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Intensification of heat exchanger performance utilizing nanofluids

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ABSTRACT

Heat exchangers are widely utilized in different thermal systems for diverse industrial aspects. The selection of HEx depends on the thermal efficiency, operating load, size, flexibility in operation, compatibility with working fluids, better temperature and flow controls, and comparatively low capital and maintenance costs. Heat transfer intensification of heat exchangers can be fulfilled using passive, active, or combined approaches. Utilizing nanofluids as working fluids for heat exchangers have evolved recently. The performance of heat exchangers employed different nanofluids depends mainly on the characteristics and improvement of thermophysical properties. Regarding the unique behavior of different nanofluids, researchers have attended noteworthy progress. The current study reviews and summarizes the recent implementations carried out on utilizing nanofluids in different types of heat exchangers, including plate heat exchangers, double-pipe heat exchangers, shell and tube heat exchangers, and cross-flow heat exchangers. The results showed that nanofluids with enhanced thermal conductivity, although accompanied by a considerable decrease in the heat capacity and raising viscosity, has resulted in performance enhancement of different heat exchangers types. So, the performance evaluation criterion that combines the thermal enhancement and increases the pumping power for any type of heat exchangers is requisite to evaluate the overall performance properly. The challenges and opportunities for future work of heat transfer and fluid flow for different types of heat exchangers utilizing nanofluids are discussed and presented.

1. Introduction

Nowadays, the rapid progress in thermal technologies for different heat exchangers (HExs) applications, associated with power-saving and intensification of heat transfer, is a critical issue for scientists. The heat transfer intensification (HTI) may be assorted to active, passive, or compound approaches based on the necessity of an external power device such as a pump or fan [1–3]. The active techniques of performance intensification may be accomplished either utilizing the electrostatic fields, vibrate the surface or the working fluid, or supplying nanofluids rather than conventional fluids [4–6]. However, the passive approach uses coiled tubes with different geometries, swirling flow devices, processed, rough and extended surfaces, and utilizing phase-change or nanoparticles materials. In the compound systems, two or more passive or active individual methods can be employed synchronously to practically intensify the heat transfer using a rough surface with twisted tapes [7,8]. One of the promising active methods to enhance the heat transfer in HExs is modifying the surface roughness [9,10]. The synthetic techniques of surface roughness include sandpaper [11], erosion-corrosion [12], V-grooves [13] and square rib [14,15]. The inference of height of the rough element, size of rough elements, pitch to height ratio, etc., significantly impacts the performance of HEx.

Utilizing conventional working fluids in different HExs is not adequate to remove the required heat rate for various applications. Adding nanoparticles (NPs) or phase-change materials into the base working fluids such as gasses or liquids belong to passive

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Nomenclature

b	corrugation depth (m)
cp	specific heat capacity (J/m K)
D_{sh}	shell diameter (mm)
d_t	tube diameter (mm)
De	Dean number (−)
f	friction factor (−)
h	convective heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m^{2}K)
L	plate length (m)
L_p	port to port length (m)
$\dot{m}$	mass flow rate (kg/s)
n	number of turns (−)
NTU	number of tranfer unit (−)
Nu	Nusselt number (−)
p_i	vortex generator pitch (mm)
p	pressure (N/m^2)
Re	Reynolds number (−)
U	overall heat transfer coefficient (W/m^2 K)
$\dot{V}$	volume flow rate (Lit/min)
W	plate width (m)

Subscripts

c	coil
i	inner
nf	nanofluid
o	outer
sh	shell
t	tube

Greek symbols

ε	effectivness (%)
θ	chevron angle (degree)
λ	corrugation pitch (m)
γ	curvature ratio
ρ	density (kg/m^3)
δ	plate thickness (m)
ϕ	volume fraction of nanoparticles
μ	dynamic viscosity (Ns/m^2)

Abxxbrxxeviaxxtions

DPHEx	double-pipe heat exchanger
HEx	heat exchanger
HTC	heat transfer coefficient
MWCNT	multi-walled carbon nanotubes
NPs	nanoparticles
PEC	performance evaluation criterion
PHEx	plate heat exchanger
RSM	response surface methodology
STHEx	shell and tube heat exchanger

intensification methods [16–18]. Nanofluids (NFs), as formed by dispersing nanoparticle (NPs) to conventional heat transfer fluids, i.e., base fluids (BF), have higher thermal conductivity compared and high intensity of the thermal performance, should be employed to achieve the thermal engineering requirements in various application such as water desalination, heat storage, heat exchangers [19–24]. This is in return provides a very promising approach to increase the energy efficiency in many applications at lower environmental impacts [25]. One of the promising applications for the use of nanofluid is to harness renewable and sustainable energies, which are usually characterized by being diffusive and diluted, hence energy conversion enhancement present one of the major activates [26–28].

The application of various NFs has an intensive potential for augmenting the heat transfer of HExs. Utilizing traditional working fluids such as air or water has low thermal conductivities restricting the heat transfer rates. The main parameters that influence the thermophysical properties of NFs and hence the thermal performncae of HEx are the size of NPs and their morphology and concentration and other parameters involved in the preparation of nanofluids such as the aggregation of nanoparticles into the nanofluids and sonication and agitation time [29–31], pH of nanofluids [32,33], adding surfactants [34]. However, the stability of NPs in the base working fluid is a critical issue that impacts the rheological and the thermophysical properties of NFs. As well, for diverse applications of NFs, there are a number of serious issues that should be taken into consideration such as sedimentation, erosion, and fouling. Utilizing NFS in HExs as working fluids is a promising solution to augment the thermal performance, However, it increases the pressure drop through the heat exchanger. Hence, the improvement of thermal performance of HExs due to using NFs relative to the corresponding pressure drop is investigated by studying the performance evaluation criterion (PEC) [35,36].

Elevating conventional fluids' thermal conductivity by dispersing NPs changes the thermophysical properties, leads to augmenting the heat transfer rate. However, the increase in NPs volume fraction φ, i.e., concentration, raises the viscosity of NF, resulting in higher pressure drop and hence high pumping power [37–39]. Several studies have been conducted to investigate the thermophysical properties of different NFs to obtain higher thermal conductivity at lower viscosity raise [40–43]. The heat transfer augmentation utilizing NFs in HExs is due to the different generated forces [44]. Recently, the thermophysical properties of NFs can be determined using computer-aids such as artificial neural networks [45–47], least squares support vector machines [48], genetic algorithm optimization [49,50], and neuro-fuzzy models [51].

Qiu et al. have comprehensively reviewed the recent advances in manufacturing NPs with different materials and thermophysical properties measuring and modeling [31]. Mahian et al. reviewed the synthesis, thermophysical properties, and applications of NFs [44]. The group studied the various generated forces due to dispersing nanoparticles into the based fluids such as van der Waals, drag, lift, Brownian, electrostatic forces, and thermophoretic. Afterward, the physical models of the fluid flow and heat transfer of NFs in single- and two-phase were introduced. The rheological behavior and the thermophysical properties of different NFs, i.e., copper oxide CuO, silicon dioxide SiO_2, and aluminum oxide Al_2O_3 in ethylene glycol/water (60/40%) were measured by Vajjha et al. [52].

The hybrid NFs are produced by dispersing NPs of two or more material into a BF and result in higher thermophysical properties than the NFs with a single nanoparticle material, i.e., mono NF [53,54]. The hybrid NFs improve the heat transfer at a reduced pressure drop by trading-off the advantages and disadvantages of single NPs [55,56]. The detailed information on characterization, preparation, thermophysical properties, and stability of the hybrid NFs were introduced by Kumar and Valan Arasu [57]. Munkhbayar et al. shown that the thermal conductivity of the hybrid NF was lower than that of mono NF due to the lack of collaboration between pair nanoparticles [58]. Utilizing NFs in HExs as promizing working fluids are a promised solution for augeinting the heat transfer however it increase the pressure drop through the heat exchanger.

The present study reviews and summarizes the recent implementations of utilizing NFs in different HExs types, including plate heat exchangers (PHExs), double-pipe heat exchangers (DPHExs), shell and tube heat exchangers (STHExs), and cross-flow heat exchangers (CFHExs). The effect of NFs on the thermal efficiency and performance along with pressure drop for each type of HEx is investigated. Moreover, the thermophysical properties of nanoparticles (NPs) such as thermal conductivity, density, heat capacity, and viscosity and

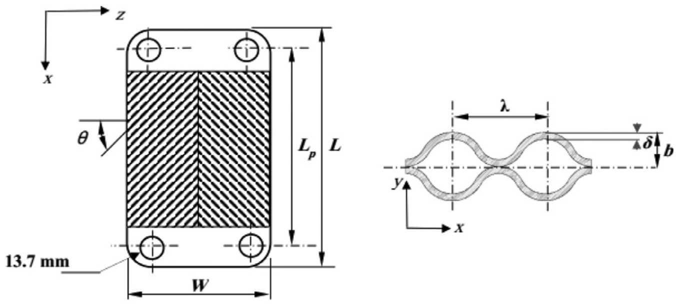

Fig. 1. Plate heat exchanger (a) representational outline (b) corrugated plate [67], reused with permission from Elsevier license number 5016670637890.

their effect on the properties of NFs are addressed. The performance evaluation criterion (PEC) that combines the improvement in heat transfer effectiveness and raising the pumping power in HEx is investigated to evaluate the overall performance precisely. The challenges and future work for the intensification of heat transfer and fluid flow for different types of HExs utilizing NFs are thoroughly discussed and presented.

2. Applications of nanofluids in heat exchangers

Due to the signficant improvement in the thermal conductivity, the nanofluids are promized to enhance the heat transfer coefficients in HEx. While, the suspensions of NPs in the base working fluids impacts all thermophysical properties other than the thermal conductivity (k) such as the thermal capacity (cp), density (ρ) and viscosity (μ) of NFs. So in this section, the effects of utilizing different nanofluids with various thernphysical properties on a number of heat exchangers i.e., plate heat exchangers (PHExs), double-pipe heat exchangers (DPHExs), shell and tube heat exchangers (STHExs), and cross-flow heat exchangers (CFHExs) will introduced.

2.1. Plate heat exchangers (PHExs)

The high thermal efficiency, operating at variable load, size compactness, operation flexibility, compatibility with different working fluids, better temperature control, and comparatively low maintenance cost are the main advantages of the plate heat exchangers (PHExs) [59–62]. So, the PHExs are excessively utilized in different cooling/heating applications such as pharmaceutical, chemical, food industries, air-conditioning systems, etc. Passing the cold and hot streams through the parallel channels in PHEx generates high turbulence, thus intensify the heat transfer rate, and consequently, it improves the HEx effectiveness [63–66]. The fundamental geometry of PHExs and its configuration are illustrated in Fig. 1 [67].

Pantzali et al. explored the effect of the surface modulation on the heat transfer of miniature PHEx using 4 vol.% of Cu/water NF as represented in Fig. 2 [68]. The results indicated that a lower NF flowrate than that of water maintained a low-pressure drop and low-pumping power. Sun et al. studied the flow characteristics and convective heat transfer of PHEx using Fe_2O_3, Al_2O_3, and Cu/water at 0.1, 0.2, and 0.3 wt.% [69]. The results revealed that the convective HTC (h) was enhanced compared with that of water, with Cu/water NF performing better, while the stability of Al_2O_3/water NF was the best. Pandey and Nema investigated the influence of Al_2O_3/water NF at 2, 3, and 4 vol.% on the heat transfer, friction factor, and exergy loss for a counterflow PHE [70]. The experiments were carried out at flowrate ranges of 2–5 Lit/min for the NF and water. The results revealed that for Al_2O_3/water NF with 2 vol.% introduced the most effective heat transfer and lowest exergy loss at 3.7 Lit/min as a results of its enhanced thermophysical properties compared with water.

Taws et al. examined the effect of utilizing the CuO/water NF on heat transfer and fluid flow of chevron type two-channel PHEx experimentally [71]. The results indicated that the heat transfer of the CuO/water NF with 2 vol.% concentration was higher than that for 4.65 vol.%. Similarly, Barzegarian et al. investigated the heat transfer and pressure drop in a smooth brazed PHEx using TiO_2/water NF [72]. The results indicated heat transfer was enhanced by increasing the Reynolds number Re and increasing the weight fraction of NPs. The maximum overall heat transfer coefficient (U) enhancement obtained were 2.2, 4.6, and 8.5%, for 3, 0.8, and 1.5 wt.%, respectively. Moreover, the pressure drop through the HEx increased insignificantly due to using NF compared with the considerable augmentation of U.

The heat transfer and pressure drop of PHEx using Al_2O_3 and multi-wall carbon nanotubes (MWCNT)/water NFs were evaluated by Huang et al. [73]. The experimental results concluded that as a result of improver thermophysical properties of Al_2O_3 rather than that for MWCNT, the heat transfer enhancement for the Al_2O_3/water NF was

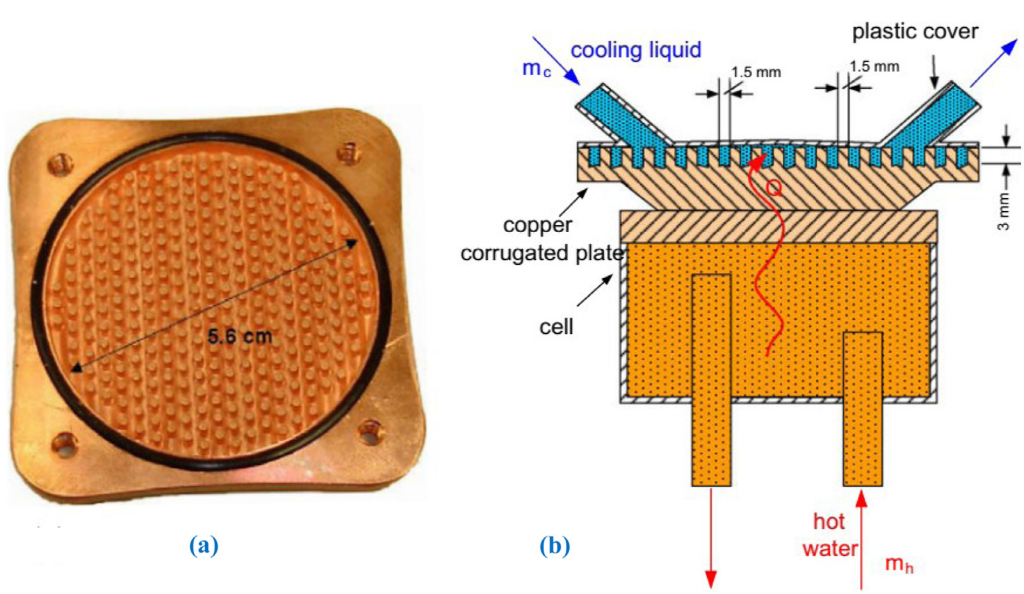

Fig. 2. Plate heat exchanger (a) modulated copper plate (b) heat exchanging unit [68], reused with permission from Elsevier license number 5016671006737.

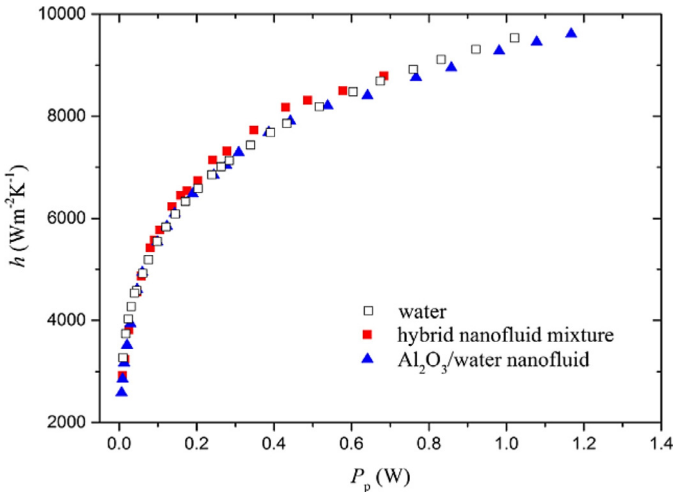

Fig. 3. Heat transfer coefficient (h) versus the pumping power (P_p) [74], reused with permission from Elsevier license number 5016671200098.

higher than that of MWCNT/water NF. Moreover, correlations for the Nusselt number (Nu) and the friction factor (f) were proposed based on the obtained results. Huang et al. tested the hybrid Al_2O_3–MWCNT/water NF on the convective heat transfer coefficient (h) and pumping power (P_p) of PHEx [74]. The results revealed that (h) for the hybrid NF was slightly greater than the corresponding value of Al_2O_3/water NF, contrary to the (P_p) as illustrated in Fig. 3. Goodarzi et al. studied the influence of the covalent functional groups such as cysteine and silver on the thermal properties of MWCNT/water NF [75]. The water as BF, and MWCNT with Gum arabic (GA), MWCNT with cysteine (Cys), and with silver (Ag) in water were examined. The experimental results indicated that increasing the (Re), Peclet number (Pe), and the φ enhanced the heat transfer as well as increased the pumping power compared to water.

The thermal efficiency as well as the pressure drop of PHEx employing Al_2O_3/water NF considering the surface roughness were examined experimentally by Attalla et al. [76]. The results showed that the increase of the φ enhanced the heat transfer rate, while it increased the pressure drop in PHEx. Furthermore, increasing φ in the laminar flow region has a slight effect on the heat transfer enhancement. On the other hand, Pantzali et al. investigated the effectiveness of PHEx using different NFs, concluding that for industrial HExs, high φ and turbulent flow were necessary, making the substitution of the conventional fluids by NFs impractical [77]. Tiwari et al. studied the performance of PHEx using CeO_2/, Al_2O_3/, TiO_2/, and SiO_2/water at various φ values and flow rates experimentally [78]. The results demonstrated that at low φ, the TiO_2/ and CeO_2/water NFs maintained higher heat transfer, while at high φ, the Al_2O_3/ and SiO_2/ water NFs were more efficient. The highest obtained overall HTC (U) was for CeO_2/water NF, followed by Al_2O_3/water, TiO_2/water, and lastly SiO_2/water. Furthermore, at the optimum φ value for each, the maximum improvement of PHEx effectiveness was 13.5, 9.6, 7.9, and 5.0% for CeO_2/, Al_2O_3/, TiO_2/, and SiO_2/water NFs, respectively as shown in Fig. 4.

Barzegarian et al. experimentally investigated the effect of (Re) for TiO_2/water NF on the heat transfer augmentation and pressure drop of a PHEx [79]. The results demonstrated that the maximum (h) enhancement for TiO_2/water NF at 0.3, 0.8, and 1.5 wt.% were 6.6, 13.5, and 23.7%, respectively. Meanwhile, the pressure drop increase was negligible compared to the improvement in the heat transfer. Similarly, Kabeel et al. studied the impact of φ on the performance of PHEx [80]. The results show a 13% heat transfer improvement at 4 vol.% compared to water, but at a 90% increase in pumping power, as shown in Fig. 5. Summary of PHExs performance enhancement utilizing different NF, and the main findings is listed in Table 1.

2.2. Double pipe heat exchangers (DPHExs)

The double-pipe heat exchanger (DPHEx) is considered as the simplest HExs utilized for low heat duty in industrial applications, simply consists of one tube inside another, i.e., concentric, with the inner one is finned or plain [16,81,82]. One fluid passes through the inner pipe, while the other fluid passes into the annulus space of the two pipes. The counter-flow configuration helps to achieve the best thermal performance, while parallel or concurrent flow is utilized for application in which constant wall temperature is required. The DPHEx has the advantages of simplicity, compactness, ease of manufacturing, ease of maintenance, etc. [83–85].

Rennie et al. studied the DPHEx for parallel- and counter-flow configurations, with the Wilson plot, was employed to evaluate the h in inner and annulus tubes and the) [86]. The results indicated that

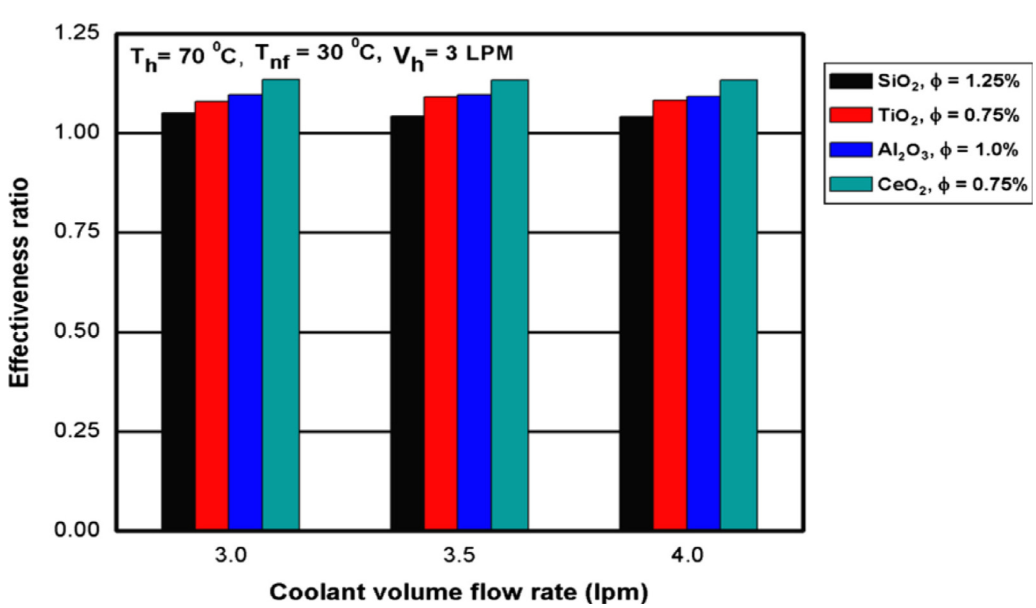

Fig. 4. Effectiveness ratio versus coolant flow rate for different NFs [78], reused with permission from Elsevier license number 5016671436964.

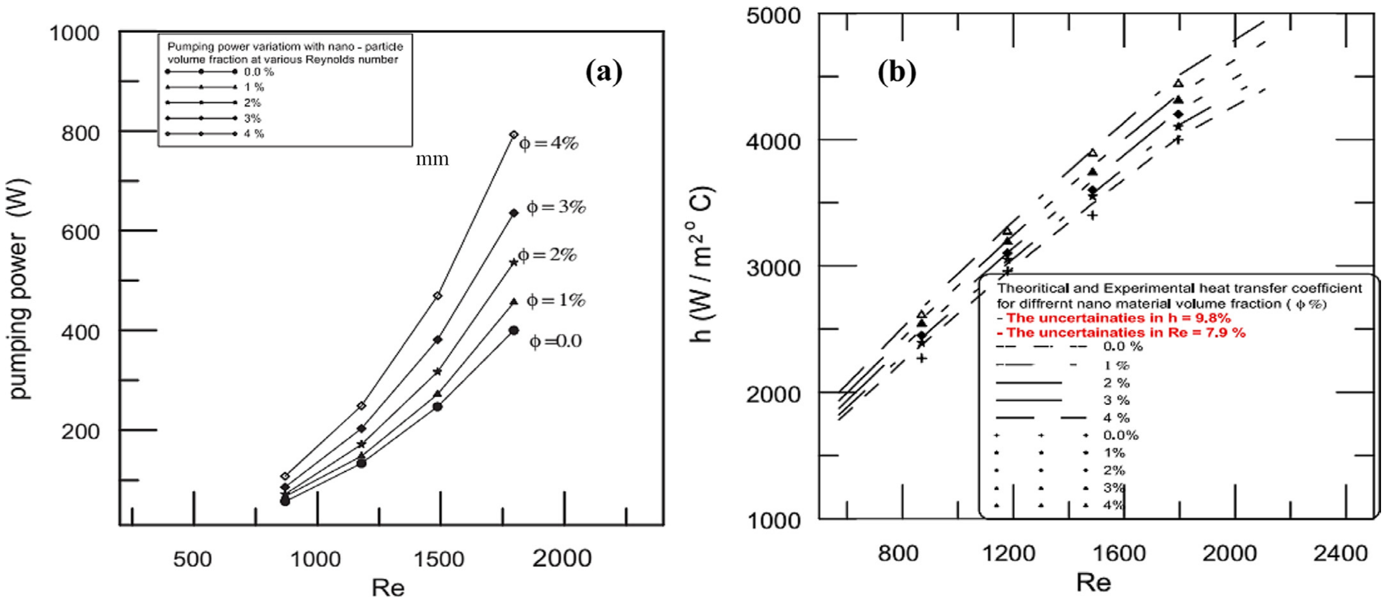

Fig. 5. (a) Pumping power and (b) convective heat transfer coefficient (h) versus Reynolds number for different volume fractions [80], reused with permission from Elsevier license number 5016680167876.

the experimental and numerical results of the Nusselt number (Nu) in the annulus for large coil were matched with a high deviation, while this deviation is less for small scale HEx. Khedkar et al. studied the impact of Al_2O_3/water NF on the heat transfer of DPHEx, showing an increase h by about 16% at 3 vol.% [87]. The heat transfer characteristics and friction of turbulent flow in DPHEx using Al_2O_3/ and TiO_2/water with a size of 13 nm and 27 nm, respectively, were investigated experimentally by Pak and Cho [88]. The results concluded that a better selection of particles with large size and better thermophysical properties such as thermal conductivity improves the thermal performance of the NF. Additionally, the viscosity increase of NFs resulted in a 30% additional power consumption at a 3 vol.% NF.

The heat transfer and fluid flow performance using Cu/water NF at different φ values were investigated experimentally by Xuan and Li [89]. The authors evaluated and correlated the h for the NF considering the micro-diffusion and -convection effects. Similarly, the heat transfer and friction factor characteristic in a counter-flow DPHEx using SiO_2/water NF were studied by Kassim and Lahij, obtaining the maximum Nu was achieved at 0.3 vol.% [90]. The results Gnanavel et al. improved the heat transfer in DPHEx using a twisted tape HEx as a passive technique, as shown in Fig. 6 [91,92]. The numerical results show that the thermal performance of NFs was larger than unity and significantly higher than those of water. The thermal performance for TiO_2/water NF was the highest with 1.879 in the laminar flow region, followed by BeO/, ZnO/, and CuO/water NFs at 1.795, 1.798, and 1.601, respectively.

The optimization and thermal performance of a mini HEx using a hybrid NF containing tetra-methylammonium hydroxide (TMAH) coated by magnetite (Fe_3O_4) NPs and gum arabic (GA) coated CNTs were investigated numerically by Shahsavar et al. [93]. The results indicated that low entropy generation with high heat transfer was achieved at low Re values with a high φ of CNT and Fe_3O_4. Utilizing the objective functions, the optimum values of ϕ_{CNT}, $\phi_{\text{magnetite}}$, and Re were 0.88%, 1.1%, and 500, respectively as illustrated in Fig. 7. Jafarzad and Heyhat studied experimentally the injection of air bubbles into NF flow inside the annulus of DPHEx in a vertical orientation as illustrated in Fig. 8 [94]. The authors evaluated the thermal performance, exergy efficiency, and pressure drop of the proposed system. Additionally, a multi-objective optimization based on the artificial neural network and the genetic algorithm was carried out to evaluate the best HEx performance according to its thermal performance and exergy efficiency. The results indicated that the proposed combined method increased the NF surface tension that responsible for creating a stream of smaller air bubbles with high frequency, that improved the performance rather than each method separately. Additionally, the Air bubble injection reduced the pressure drop by 94%, where the gas bubbles replaced the liquid momentum near the contact wall. Consuming additional power to supply air flow was considered as the fundamental reason for reducing the exergy efficiency in the proposed system.

Bezaatpour and Goharkhah proposed a method to improve the convective heat transfer in DPHEx and reduce the pressure drop using NF exposed to an external magnetic field, inducing a swirling flow [95]. The results revealed that applying an external magnetic field intensified the heat transfer up to 320% with an inconsiderable pressure drop increase, which was attributed to the generated swirling flow disrupted the thermal boundary layer and consequently improved the inside flow mixing of the HEx, as shown in Fig. 9 Alternatively, Singh and Sarkar proposed a novel enhancing technique in a DPHEx using wire coil turbulator and Al_2O_3-MgO/water hybrid NF for turbulent flow [96]. The effect of coil configurations such as converging (C), diverging (D), and conversing-diverging (C-D) types were examined. The results indicated that the D-type of the wire coil produced better hydrothermal performance compared with the other types. The Nu of the hybrid NF using D-type, C-D type, and C-type wire improved up to 84, 47, and 57%, respectively than that of HEx using water without insert in a tube, while the corresponding values of the friction factor (f) were 71, 68, and 46%, respectively. For all types of coil inserts, the thermal performance factor due to using hybrid NF was found more than unity.

Arjmandi and Pour studied the impact of employing combined vortex generators and twisted tape turbulator with Al_2O_3/water NF flowing through the inner tube of DPHEx as illustrated in Fig. 10 [97]. The response surface methodology (RSM) was employed to acquire the combined vortex generator's optimum geometry and the twisted tape turbulator. The pitches ratio, angle of vortex generator, annulus Re were assessed. The numerical results indicated that increasing the number of vortex generators, the vortex generator angle, and Re improved the heat transfer. While, increasing the of vortex generators raised the pressure drop. Accordingly, the performance

Table 1
Summary of plate heat exchangers (PHExs) performance enhancement using different nanofluids (NFs) with base water.

Ref.	Study	PHEx Type	Nanoparticles	Size, nm	Concentration (φ)	Main findings
Pantzali et al. [68]	Exp. and Num.	Counter-flow miniature	CuO		0.4 vol.%	▫ The k_{nf} increased by 10%. ▫ The ρ_{nf} increased by 25%. ▫ The cp_{nf} decreased by 20%.
Sun et al. [69]	Exp.	Brazed	Cu, Fe_2O_3 and Al_2O_3	50	0.1- 0.5 wt.%	▫ Al_2O_3/water is the most stable. ▫ Cu/water is the most effective.
Pandey and Nema [70]	Exp.	Counter flow with corrugated plates	Al_2O_3	40–50	2 - 4 vol.%	▫ The maximum rate of heat transfer was maintained at the lowest φ.
Taws et al. [71]	Exp.	Three corrugated plates with herringbone pattern	CuO	29	2 – 4.65 vol.%	▫ CuO/water increased the friction factor. ▫ Heat transfer decreased for 4.65 vol.% nanofluid compared with that for 2 vol.%.
Barzegarian et al. [72]	Exp.	Brazed	TiO_2	20	0.3 - 1.5 wt.%	▫ The heat transfer coefficient for 0.3, 0.8 and 1.5% increased by 6.6, 13.5 and 23.7%.
Huang et al. [73]	Exp.	Corrugated with 10 channels	Al_2O_3, MWCNT	40 1.5 μm (length), 9.5 nm (diameter)	2.18 - 10.36 wt.% 0.02 - 0.1 wt.%	▫ The HTC for MWCNT/water nanofluid decreased with increasing the φ.
Huang et al. [74]	Exp.	Chevron corrugated with 5 channels	Al_2O_3 MWCNT	40	1.89 vol.% 0.0111 vol.%	▫ The pressure drop of hybrid NF was less than Al_2O_3/water and slightly higher than water.
Goodarzi et al. [75]	Exp. and Num.	Counter flow corrugated PHE	MWCNT-GA, FMWCNT-Cys, and FMWCNT-Ag	diameter of 10–20 nm, and length of 5–15 μm	0.5% - 1.0%	▫ Water had the lowest Nusselt Nu number, while the maximum value was maintained by 1 vol.% MWCNT-GA/water.
Pantzali et al. [77]	Exp.	Corrugated PHE with 16 stainless steel plates	Al_2O_3 CuO CNT	11 30–50 3–5 nm (dia) 8–15 μm (length)	4 vol.% 3 vol.% 0.5 vol.%	▫ The viscosity of working fluids was a crucial factor for the heat exchanger performance.
Tiwari et al. [78]	Exp.	Chevron PHE	CeO_2 Al_2O_3 TiO_2 SiO2	30 45 10 10	0.5 - 3 vol.%	▫ The CeO_2/water at 0.75 vol.% result in the best performance with 16% performance index enhancement.
Barzegarian et al. [79]	Exp.	Brazed PHE	TiO_2	20	0.3 - 1.5 wt.%	▫ The U was enhanced by 2.2, 4.6 and 8.5% for 0.3, 0.8 and 1.5% wt, respectively.
Kabeel et al. [80]	Exp.	Corrugated chevron-type with 6 plates	Al_2O_3	47	1 – 4 vol.%	▫ Heat transfer coefficient was increased by 13% for 4 vol.%. ▫ The increase in Δp was 45% at 4% vol.%

*Exp. = experimental, Num. = Numerical, φ = volume fraction, CNT = carbon nanotube, MWCNT = multi-wall CNT, FMWCNT = functionalized-MWCNT, GA = gum Arabic, Cys = cysteine, U = overall heat transfer coefficient.

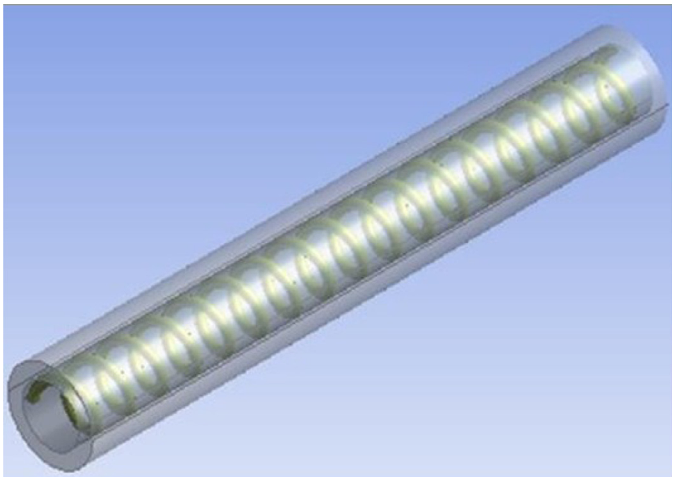

Fig. 6. Three-dimensional model of DPHEx with spring inserts [91], reused with permission from Elsevier license number 5016680360745..

evaluation criterion (PEC) and the overall performance of DPHEx combined with vortex generator was enhanced. The optimal performance of the HEx was maintained at pitch vortex generator ratio, angle, and annulus *Re* of 0.18, 0.5235 (rad), and 20,000, respectively. Poongavanam et al. analyzed the heat transfer and pressure drop in the DPHEx, where the inner surface was modified rough surface [98]. The experimental results indicated that the roughened tube surface had an appreciable effect on the HEx performance. The HTC of the MWCNT/ethylene glycol at 0.6% was enhanced by about 115% at 0.04 kg/s mass flow rate. The summary of the DPHExs performance enhancement with respect to different parameters such as the geometry of HEx, material, size, φ are presented in Table 2.

2.3. Shell and helically coiled tube heat exchangers (SHCTHExs)

The compact size and relatively high operating temperatures are the main advantages of the shell and helically coiled tube HEx (SHCTHEx) than the conventional shell and tube HEx. The SHCTHEx ensures a high turbulence flow intensity, so it magnifies the HTC as compared to that for the straight tube HEx [99,100–102]. The SHCTHEx is preferred for the medium and high heat duties [16]. The flow of the working fluid into the helically coiled tube produces a centrifugal force, thus generating a secondary flow that improves the heat transfer characteristics; however, it elevates the pressure drop compared to a straight tube [103–106]. Different technologies employ the SHCTHEx, such as heat recovery processes, food processing, refrigeration, air-conditioning systems, etc. [107–109].

Jamshidi et al. studied the intensification of heat transfer rate in the SHCTHEx shown in Fig. 11 [110]. The Taguchi-method was utilized to study the effect of the fluid flow and the geometrical parameters on the thermal performance of the HEx. The optimum operating and geometrical parameters were 0.0116 mm, 0.018 mm, 3 Lit/min, and 3 Lit/min for the coil diameter, pitch, cold flowrate, and hot flowrate, respectively. The convective heat transfer and pressure drop of a double-pipe HCTHEx for both laminar and turbulent flow using Al_2O_3/water NF at different φ were investigated by Wu et al. [111]. The results showed that increasing φ from 0.78 to 7.04 wt.% improved the heat transfer by 0.37 and 3.43% for laminar and turbulent flow, respectively. Similarly, Kumar et al. studied the heat transfer and friction factor of a SHCTHEx employing NF of Al_2O_3/water at φ of 0.1 - 0.8 vol.% [112]. The experimental results showed that the *U, h*, and *Nu* number for the NF with 0.8 vol.% were enhanced by 24, 25, and 28%, respectively, however increasing the φ raised the friction factor.

Srinivas and Venu Vinod studied the heat transfer of a SHCTHEx utilizing CuO/water NF with different φ of 0.3 – 2 wt.% experimentally [113]. The results revealed that utilizing CuO/water NF enhanced the heat transfer by increasing the Dean number (*De*) and φ. Kannadasan et al. experimentally studied the heat transfer and pressure drop of a SHCTHEx with different orientations utilizing CuO/water NF with variable φ [114]. The results indicated that increasing the *De* and φ improved the *Nu*. Whereas increasing the φ and decreasing the *De* increased the friction factor (*f*) as illustrated in Fig. 12. Furthermore, suggested correlations to compute the coil *Nu* were developed for the turbulent fluid flow. Srinivas and Venu Vinod experimentally investigated the heat transfer and effectiveness of a SHTHEx utilizing CuO/water, Al_2O_3/water, and TiO_2/water NFs at different φ of 0.3 -

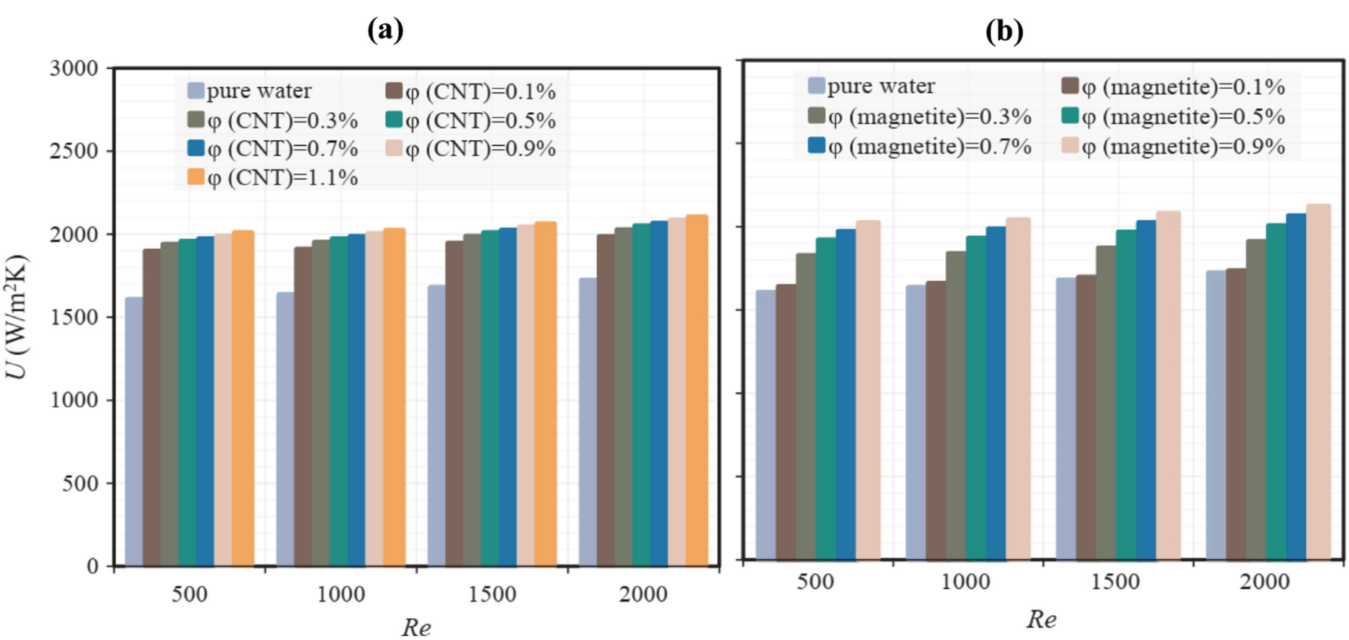

Fig. 7. Overall heat transfer coefficient (*U*) versus Reynolds number (*Re*) with the effect for of (a) CNT concentration of 0.7 vol.% (b) magnetite concentration of 0.7 vol.% [93], reused with permission from Elsevier license number 5016680952574.

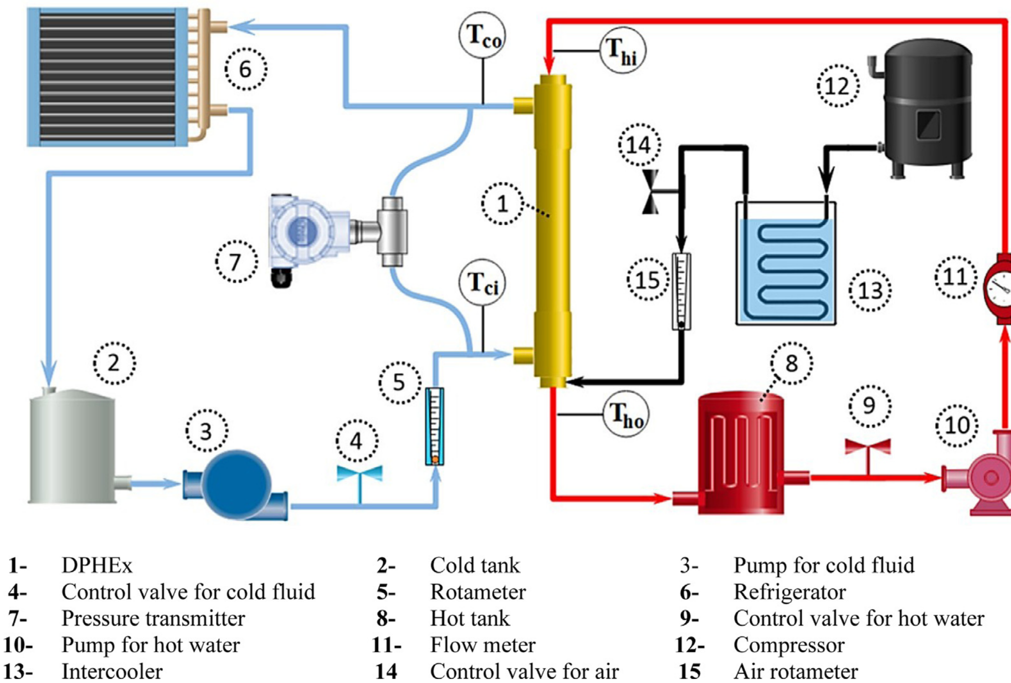

Fig. 8. Experimental setup of the proposed system [94], reused with permission from Elsevier license number 5016681103231.

2 wt.% [115]. The results showed that regarding to the thermophysical properties of different NFs, the effectiveness of the SHTHEx employing Al_2O_3/, CuO, and TiO_2/water NF were increased by 30.37, 32.7, and 26.8%, respectively.

Elshazly et al. studied the performance of a horizontal SHCTHEx utilizing a γ-Al_2O_3/water NF [116]. During the study, the coil torsion ($p_c/\pi D_c$) was varied from 0.0442 to 0.1348, and φ up to 2 vol.%. The experimental results showed that reducing the coil torsion enhanced the heat transfer but raised the friction factor. Additionally, correlations were developed based on the experimental results to compute the average *Nu*, and friction factor. Fule et al. studied the heat transfer performance of the SHCTHEx using CuO/water NF with variable φ as illustrated in Fig. 13 [117]. The experimental results revealed that employing CuO/water NF at 0.1 and 0.5 vol.% enhanced *h* by 37.3% and 77.7%, respectively. Additionally, increasing *Re* from 812 to 1895 improved increased *h* about 4.4 times.

Bhanvase et al. studied the performance of a SHCTHEx in the vertical direction using polyaniline (PANI) nanofibers at φ of 0.1 - 0.5 vol.% [118]. The experimental results revealed that the *h* for 0.1 and 0.5 vol.% PANI was enhanced by 10.52% and 69.62%, respectively. Jamshidi et al. explored the performance and friction factor of SHCTHEx utilizing Al_2O_3/water NF at φ of 1 and 2 vol.% numerically

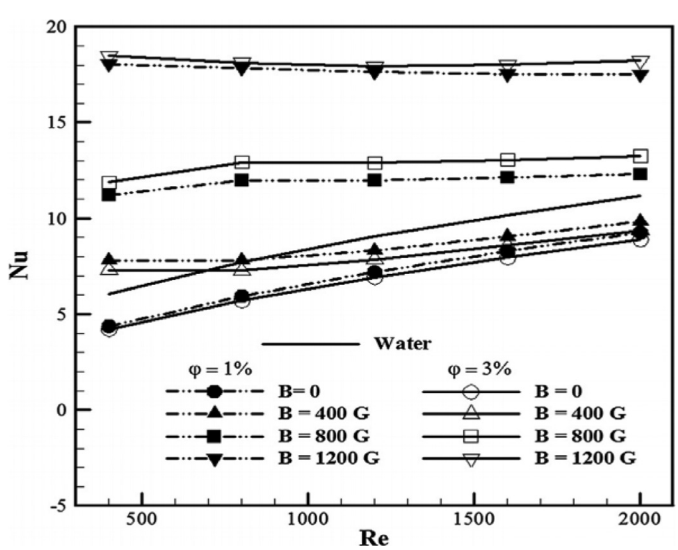

Fig. 9. Nusselt number (*Nu*) versus Reynold number *(Re)* at different magnetic field intensities and volume fractions [95], reused with permission from Elsevier license number 5016681342022.

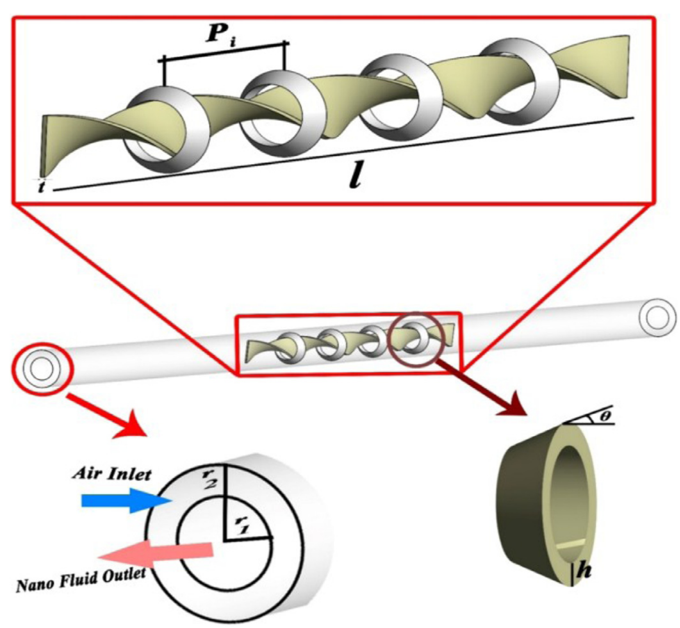

Fig. 10. Geometry details of the combined vortex generators and the twisted tape turbulator [97], reused with permission from Elsevier license number 5016681495129..

Table 2
Summary of the performance of double-pipe heat exchanger (DPHEx).

Ref.	Study	Flow direction	Nanoparticles	Size, nm	Concentration (φ)	Based fluid	Main findings
Kassim and Lahij [90]	Num. and Exp.	Counter- flow	SiO_2	15–20	0.1- 3 vol.%	water	▫ The *Nu*, *f*, and performance afctor enhanced by 15.72%, 11.51%, and 11.57% due to dusing SiO_2/water NF.
Gnanavel et al. [91]	Num.	Spiral Spring insert	TiO_2, CuO, BeO, ZnO	NA	NA	water	▫ The thermal performance factor due to using TiO_2/, BeO/, CuO/, ZnO/water NFs was 1.879, 1.795, 1.798, and 1.601, respectively.
Shahsavar et al. [93]	Num.	Counter-flow	Hybrid nanofluid of CNT-Fe_3O_4	NA	0.01 - 0.9 vol.% (Fe3O4) 0.05 - 1.35 vol.% (CNT)	water	▫ The optimum concentration values of Fe_3O_4 and CNT were 0.88% and 1.1%, respectively.
Jafarzad and Heyhat [94]	Exp.	Counter-flow	SiO_2	12	0.1 and 0.5 vol.%	water	▫ The maximum heat transfer enhancement was achieved at 0.5% concentration. ▫ Air bubble injection enhanced the exergy efficienc up to 58.1%.
Bezaatpour and Goharkhah [95]	Num.	Mini HEx	Fe_3O_4	20 nm	1 and 3 vol.%	water	▫ Utilizing external magnetic field enhanced the heat transfer up to 320% with a little increase of pressure drop.
Singh and Sarkar [96]	Num.	With wire coil turbulator	Al_2O_3–MgO	50 (Al_2O_3) 90 (MgO)	0.1 vol.%	water	▫ The *Nu* and *f* of Al_2O_3–MgO/ water NF using D-, C-D, and C-types wire inserts increased up to 84%, 71% and 47%, and 68%, 57%, and 46%, respectively.
Arjmandi et al.[97].	Num.	With twisted tape and vortex generators	Al_2O_3	NA	0.04 vol.%	water	▫ The pitch ratio of vortex had a prevalent impact on *Nu* and *f*, which increased the efficiency up to five times compared with the original case.
Poongavanam et al. [98]	Exp.	Counter-flow with an inner roughened surface	MWCNT	20–30	0.2 - 0.6 vol.%	ethylene glycol	▫ Using 0.6 vol.% MWCNT enhanced the *h* up to 115%.

*Exp. = experimental, Num. = Numerical, φ = volume fraction, NA: not applicable or value not directly available.

[119]. Taguchi-method was used to investigate the effect of geometrical parameters and fluid flow behavior, as shown in Fig. 14. The results indicated that the essential geometrical parameters were the constant tube diameter and length of the helically coiled tube. Moreover, increasing the φ and ***Re*** enhanced ***Nu***, while increasing the friction factor. Similarly, Bahrehmand and Abbassi numerically studied the heat transfer and pressure drop in a SHCTHEx using Al_2O_3/water NF at φ of 0.1 to 0.3 vol.% [120]. During the experiments, the Reynolds number in coil (Re_c) changed from 9000 to 36,000, while for the shell (Re_{sh}) it varied from 600 to 2600. The results showed that the heat transfer rate was enhanced, while the pressure drop was elevated at higher φ. Additionally, the HEx effectiveness was enhanced by increasing the diameters of coil and tube and increasing the φ, whereas it reduced with increasing the mass flow rate.

Akbaridoust et al. studied numerically and experimentally the heat transfer and pressure drop characteristics for a coiled tube with different curvature ratios utilizing CuO/water NF [121]. The results revealed that the increased coil curvature ratio, *Re*, and φ enhanced the *h* and the pressure drop. Furthermore, the heat transfer rate of the helically coiled tube was greater as compared to the straight tube. Moreover, the performance index of the helical coil was enhanced with increasing the coil curvature ratio. Rakhsha et al. investegated the thermal performance and pressure drop of through a helically coiled tube in a horizontal direction utilizing CuO/water NF at 0.1 vol.% [122]. The results showed an increased pressure drop (Δp) and *h* by 16−17% and 14−16%, respectively.

Maghrabie et al. studied the effect of the inclination angle of a SHCTHEx on its performance employing water and SiO_2/ and Al_2O_3/water NFs [123]. The results showed that changing the HEx orientation from horizontal to vertical positions enhanced the Nu_c by 11%, 8.3%, and 7.5% for water, Al_2O_3/water, and SiO_2/water NFs at φ of 0.1 vol.%, respectively. Additionally, due to the suprior thermophysical properties of Al_2O_3 NPs, the HEx vertical orientation and Re_c of 6000 for 0.1 vol.% Al_2O_3/water, the enhancements in Nu_c and HEx effectiveness (ε) increased by 35.7% and 35.5%, respectively. While, for 0.1 vol.% SiO_2/water were 16.2% and 15.6%, respectively. Wang et al. proposed an intelligent optimization design for a SHCTHEx utilizing the genetic algorithm [124]. The results indicated that at the optimal SHCTHEx structure, the heat transfer rate and flux were increased by 101% and 110%, respectively.

Mirgolbabaei et al. assessed the effects of tube diameter, coil pitch, and shell mass flow rate on h_{sh} in SHCTHEx based on the fluid-to-fluid HEx boundary conditions [125]. The results indicated that increasing the coil pitch in the medium range decreased the *h* while increasing it up to twice the tube diameter increased the *h*. Moreover, the *h* decreased by elevating the tube diameter for the same coil pitch. Wanga et al. proposed a new design of cylindrical SHCTHEx with a finned tube, as shown in Fig. 15, and analyzed the effect of shell mass flow rate and the fin geometry on exergy analysis [126]. The numerical results indicated that increasing the number and height of fins, and shell mass flow rate improved the number of the transfer unit (*NTU*) and the exergy loss. The exergy loss was found to be only 23.4% of the heat transfer rate. Additionally, correlations to identify the optimum values of the geometrical and operational parameters of SHCTHEx with fins were presented. The thermal performance and friction factor of horizontal SHCTHEx with segmental baffles using γ-Al_2O_3/water NF with sodium dodecylbenzene sulphonate as a surfactant were studied by Barzegarian et al. [127]. The experimental results revealed that using NF at φ of 0.03, 0.14, and 0.3 vol% enhanced the *Nu* up to 9.7%, 20.9%, and 29.8%, respectively, while *U* was improved by 5.4, 10.3, and 19.1%, respectively. Additionally, the thermal performance factor was enhanced up to 6.5 and 18.9%, for 0.03 and 0.3 vol%, respectively.

Kumar et al. investigated experimentally the increase in heat transfer and pressure drop of the SHCTHEx using Al_2O_3/water NF at variable φ [128]. The results indicated that the *Nu* for φ of 0.1, 0.4, and

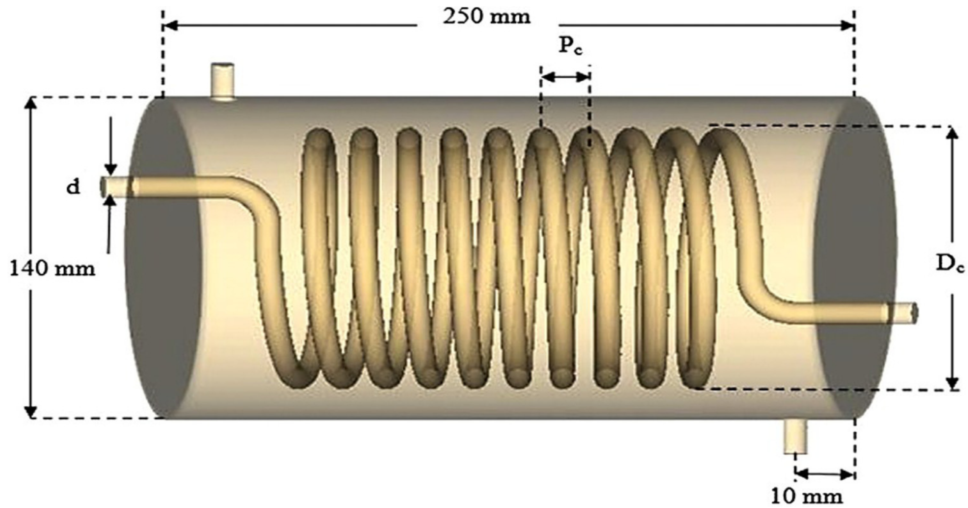

Fig. 11. Geometrical details of the SHCTHEx [110], reused with permission from Elsevier license number 5016690153179.

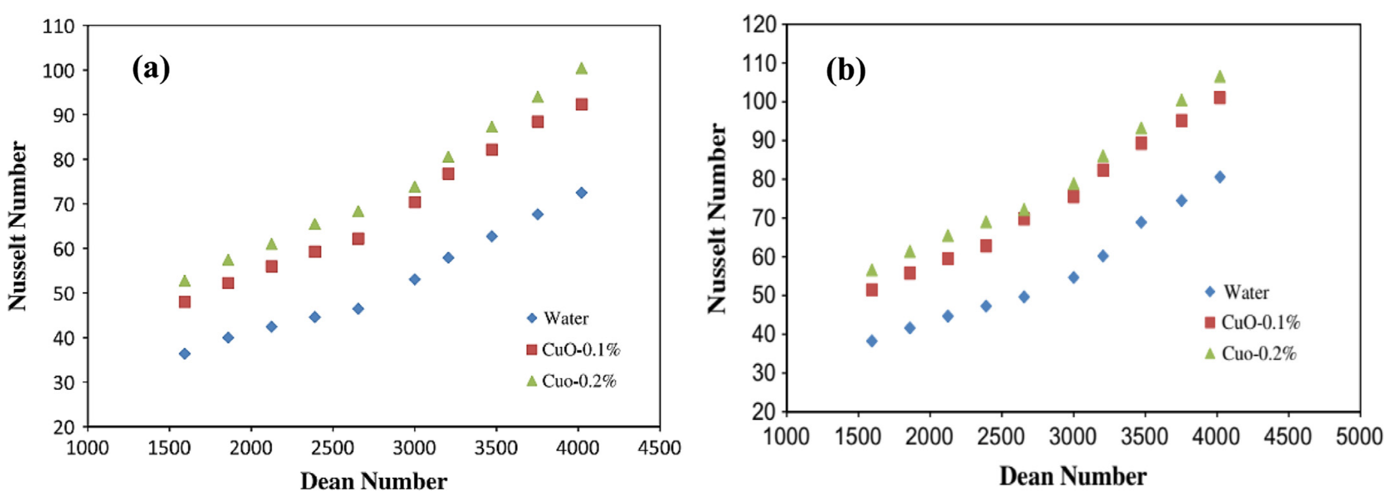

Fig. 12. Coil Nusselt number (*Nu*) versus Dean number (*De*) for (a) horizontal position (b) vertical position [114], reused with permission from Elsevier license number 5016690459229.

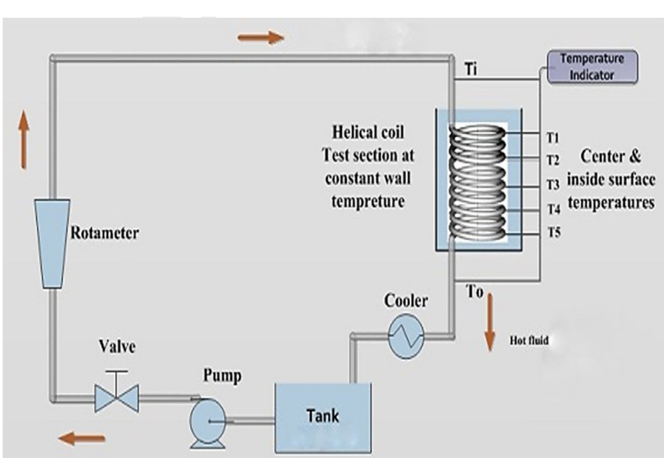

Fig. 13. Schematic of experimental setup proposed by [117], reused with permission from Elsevier license number 5016690619277.

0.8 vol.% was improved by 28, 36, and 56%, respectively. While the pressure drop was raised by 4, 6, and 9%, respectively, at the same φ values. The *h*, *Nu*, ε, and entropy generation of SHCTHEx using the three-dimensional analysis were investigated by Huminic et al. [129]. The φ of CuO and TiO_2 and mass flow rate were assessed numerically. The results revealed the maximum values of ε for CuO/water and TiO_2/water NFs at 2 vol.% were 91% and 80%, respectively. The impact of utilizing different nanoparticles of Al_2O_3, CuO, SiO_2, and ZnO with different thermophysical properties at various φ of 1 - 4 vol.% dispersed into different base fluids such as water, ethylene glycol, and engine oil on the performance of the SHCTHEx was numerically investigated by Narrein and Mohammed [130]. The results indicated that the highest *Nu* obtained value was for CuO/water NF. Additionally, the engine oil as base fluid with large viscosity had the highest pressure drop (Δp) compared to water and ethylene glycol. Table 3 presents the correlations devloped to evaluate the *Nu* number for coiled tube showing the range of applicable parameters and its error in previous works are listed in. Additionally, the summary of the thermal performance of SHCTHEx using different NFs are listed in Table 4.

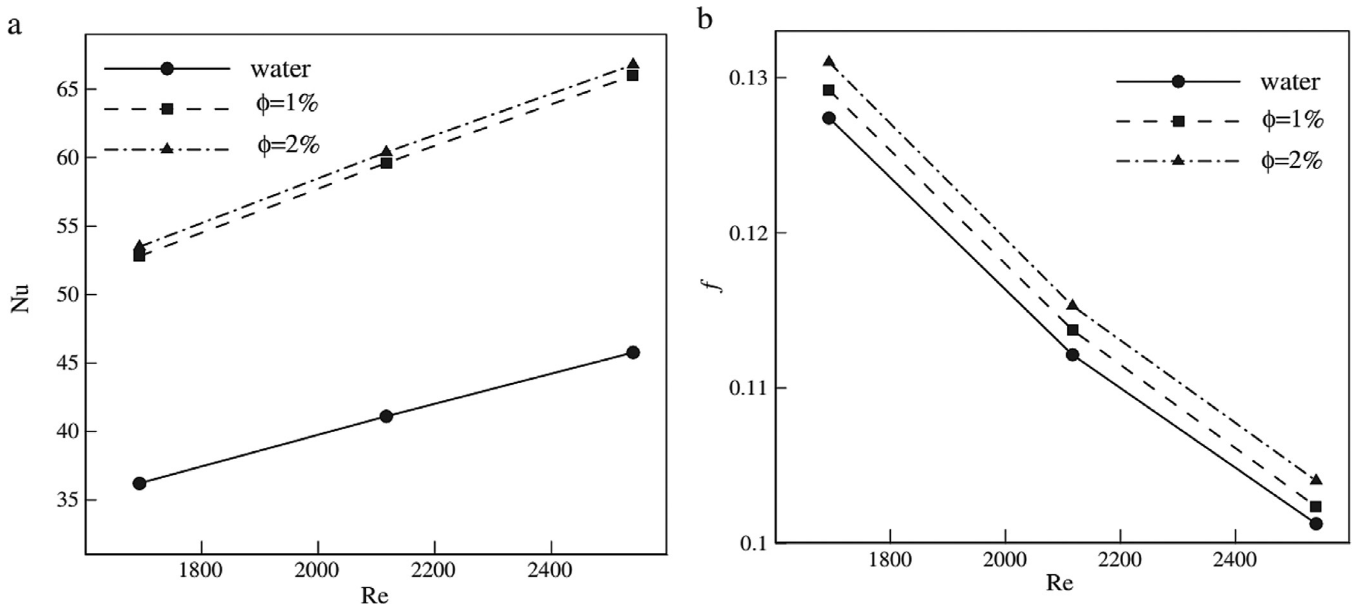

Fig. 14. Effect of suspending Al_2O_3 NPs on (a) Nusselt number (*Nu*) and (b) friction factor (*f*) [119], reused with permission from Elsevier license number 5016690787667.

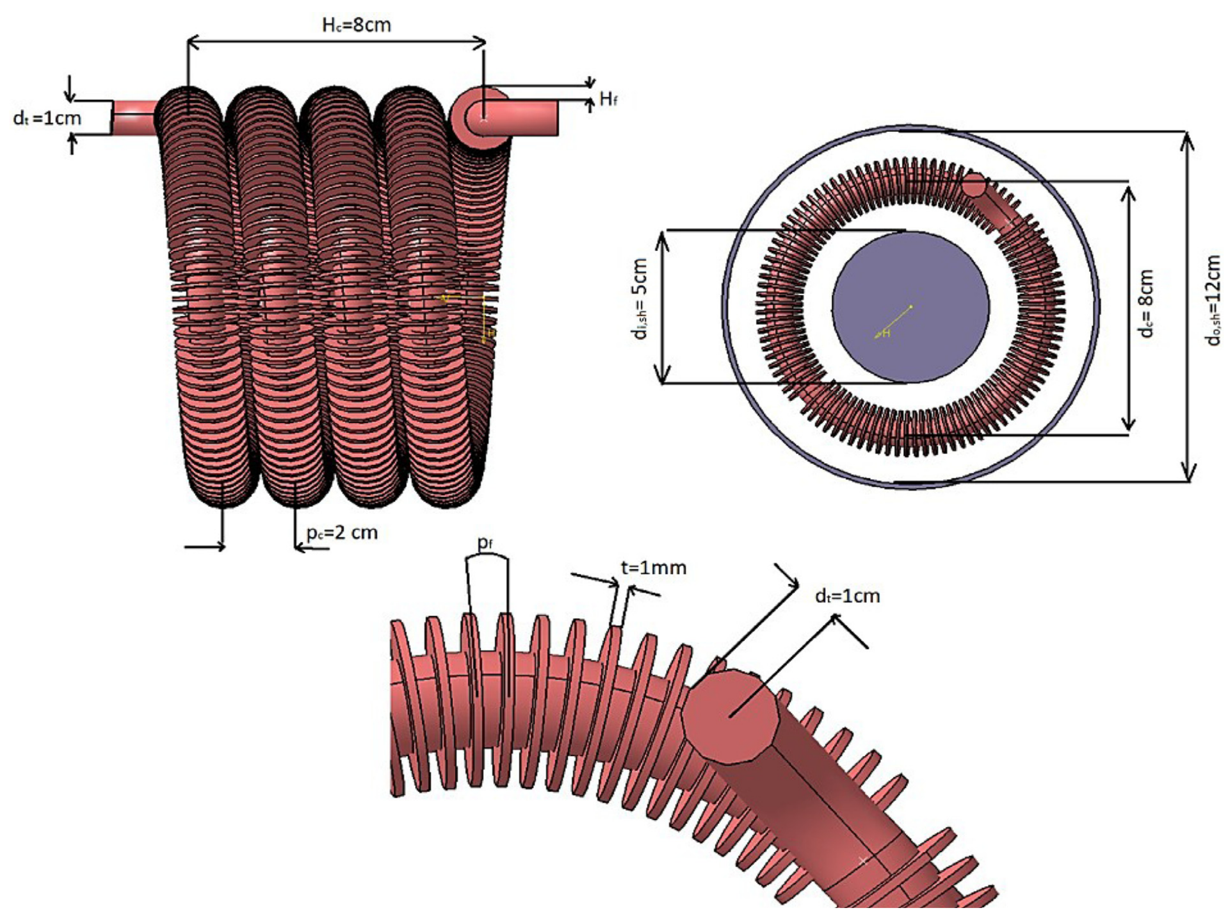

Fig. 15. The finned helical tube proposed by Wanga et al. [126], reused with permission from Elsevier license number 5020220465594.

2.4. Cross-flow heat exchangers (CFHExs)

Due to the manufacturing simplicity, possibly design, low maintenance cost, the cross-flow heat exchangers (CFHExs) are extensively used in various industrial applications, e.g., petrochemical processes, refrigeration and air conditioning applications, food processing and storage, car radiators, etc. [134–136]. The CFHExs constitute flow across a bundle of cylinders developing flow separation, boundary

Table 3
Correlations for estimating the coil Nusselt number in shell helically coiled tube heat exchangers SHCTHExs.

Ref.	Correlation	Range of parameters	NF
Kannadasan et al. [114]	For vertical orientation: $Nu_c = 1.5De^{0.827} + (d/D)^{0.0008}\varphi^{1.1694}$ For horizontal orientation: $Nu_c = 3.6De^{0.67} + (d/D)^{0.0009}\varphi^{1.004}$	$1,600 \le De \le 4,000$ $0.1\% \le \phi \le 0.2\%$	CuO/water
Elshazly et al. [116]	$Nu_c = 0.01974Re^{0.928}Pr^{1.302}\lambda^{-0.04775}\phi^{0.603}$	$5,702 \le Re \le 55,101$ $0.1\% \le \phi \le 0.2\%$ $0.0442 \le \lambda \le 0.1348$ $1.92 \le Pr \le 3.9$	γ-Al_2O_3/water
Maghrabie et al. [123]	For Al_2O_3/water NF: $Nu_c = 0.0344Re^{0.681}\theta^{0.0144}\phi^{0.2567}$ For SiO_2/water NF: $Nu_c = 0.062Re^{0.596}\theta^{0.0168}\phi^{0.2522}$	$1,600 \le Re \le 4,000$ $0.017 \le \theta\ (rad.) \le 1.571$ $0.005\% \le \phi \le 0.02\%$	Al_2O_3/water SiO_2/water
Rakhsha et al. [122]	$Nu_c = 0.061Re^{0.77}Pr^{0.4}(1+\phi)^{0.22}$	$10,000 \le Re \le 90,000$ $4 \le Pr \le 5$ $0\% \le \phi \le 1\%$	CuO/water
Kahani et al. [131]	For TiO_2/water NF: $Nu_c = 0.5He^{0.522}Pr^{0.613}\phi^{0.0815}$ For Al_2O_3/water NF: $Nu_c = 0.7068He^{0.514}Pr^{0.563}\phi^{0.112}$ $He = De[1+ (\frac{p}{2\pi D})^2]^{0.5}$	$115.3 \le He \le 1311.4$ $5.89 \le Pr \le 8.95$ $0.25\% \le \phi \le 1\%$	TiO_2/water Al_2O_3/water
Hashemi and Akhavan-Behabadi [132]	$Nu_c = 41.73Re^{0.346}Pr^{0.286}(1+\phi)^{0.18}$	$Re \le 125$ $7 \le Pr \le 2050$ $0\% \le \phi \le 2\%$	CuO/water
Mahdi et al. [133]	$Nu_c = 0.0104De^{0.92}Pr^{0.1.2}(1+\phi)^{-0.09}$	$De \le 2000$ $0.08\% \le \phi \le 0.3\%$	Al_2O_3/water

NA: not applicable or value not directly available.

layer, and vortex formation. The intensification of CFHEs is accomplished using fins on the tubes with different pitch ratios and geometries as well as using a vortex generator or winglet to augment the turbulence intensity [137,138]. Various fin configurations plain fin, slit fin, fin with winglets, and crimped spiral, were investigated experimentally and numerically as illustrated in Fig. 16 by Tang et al. [139]. The performance of the air-side HEx with the above-mentioned configurations of fins was evaluated, and it was found that the HEx with mixed fin had the best performance than that for a fin with vortex generators.

Hussein et al. examined the heat transfer enhancement of car radiators using SiO_2/ and TiO_2/water experimentally [140]. The results showed that according to the thermophysical properties of each NF, the heat transfer of SiO_2/ and TiO_2/water NFs was enhanced by 32% and 20%, respectively. Moreover, there was an insignificant effect of φ of SiO_2/ and TiO_2/water on the friction factor. Hussein et al. [141] discussed the effect of using the SiO_2/water NF on the convective heat transfer of car radiator at φ of 1 - 2.5 vol.% both numerically and experimentally. The results showed that the thermal performance intensified with increasing the NF flow rate, φ, and inlet temperature, as shown in Fig. 17, achieving the maximum heat transfer enhancement of 46% with 2.5 vol.% SiO_2/water NF.

Hussein et al. [142] examined the thermal performance of the automotive cooling system using SiO_2/ and TiO_2/water at φ of 1 - 2 vol.% experimentally. In addition, a statistical model for cooling components based on the input and output parameters was

Table 4
Summary of previous studies of SHCTHEx using nanofluids.

Ref.	Study	Orientation	Nanoparticles	Size, nm	φ	Heat exchanger dimensions
Wu et al. [111]	Exp.	Horizontal double pipe	Al_2O_3	40	0.78 - 7.04 wt.%	d_t = 13.28 mm, D_{sh} = 44.4 mm, D_c =254 mm, n = 4.5, p=34.5, L 3.591 m, Re_t= 3019–4824
Kumar et al. [112]	Exp.	Horizontal	Al_2O_3	13	0.1 - 0.8 vol.%	d_t = 10.5 mm, D_{sh} = 124 mm, D_c =93 mm, p=19 mm, L_t= 3.7 m, Re_t= 5100 – 8700
Kannadasan et al. [114]	Exp.	Vertical and horizontal	CuO	10 - 15	0.1 and 0.2 vol.%	d_t = 9 mm, D_{sh} = 124 mm, D_c =93 mm, n = 13, p=17 mm, L_{sh}= 370 mm, De_t= 1600 - 4000
Srinivas and Venu Vinod [115]	Exp.	Vertical	Al_2O_3 CuO, TiO_2	20–30 40 10	0.3 - 2 wt.%	d_t = 9.8 mm, D_{sh} = 275 mm, D_c =165 mm, n = 10, p=32 mm, L_t= 6 m, $\dot{V}_t$= 0.5 – 5 Lit/min
Elshazly et al. [116]	Exp.	Horizontal	γ-Al_2O_3	40	0.5 - 2 vol.%	D_c =131 mm, n = 10, p and L_t= variable, Re_t= 5702 – 55,101
Fule et al. [117]	Exp.	Vertical	CuO	10	0.1 - 0.5 vol.%	d_t = 13 mm, n = 10, p=35 mm, L_t= 10 m, Re_t= 812 – 1895
Bhanvase et al. [118]	Exp.	Vertical	Poly aniline PANI	< 100	0.1 - 0.5 vol.%	d_t = 13 mm, D_{sh} = 275 mm, D_c =290 mm, n = 10, p=35 mm, L_t= 10 m, Re_t= 812 – 1896
Bahrehmand et al. [120]	Num.	Vertical	Al_2O_3	20	0.1 - 0.3 vol.%	d_t, 13 mm, D_{sh} = 80 mm, n = 19.25, p=20 mm, L_{sh}= 420 m, Re_t= 9000 – 36,000, Re_{sh}= 600 – 2600
Akbaridoust et al. [121]	Exp. and Num.	Helically coiled tube	CuO	68	0.1 - 0.2 vol.%	d_t and n are variables, $\dot{V}_t$= 0.1 – 2.5 Lit/min
Barzegarian et al. [127]	Exp.	Horizontal with segmental baffles	γ-Al_2O_3	15	0.03 - 0.3 vol.%	d_t =5 mm, D_{sh} = 71.4 mm, n = 48, L_t= 202 mm, Re_t= 200– 1200
Kumaret al. [128]	Exp.	Horizontal	Al_2O_3	45 - 50	0.1 - 0.8 vol.%	d_t =12 mm, D_{sh} = 130 mm, n = 48, p=20 mm, L_t= 3.7 m, D_c =95 mm, Re_t= 9500 – 13,000

*Exp. = experimental, Num. = Numerical, φ = volume fraction.

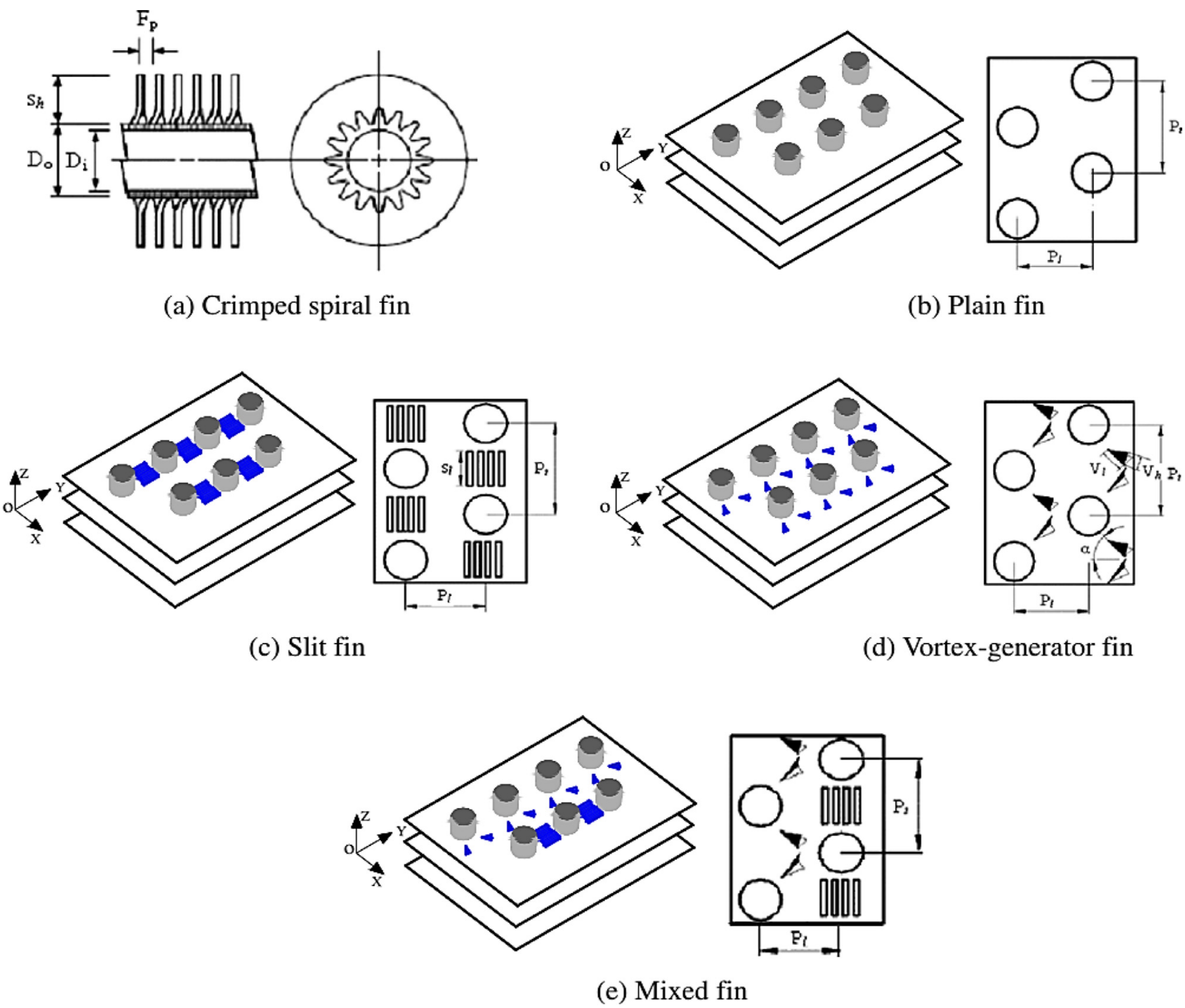

Fig. 16. Heat exchanger with different fin configurations [139], reused with permission from Elsevier license number 5016691432059.

developed. The experimental and the statistical results revealed that the *Nu* strongly depended on the NFs flowrate, inlet temperature and φ. Moreover, the maximum increase in *Nu* was 22.5% and 11% for SiO_2/ and TiO_2/water NFs, respectively. Peyghambarzadeh et al. [143] investigated the convective heat transfer of CFHEx as shown in Fig. 18, using Al_2O_3 in water and ethylene glycol (EG) as base fluids at φ up to 1 vol.% experimentally. The results showed that the highest *Nu* enhancement was 40% at the best conditions for both Al_2O_3/water and Al_2O_3/ ethylene glycol NFs.

Ray and Das studied the cooling of cross-flow, mixed (air)/ unmixed using Al_2O_3, CuO, and SiO_2 in ethylene glycol/water (60EG/ 40 W wt./wt.) mixture computationally [144]. The authors coded the effectiveness-number of transfer unit method in MATLAB with variable φ of $1 - 6$ vol.%. The results showed superior cooling performance was obtained at 1 vol.% of NFs, the high inlet temperature of the coolant, low turbulent flow for coolant-side ($Re \leq 5,500$), and high air-side ($Re \geq 1000$). Furthermore, the SiO_2-based NF showed the least performance gain, but could still reduce the pumping power. Esfe et al. evaluated the thermal conductivity of ZnO/DWCNT hybrid NF at φ of 0.045 - 1.9 vol.% and at inlet temperature of 30 - 50 °C experimentally [145]. The results showed that the thermal conductivity of the hybrid NF was enhanced by increasing the φ and temperature of the NF. The maximum enhancement in thermal conductivity of 24.9% was achieved at a temperature of 50 °C and φ of 1.9%. An experimental study to evaluate the thermal performance of car radiator using ZnO/water NF at φ of 0.01 - 0.3 vol.% was carried out by Ali et al. [146]. The results indicated that increasing the φ enhanced the thermal performance, where at φ of 0.2 vol.% the maximum enhancement of heat transfer was 46% as illustrated in Fig. 19.

3. Challenges and future work

Utilizing NFs is a promising practical solution for designing effective HExs, predominantly when the equipment volume is an essential issue. The sole drawbacks of employing different NFs are its extensive and possible instability. There are some challenges and future work directions that have to be implemented to well assess the intensification of heat transfer and the corresponding possible pressure drop due to the use of NFs in various HExs for different engineering application such as follow:

- Due to the higher cost of NF relative to BF, experiments should be accomplished taking into consideration the techno-economic of NFs to adjusted the best use of various NFs under different

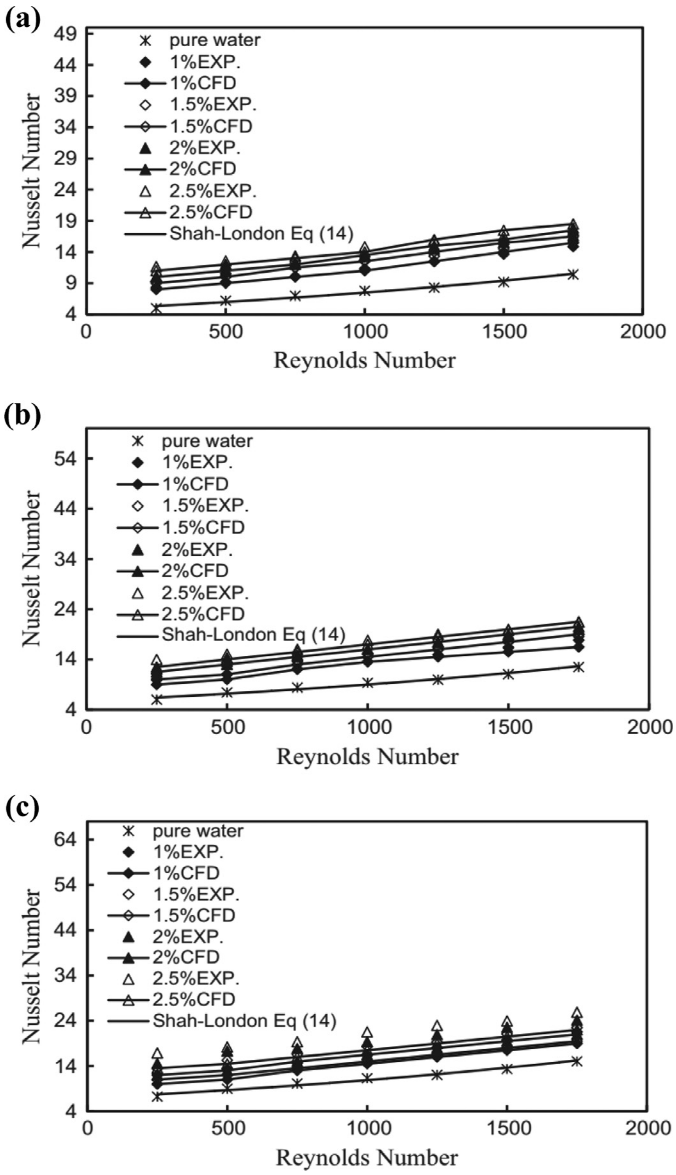

Fig. 17. Nusselt number (*Nu*) versus Reynolds number (*Re*) for different inlet temperature (a) 60 °C (b) 70 °C (c) 80 °C [141], reused with permission from Elsevier license number 5016700106544.

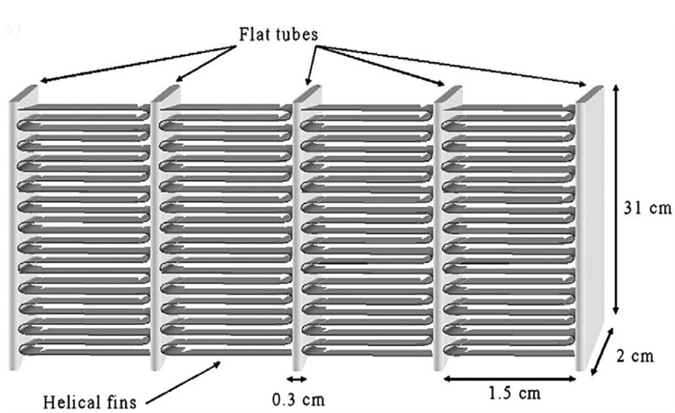

Fig. 18. Schematic of louvered aluminum fin and flat tube in cross-flow heat exchanger [143], reused with permission from Elsevier license number 5016700267568.

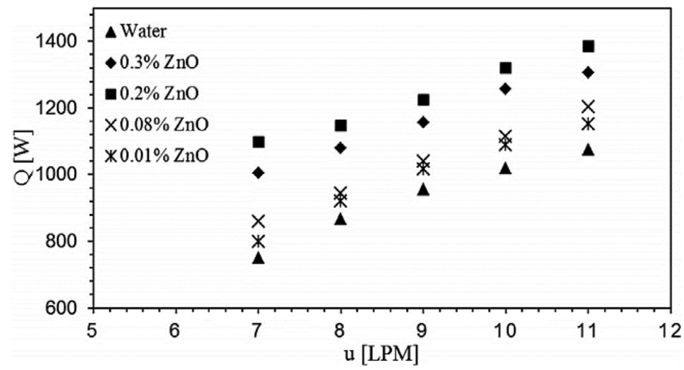

Fig. 19. Heat transfer rate versus the coolant flow rate [146], reused with permission from Elsevier license number 5016700485629.

operating and geometrical conditions of HEx, material and size of NPs, environments, and base fluid.

- Various examined NFs should be tested to assess the best material of NPs for each particular application considering the heat transfer rate, pressure drop, and exergy loss.
- The major challenge behind the applications of the NF in various HExs is the selection of suitable nanomaterials with optimum concentration, long term NF stability, manufacturing, and effective cost of NPsmaterial. It is required to determine the optimum value of volume fraction φ to obtain the best thermal performance, lower pressure drop, and NF stability.
- The stability of NFs is a crucial issue, so maintaining the NF stability requires proper NFs preparation and might require the addition of surfactant.
- Hybrid NFs of two different NPs materials with various shapes and sizes may cause higher viscosity leading to a higher pressure drop, increasing the pumping power. Accordingly, attention must be paid to selecting the different materials for hybrid NFs.
- The suitable aspect ratio of nanomaterials pair in hybrid NFs must be selected properly to improve the thermal path between NPs and the synergistic effect, leading to a high heat transfer rate.
- Most of the published investigations were dedicated to water and ethylene glycol as base fluids, while literature is limited concerning other base fluids such as engine oil, silicone oil, refrigerants, etc.
- Heat transfer intensification in HExs based on the active methods such as maintaining the rough surface needs a further precaution to avoid the sedimentation and accumulation of NPs, leading to the deterioration of thermophysical properties of NFs.
- The optimization criterion of HEx indicating the maximized heat transfer rate and reduced cost is required when studying the HExs. In addition, using various optimizing methods based on numerical results, reliable correlations considering the design and operating parameters are required to facilitate optimizing different types of HExs.

4. Conclusions

As a rapid progress report in the applications, NFs for different heat exchangers would be highly useful to the designers, researchers, and engineers working in this critical area to understand the up-to-date achieved efforts properly and identify the advances of utilizing NF for HExs. With this aim, the current work comprehensively reviews the thermal and fluid flow characteristics for different types of HExs, considering the thermophysical properties of NFs, with the following points concluded:

- The thermophysical properties of NFs were systematically investigated, emphasizing the common trends reported of increasing

the thermal conductivity, decreasing the heat capacity, increasing the density, increasing the viscosity, and the possibility of generating a non-Newtonian behavior.
- Utilizing NFs is a promising solution for designing an efficient HEx, specifically when the equipment footprint is critical.
- The superior heat transfer performance of NFs is due to the generation of various forces such as lift, drag, electrostatic, Brownian, van der Waals, and thermophoretic forces.
- Hybrid NFs introduce a better improvement in thermophysical properties, particularly the thermal conductivity compared with that for single/mono NF.
- The pressure drop and pumping power in HExs increased due to the use of NF and increased with the increase of the concentration of NPs.
- Using different nanofluids with air bubble injection, rough surface, etc., enhances additionally the effectiveness of heat exchange.
- Inducing swirling flow in a HExs using a magnetic field, twisted tape turbulators, vortex generators, etc., is favorable for a small size heat exchanger at low Reynolds numbers, and high volume concentrations of nanofluid.

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.

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