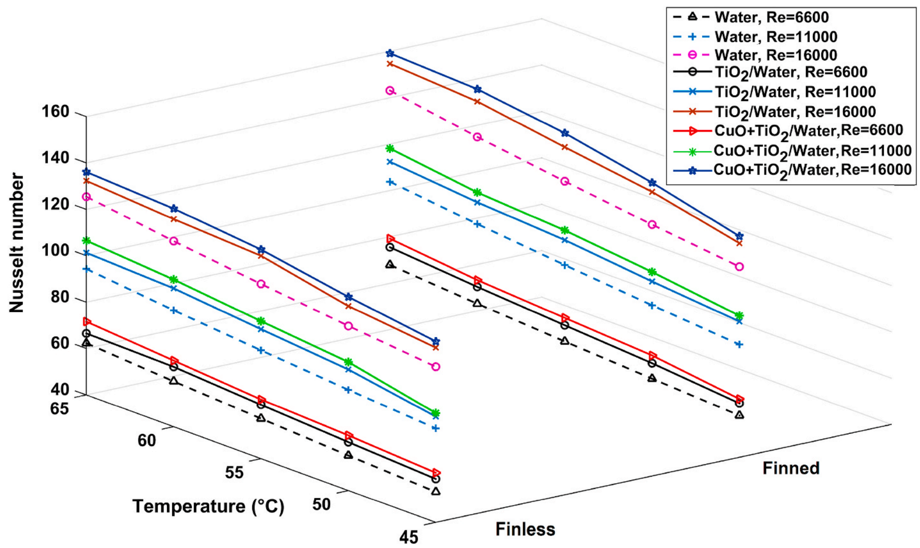

Fig. 14. Variation of Nusselt number of hot side of both SHCHEs using water and nanofluids.

the coil side of SHCHEs. Moreover, mean increment values of HTC of shell loop of unmodified and modified SHCHEs indicated the crucial impact of applying rectangular fins on heat transfer improvement in both sides. In this research, HTC in shell loop of SHCHEs was gained between 2240 and 5180 W/m^2. K circulating water, single and hybrid nanofluids in the hot loop of the system. In a similar investigation on SHCHE, Bahrehmand and Abbassi [74] calculated HTC in the shell loop of the SHCHE in the range of 1100–1500 W/m^2K by testing pure water and Al_2O_3/water as working fluids.

Fig. 14 illustrates the change in Nusselt number of hot side of both SHCHEs using water, single and hybrid nanofluids at varying temperatures and three different Reynolds numbers of coil side. Utilization of TiO_2/water single nanofluid in the coil side of unmodified and modified SHCHEs averagely increased Nusselt number as 8.7% and 11.3%, respectively. In addition, circulation of CuO–TiO_2/water hybrid nanofluid in the coil side of unmodified and modified SHCHEs averagely enhanced Nusselt number as 12% and 14.5%, respectively. Fig. 14 represents that Reynolds number and temperature have crucial impacts over *Nu* number of coil side. Also, the important impact of applying fins in the SHCHE could be obviously seen in Fig. 14. Integrating turbulators upon the coil of SHCHE led to raise turbulence intensity inside the heat exchanger and caused to increase the flowing fluid velocity in the regions near to the coil of SHCHE that could be given as the base reason for raising heat transfer in the modified type SHCHE. In this work, Nusselt number of coil side of SHCHE was gained in the range of 54–159 by using water, TiO_2/water and CuO–TiO_2/water fluids. Wang et al. [77] designed and optimized a SHCHE and determined the nusselt number of tube side approximately between 35 and 105. Etghani and Hosseini Baboli [13] designed and investigated a similar SHCHE and achieved *Nu* number between of 53–76. Kannadasan et al. [78] studied a SHCHE and they calculated *Nu* number between 35 and 105 using CuO/water as working fluid. Wang et al. [79] designed and tested a twisted-coil type SHCHE and gained the *Nu* number between the range of 25–375. Sepehr et al. [80] simulated overall characteristics of a fin integrated SHCHE and calculated mean Nusselt number as 125. Kulkarni et al. [76] utilized biosynthesized zinc nanofluid in a SHCHE at different working conditions and Nusselt number obtained approximately between the range of 25–240. In addition, Noorbakhsh et al. [81] designed a new geometry for coil side of a SHCHE and achieved Nusselt number approximately between 30 and 70.

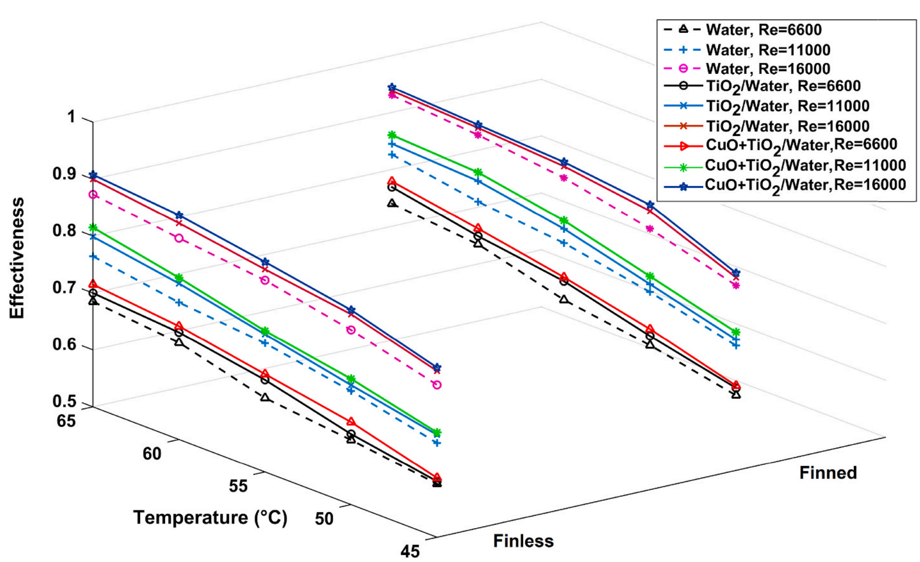

Fig. 15. Effectiveness variation of SHCHEs with temperature at different Reynolds numbers using water and nanofluids.

Fig. 15 shows the change in effectiveness of modified and unmodified SHCHEs using water, TiO_2/water and CuO–TiO_2/water working fluids. As it could be clearly seen in Fig. 15, using both TiO_2 and CuO–TiO_2 including nanofluids in the hot loop of both SHCHEs importantly raised the effectiveness. Utilization of TiO_2/water single type nanofluid in the hot loop of unmodified and modified SHCHEs averagely raised the effectiveness as 4.5% and 5.3%, respectively. Also, circulating CuO–TiO_2/water hybrid type nanofluid in the hot loop of unmodified and modified SHCHEs averagely raised the effectiveness as 4.9% and 5.6%, respectively. In a work conducted by Khanlari et al. [70], TiO_2/water single type nanofluid was empirically tested in a brazed plate heat exchanger and highest enhancement in the effectiveness gained as 5%. In another work done by Sunu et al. [82], Al_2O_3/water tested in a SHCHE and effectiveness of the heat exchanger improved by 2.2% in comparison to the water.

Table 2 represents a general comparison between available researches on nanofluid application in various type heat exchangers. Given studies in the table clearly exhibit the positive impact of nanofluid utilization in heat exchangers as circulating fluid. A detailed investigation over the given researches indicates the importance of particle size, particle concentration and working conditions like temperature and flow rate on thermal performance improvement. Also, heat exchanger type has crucial role on thermal behavior of the utilized nanofluid. In other word, the same nanofluid can present different thermal characteristics in various systems. Comparing improvement ranges in the present work with given studies illustrated in Table 2 clearly shows acceptable findings of this research. Generally, it was observed that utilizing TiO_2/water and CuO–TiO_2/water nanofluids in unmodified and modified SHCHEs importantly raised the thermal performance. However, utilization of hybrid type nanofluid presented better performance than single nanofluid in both SHCHEs. Moreover, the outcomes exhibited further positive impacts of integrating turbulators on performance enhancement with both single and hybrid nanofluids.

5. Conclusion

In the present work, it was aimed to raise the thermal performance of newly developed shell and helically coiled heat exchangers with and without fins using single and hybrid type nanofluids. In this regard, TiO_2/water and CuO–TiO_2/water nanodfluids with 1% (wt./wt.) concentration was prepared and circulated in the hot side of both heat exchangers. The major findings of the present research can be given as:

- Utilizing TiO_2/water and CuO–TiO_2/water nanofluids as working fluid in finless SHCHE led to average increase in the heat transfer rate as 9% and 13%, respectively. While, using TiO_2/water and CuO–TiO_2/water nanofluids in modified SHCHE improved the rate of heat transfer averagely as 9.6% and 13.8%, respectively.
- Employing TiO_2/water single type nanofluid in the coil side of SHCHEs with and without fins averagely upgraded HTC parameter as 9.2% and 14%, respectively. Also, circulating CuO–TiO_2/water hybrid type nanofluid in the coil side of finless and finned SHCHEs averagely increased HTC parameter as 13% and 18.1%, respectively.
- It was seen that the impact of using TiO_2/water single and CuO–TiO_2/water nanofluids in high Reynolds numbers is relatively high when compared to the lower Reynolds numbers.
- Adding longitudinal fins over the coil of SHCHE led to raise turbulence intensity and improved the flowing fluid velocity in the regions near the coil surface of SHCHE that can be shown as the major reason for increasing heat transfer in the modified type heat exchanger.

Generally, it was observed that utilizing TiO_2/water and CuO–TiO_2/water nanofluids in unmodified and modified SHCHEs importantly raised the thermal performance. However, utilization of hybrid type nanofluid presented better performance than single nanofluid in both SHCHEs. Moreover, the outcomes exhibited further remarkable potential of integrating extended heat transfer surfaces like turbulators on performance enhancement of both single and hybrid nanofluids. In future studies, tri-hybrid nanofluids can be tested in the developed heat exchangers to evaluate their thermal behavior.

Table 2
A comparison between available researches on nanofluid application in heat exchangers.

Ref.	Type of utilized nanofluid	Weight or volume concentration of particles	Heat exchanger	Reynolds number	HTC ($W.m^{-2}.K^{-1}$)	Major results
[83]	SiO_2/water, Ag/water	0.1 and 0.3 (vol%)	Helically coiled heat exchanger	8900–11970	~5200-8800	Transferred heat improved between 8 and 23%.
[42]	TiO_2/water, Al_2O_3/water	0.1, 0.2, and 0.3 (vol%)	Shell and tube heat exchanger	~3150-4500	~2500-4500	A highest improvement of 42.37% for HTC.
[84]	TiO_2/water, Al_2O_3/water, CeO_2/water, SiO_2/water	0-3 (vol%)	Plate heat exchanger	–	~690-880	A highest enhancement of 7.9% by using TiO_2/water.
[70]	TiO_2/water	2 (Wt.%)	Plate heat exchanger	~1500-4000	2680–5320	HTC increased in the range of 6–11%.
[85]	TiO_2/water	0.3–1.5 (Wt.%)	Plate heat exchanger	~160-530	~1400-3800	HTC raised between 6.6 and 23.7%.
[86]	CuO/water, CuO–Al_2O_3/water	0.5 and 1 (Wt.%)	U-type Tubular heat exchanger	~8000-16000	12,000–23900	Maximum enhancement of 12% obtained using hybrid nanofluid.
[36]	TiO_2/water, TiO_2–Al_2O_3/water	1 (Wt.%)	Plate heat exchanger	1600–3800	~2650-6300	TiO_2–Al_2O_3/water utilization led to obtain mean increment in heat transfer between 7.5 and 12.3%.
[87]	Al_2O_3/water	0.15, 0.3, 0.45, 0.6 and 0.75 (Wt.%)	SHCHE	–	–	Highest energy savings of 10.65%.
[2]	Al_2O_3/water, SiO_2/water	0.1–0.3 (vol%)	SHCHE	6000–15000	–	Utilizing nanofluids importantly upgraded the performance.
[73]	Carbon nanotubes/water	0.1, 0.3, and 0.5 (Vol. %)	SHCHE	–	~3800-6800	HTC raised in the range of 14–41%.
Present work	TiO_2/water and CuO–TiO_2/water	1 (Wt.%)	SHCHE	6600–16000	5668–17158	HTC of hot side of SHCHEs averagely improved between 9.2 and 18.1%.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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