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Geometrical effect coupled with nanofluid on heat transfer enhancement in heat exchangers

A.G. Olabi[a,b,*], Tabbi Wilberforce[b], Enas Taha Sayed[c,d], Khaled Elsaid[e], S.M.Atique Rahman[a], Mohammad Ali Abdelkareem[a,c,d,*]

[a] Department of Sustainable and Renewable Energy Engineering, University of Sharjah, P.O. Box 27272, Sharjah, United Arab Emirates
[b] Mechanical Engineering and Design, Aston University, School of Engineering and Applied Science, Aston Triangle, Birmingham, B4 7ET, United Kingdom
[c] Center for Advanced Materials Research, University of Sharjah, PO Box 27272, Sharjah, United Arab Emirates
[d] Chemical Engineering Department, Minia University, Elminia, Egypt
[e] Chemical Engineering Program, Texas A& M University, College Station, TX, United States

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ABSTRACT

This investigation summarized the application of nanofluids (NFs) in heat exchangers (HExs) with different geometries. The quest for heat devices with quick response for the industrial sector is still a major challenge that has been an active research direction over the years. Addressing this issue is likely to increase the capacity of several industries. There is a direct relationship between expanding the heat capacity and the pressure drop. The common approach in increasing the rate of heat transfer often leads to an increment in pressure drop. This study reviews and summarizes the investigations on various geometrical effects inside the channel combined with NF in HExs. This review explored the potential of NFs as possible heat transfer fluid in HExs. From a detailed literature review compiled and evaluated, it has been deduced that NFs application significantly improves the thermal efficiency of HExs. The investigation further evaluated plate, helical, as well as shell and tube HExs. The review explored NFs application in HExs and how they can significantly improve the HExs' thermal characteristics. It was deduced that the use of NFs improved the heat transfer both experimentally and numerically . This equally has a direct relation to energy savings as well as industrial waste heat.

1. Introduction

The rapid growth in the world population and the rapid technological advances result in an exponential growth in energy consumption. Currently, fossil fuel, with a major share of energy supply, is limited in resources and has severe environmental impacts [1–3]. Researchers tend to control such environmental impacts by increasing the efficiency of the current industrial processes [3–6], developing efficient and environmentally friendly devices [7, 8], using environmentally friendly materials [9], and applying environmentally friendly renewable energy sources [10–13]. Although relying on renewable energy resources is the most promising replacement of fossil fuel, it is still costly, limiting its expansion, and the need for proper energy storage medium to overcome the intermittent nature of renewable energies [14–17]. Therefore, significant effort is given to increase the current technologies' efficiency through the waste heat recovery that plays a significant role in improving the overall energy efficiency [18–21].

Heat exchangers (HEx) are used extensively in the energy sector and process industries to transfer one fluid's thermal energy to another [22–24]. Research works are geared recently towards curved tubes for waste heat recovery [25–28]. Other research work explored thermal devices with higher efficiency like refrigerators and HEx [29]. This led to new methods for heat transfer (HT) enhancement techniques, mainly to reduce thermal resistance in HExs. HT enhancement techniques are subdivided into two main classes, namely active and passive [30]. The active technique is designed to include an external source of energy, whiles the passive one works with the changes made in the system's configuration and other system components to enhance the flow mixing. The active technique also curbs the formation of the thermal boundary layer to increase the rate of HT [31]. The passive techniques revolve around the creation of swirl flows, which provides a better flow mixing. This usually results in the HT coefficient, increasing appreciably.

The passive technique enhances thermofluidic system performance. Therefore, the passive method is suitable for increasing the thermal device's entire efficiency; hence activities in this field have

* Corresponding authors at: Department of Sustainable and Renewable Energy Engineering, University of Sharjah, P.O. Box 27272, Sharjah, United Arab Emirates.
E-mail addresses: aolabi@sharjah.ac.ae (A.G. Olabi), mabdulkareem@sharjah.ac.ae (M.A. Abdelkareem).

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seen a huge increase due to their industrial applications viability [32–36]. The application of rib channels is one of the commonly used passive techniques for thermal applications. Investigations into the effect of a wavy rib on the HT in a U-shaped channel has been reported [37]. It was argued that the ribs caused a lower stagnation of air around the wall, leading to an increase in heat flux. Similarly, it was deduced that V-shaped ribs led to vortices creation, which improved supported flow mixing. Numerical investigations considering thermal and frictional phenomenon for a square-shaped channel have been reported [38]. The enhanced flow-mixing results in a significant increase in the Nusselt number, which increases the overall HT coefficient. Investigations on the thermal efficiency for a square channel with high blocked ribs have shown that the presence of the rib enhanced the rate of HT [39]. The effect of a V-shaped rib on thermofluidic characteristics for a solar air heater also confirmed the effect of the shape on the system's performance [40]. According to this investigation, the HT rate improved significantly, increasing the thermal performance by a factor of 2.35.

A recent trend to enhance the performance of HEx is to employ nanofluids (NFs) due to their excellent thermophysical properties, hence making them suitable for several industrial applications [41–47]. NF is simply a stable suspension of nanoparticles (NPs) in conventional heat transfer fluid (HTF), i.e., base fluid (BF). It has been reported that metallic NPs in NF reduce thermal resistance, unlike other conventional fluid, making them suitable for HT devices due to improved HT [48–55]. The solar collector performance operated with TiO_2/water NF coupled with rib channels has been investigated, showing 10% enhanced collector efficiency, with an increment in the volume fraction of the NPs increasing the collector's efficiency [56]. Additionally, CuO/water NF shows a better results compared to TiO_2/water. Additionally, TiO_2/water NF significantly improved the HT coefficient by 116% [57]. Thermohydraulic properties of Al_2O_3/water NF, assessed in spiral HEx, was found to improve the HT coefficient, and hence heat flux, by nearly 26.3% [58].

Utilizing NFs is one of the most interesting strategies for HT improvement in HExs, with numerous studies published in this domain. Still, no reports discuss the thermophysical properties considering various channel's geometrical effects coupled with NF in different HEx applications. Therefore, this review article attempts to present the potentiality in the use of NFs coupled with the various geometrical design of HExs. At first, the review focuses on the investigations conducted on different types of geometrical effect of HExs in which NFs have been employed, and finally, some interesting aspects in this field are introduced and discussed. Challenges and scope for further studies in this area were identified and proposed. Indeed, this review could help in designing efficient heat exchange equipment combining the improvements due to geometrical and NFs effects.

2. Nanofluids: chemistry, preparation, and properties

Nanofluids (NFs) are simply a stable suspension of solid nanostructures or nanoparticles (NPs) in liquid, commonly called base fluid (BF), which can be any heat transfer fluid (HTF), with water as the most commonly used HTF [59,60]. Suspension of NPs in BF has been employed mainly to increase the relatively low thermal conductivity of BF, which is 0.607 W/m.K in case of water, by addition of highly thermal conductive metallic, non-metallic, and carbon-based NPs which can have a thermal conductivity in the range of 1.4–5,000 W/m.K [61,62]. Table 1 below shows the typical thermophysical properties of common BF and NPs, showing the relatively higher thermal conductivity of NPs. NPs of different natures, i.e., metallic such as silver Ag, copper Cu, and gold Au have been used, as well as oxides such as silica SiO_2, alumina Al_2O_3, titania TiO_2, Zinc oxide ZnO, and copper oxide CuO. Additionally, carbon-based NPs such as graphite, graphene, graphene oxide, reduced graphene oxide, carbon nanotube, carbon nanofiber have been used as well [59–62].

In association with the increase of thermal conductivity of NF relative to BFs, it is noted that there is a decrease the specific heat capacity, while increasing the density and viscosity, which are not favored changes. However, due to the significant enhancement in heat transfer characteristics, NFs have outstanding performance in HT applications [63–65]. The reduced specific heat capacity will reduce the heating/cooling capacity of the fluid, while the increased density and viscosity will increase the pressure drop upon flow, which will increase the pumping power requirements. The high thermal conductivities of solid NPs enable high thermal conductivities of NFs even at small volume fraction or concentration φ, of NPs in the BF, typically up to 1% for highly thermal conductive NPS, and up to 5% for less thermal conductive NPs. Eqs. (1)–(4) relate the different thermophysical properties of NFs to those of the NPs and BF, along with the volume fraction, while Eq. (5)–(7) relates these thermophysical properties to the HT characteristics of the fluid [59–62].

$$k_{NF} = \frac{k_{NP} + 2k_{BF} + 2\varphi(k_{NP} - k_{BF})}{k_{NP} + 2k_{BF} - \varphi(k_{NP} - k_{BF})} k_{BF} \tag{1}$$

$$\rho_{NF} = (1 - \varphi)\rho_{BF} + \varphi\rho_{NP} \tag{2}$$

$$\mu_{NF} = \left(1 + 2.5\varphi + 6.25\varphi^2\right)\mu \tag{3}$$

$$C_{p,NF} = \left[(1 - \varphi)\rho_{BF}C_{p,BF} + \varphi\rho_{NP}C_{p,NP}\right]/\rho_{NF} \tag{4}$$

$$Re = \frac{\rho du}{\mu} = \frac{du}{\nu} \tag{5}$$

$$Pr = \frac{\nu}{\alpha} = \frac{C_p\mu}{k} \tag{6}$$

$$Nu = \frac{hL}{k} = f(Re, Pr) = aRe^n Pr^m \tag{7}$$

Where: k = thermal conductivity, ρ = fluid density, μ = fluid dynamic viscosity, ν = fluid kinematic viscosity, C_p = specific heat capacity, φ = volume fraction of NPs, d = characteristic diameter, u = flow velocity, α = thermal diffusivity, h = convective heat transfer coefficient, L = characteristic heat transfer length, *a, m, and n* = correlation coefficients, Re = Reynolds number, Pr = Prandtl number, Nu = Nusselt number, subscripts: NF for nanofluid, BF for base fluid, NP for nanoparticles.

NF preparation is a very critical step as it has a crucial impact on the stability and properties of the obtained NF. There are two common approaches for NF preparation, one-step or two-step [68,69]. In the one-step NF preparation, the NPs are produced and dispersed in the BF simultaneously, i.e., NPs are formed from precursors present in the intended BF, hence it is characterized by high NF stability and minimized agglomeration of NPs. One-step NF preparation can be realized by direct evaporation, physical vapor deposition, and chemical vapor deposition. One-step NF preparation eliminates the need for drying, storage, and transportation of NPs [63,64,66]. However, the one-step method is limited to a few NPs and BF and their explicit combination, in addition to being costly. In the two-step method, the NPs are produced separately or readily acquired and then dispersed in the BF by chemical or physical means. Two-step preparation of NFs is much simpler, as the NPs are synthesized separately, without complications or constraints related to the NP-BF combination, which enable the preparation of a wide range of NFs [61,62]. However, the two-step NF preparation requires good dispersion of NPs in the BF, and to maintain the stability of such suspension avoiding the formation of NPs clusters or aggregates. This in return might affect the thermophysical properties, and even lead to sedimentation and blockage of NPs in flow channel [65,67,68].

One of the main challenges encountered with NFs application is the agglomeration or aggregation of NPs to form clusters or

Table 1
Thermophysical properties of common base fluids and nanoparticles [59–62, 66, 67].

	Thermal conductivity, W/m.K	*Specific heat, kJ/kg.K*	*Density, kg/m³*	*Viscosity, 10⁻³ Pa.S*
Common base fluids				
Distilled water (DI)	0.607	4.18	998	0.855
Ethylene glycol (EG)	0.255	2.35	1111	15.5
Common nanoparticles materials				
Silver Ag	429	0.234	10,400	–
Copper Cu	398	0.385	8933	–
Alumina Al_2O_3	36–40	0.775	3970	–
Copper oxide CuO	32.9	0.525	6500	–
Silica SiO_2	1.38	0.680–0.745	2220	–
Graphene*	6 - 5000	0.643- 2.100	2000–2500	–

* Graphene due to the unique properties have a wide range of reported thermophysical properties.

aggregates, hence losing the stability of the NF. The nature of NPs, volume fraction or concentration (φ), and their interaction with the BF have a substantial impact on NF stability [70,71]. NPs are commonly negatively charged which keeps them in suspension due to electric repulsion forces. However, such negative charges attract positive charges as well, hence the charge is neutralized, and stability is lost. One of the simplest approaches is to properly prepare the NF considering the strong agitation during the dispersion of NPs in the BF in the two-step method. Surfactants addition, as surface modifiers causing surface charge repulsion among NPs, hence improves the stability of NF [72]. The NF stability can be measured by the polydispersity index (PDI), Zeta potential, and the measurement of ultraviolet UV absorbance [73].

NFs are numerically studied assuming single-phase simulations, with limitations regarding the thermophysical properties [58]. Two-phase models are more accurate to simulate the NF's thermophysical properties, as it considers NPs and BF effects on the HT along with the flow characteristics [74–78]. Several work have showed that the mixture theory-based model is ideal for the simulation of NFs as it considers the impact of the NPs and their interactions with the BF [78]. The two-phase models have been reported to have better agreement with experimental results than that of single-phase models. The thermal and frictional properties for Al_2O_3/water NF in a ribbed channel using both the two-phase and single-phase models were investigated, showing the better accuracy of the two-phase model [78]. The thermohydraulic characteristics of SiO_2/water NF using a two-phase model showing that the impact of NP volume fraction was predominant at low Re [79]. Numerical investigations on a two-phase model on Al_2O_3/water NF via an annulus revealed that the presence of the NPs affected the HT coefficient, especially at the top of the inner cylinder [80].

3. Heat exchangers (HExs)

Devices that transfer thermal energy, i.e., heat, between two streams at different temperatures are referred to as heat exchangers (HExs) and are extensively used in industrial processes as an integral part of the process itself or for heat recovery [5,81,82]. There are different types of HExs, such as double pipe, flat plate, shell and tube, and many other HExs [83–90]. The quest for cost-effective and efficient energy sources has necessitated the need for HExs with higher efficiencies at a reasonable cost, which can be achieved by reducing the size of HExs. HT improvement in HExs will significantly increase their efficiency, reducing its size, and hence cost. Several studies were carried out to authenticate the cavities' design in HExs primarily to improve the HT characteristics. Others considered them as an open-end and explored the fluid flow characteristics in these ducts. Several investigations on the impact of inclination angle on the rate of HT have been reported in the literature [91–108]. Other researchers also introduced a magnetic and electric field to alter the flow field [109–114]. For any system, the energy exchange is usually dependent on the HTF's thermophysical properties, including density, viscosity, thermal conductivity, and heat capacity, among many. The main challenge associated with HTF is the low thermal conductivity. Therefore, NFs are supported as a better HTF due to their higher thermal conductivities [114–116].

3.1. Application of nanofluids in heat exchangers

The functionality of all HExs is impeded by certain factors that limit their performance and, in some instances, destroys the HEx, with considerable efforts to address this challenge. Recent studies revealed that the rheological characteristics of fluids coupled with passive HT devices are expected to be a promising technique to overcome the above limitation and fulfill industries' needs. The technique involves restricting the laminar sublayer's enlargement and enhancing the disturbance by generating vortices while increasing the HT area. Improving the HT rate will also imply an adjustment to the equipment's structure. Some of these modifications include an adjustment to the thermal surface, fluid injection, and the introduction of a magnetic field. Though these approaches have been suitable in the past, the high current request for efficient HT is calling for an alternative method. NFs with metallic or non-metallic NPs having good thermal characteristics is one of the efficient approaches to improve the thermal efficiency of HExs [117–128]. However, attention to energy consumption for pumping NFs due to the increased density and viscosity has to be considered [129,130].

3.2. Modeling of nanofluids in heat exchangers

There are primarily two approaches to study NFs performance in HExs, i.e., numerical and experimental. Numerical techniques with the aid of computers can report the principles behind NFs performance in HExs and enable design alteration. The application of numerical techniques comes with some practical importance in evaluating the solution to a problem before conducting any experimental work. Using computational fluid dynamics can also help supporting the evaluation of some thermophysical properties of the NF [131]. Many experimental investigations on the application of NFs in HExs have highlighted the important role of NF in enhancing thermal efficiency [132–136]. The modeling of NF in HEx relies on the solution of the two primary momentum transfer equation Eq. (8)) and heat transfer equation (Eq. (9)) [137–139]. These two equations are highly dependant on the thermophysical properties of the NF, which are in turn highly dependant on the thermophysical properties of the NPs and BF as expressed earlier in Eqs. (1)–(4):

$$v_y \frac{\partial v_y}{\partial y} = -\frac{\partial P}{\partial y} + \frac{\mu}{r}\frac{\partial v_y}{\partial r} + \mu \frac{\partial^2 v_y}{\partial r^2} \tag{8}$$

$$p\widehat{C_p}\left[v_y \frac{\partial T}{\partial y}\right] = \frac{1}{r}\left[k\frac{\partial T}{\partial r}\right] + k\frac{\partial^2 T}{\partial r^2} + k\frac{\partial^2 T}{\partial y^2} + 2\mu\left(\frac{\partial v_y}{\partial r}\right)^2 + \frac{4}{3}\mu\left(\frac{\partial v_y}{\partial r}\right)^2 \tag{9}$$

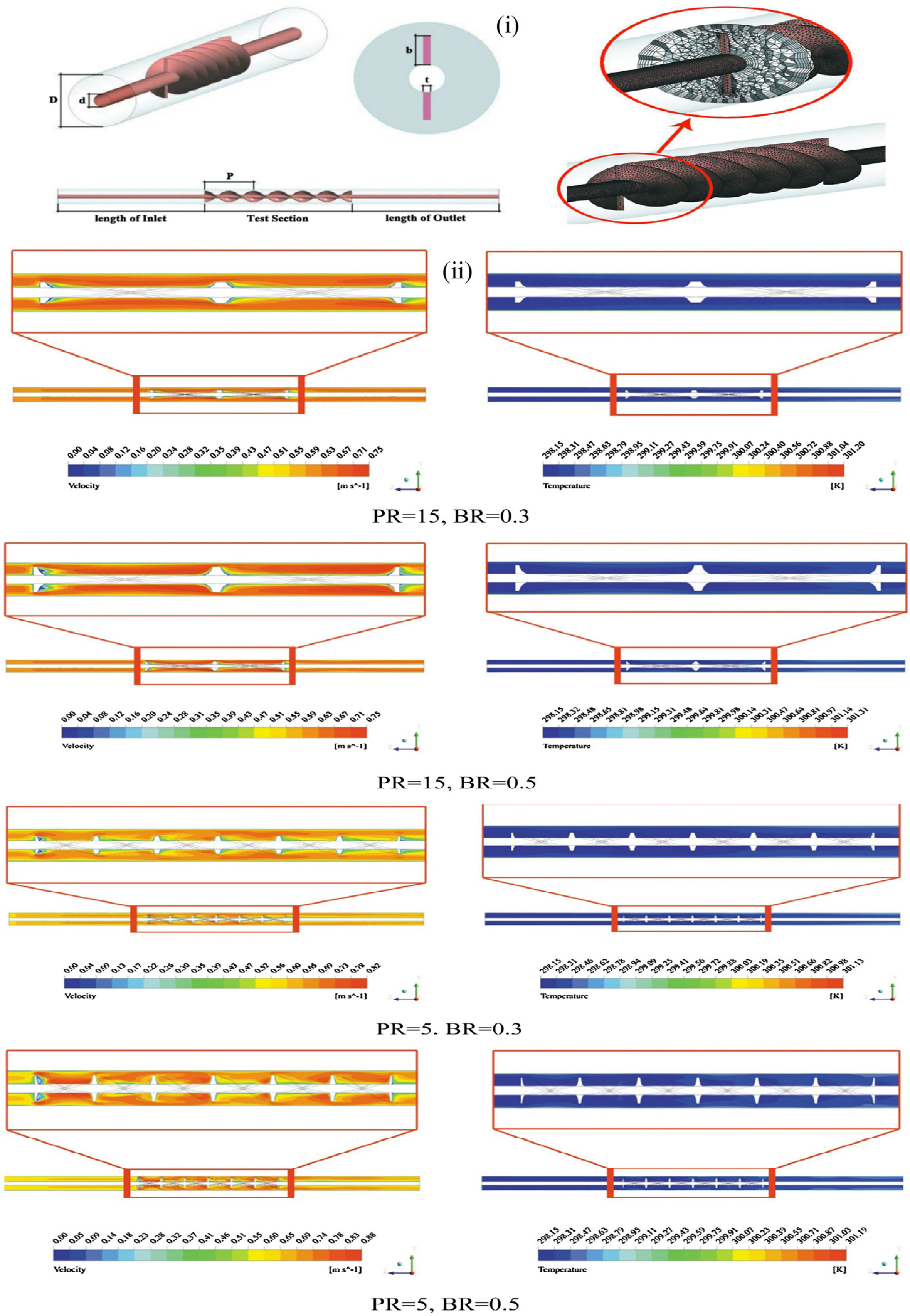

Fig. 1. (i) Geometry design and mesh used for circular cross-section, (ii) Velocity and temperature contours at *Re* of 2000 for different pitch and hight ratios, adapted with permission from Elsevier [180].

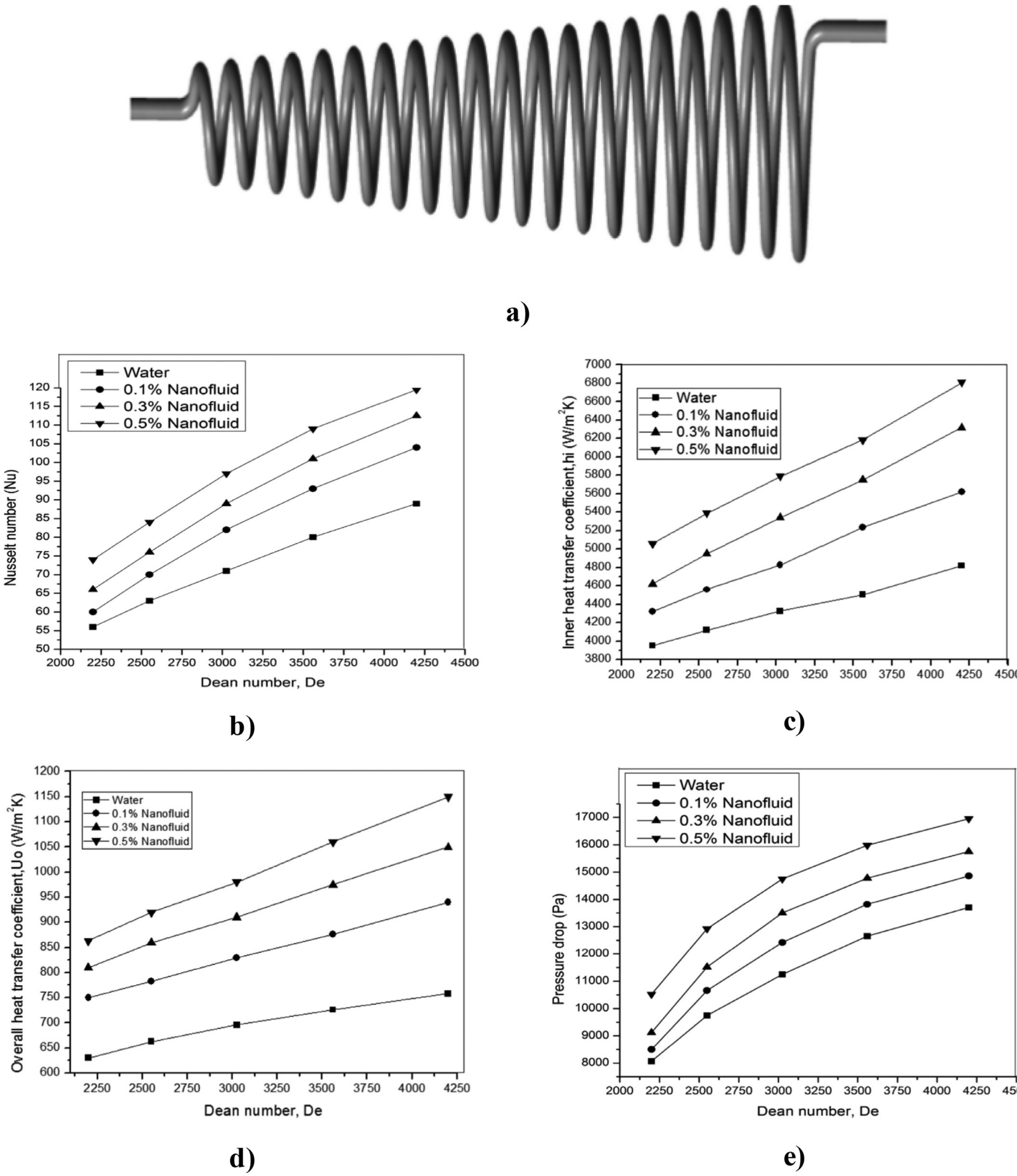

Fig. 2. (a) Geometry for the helically coiled tube heat exchanger, (b) overall heat transfer coefficient against, (c) Inner heat transfer coefficient, (d) Nusselt Nu number, (f) Pressure drop against Dean *De* number at a various nanofluid volume fraction [182].

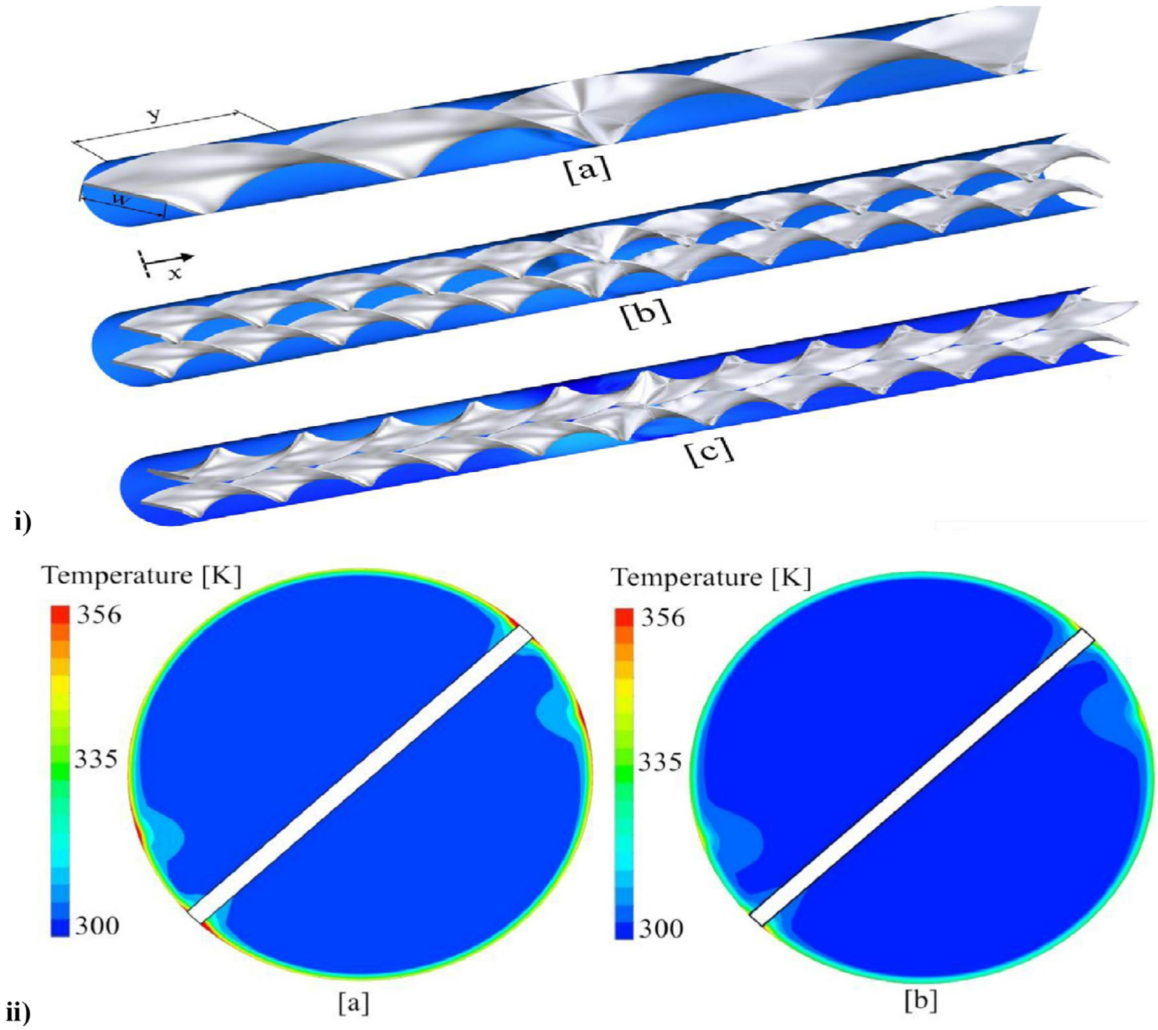

Fig. 3. (i) Geometry of the twisted tapes used for the investigation (a) Single twisted tape, (b) Co twisted tape, (c) Counter twisted tape; (ii) Temperature contours of single-twisted tape with twist ratio of 3 for: (a) φ = 0%, (b) φ = 0.1%, adapted with permission from Elsevier [51].

Where v = velocity, ρ = density, t = time, P = pressure, g = acceleration due to gravity, τ = shear stress, μ = viscosity, Cp =e specific heat capacity, T = temperature, r = radius, k = thermal conductivity, and y = longitudinal flow direction. These equations are solved numerically using mathematical solvers, such as Matlab, and computational fluid dynamics and heat transfer tools to obtain the description of the complete behavior of the fluid across different geometries. Different software packages are currently available such as Fluent and COMSOL

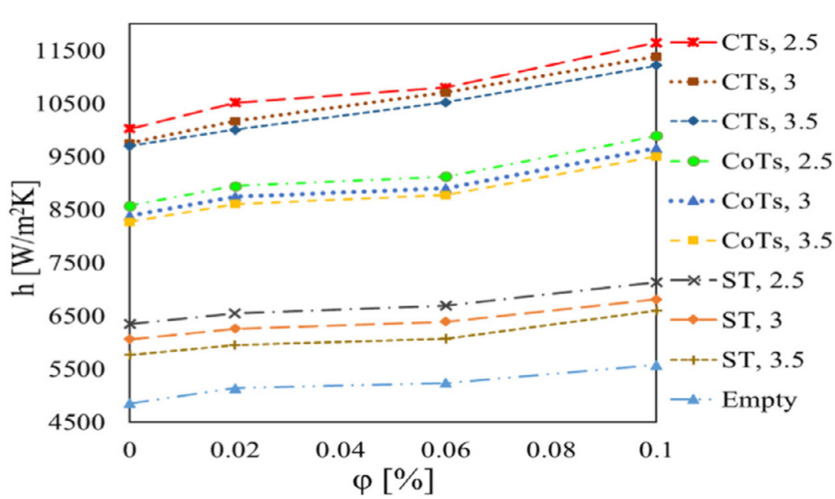

Fig. 4. Convective heat transfer coefficient for the single twisted (ST), twin co-twisted (CoTs), and counter twisted (CTs) tape configurations at different twist ratios, with permission from Elsevier [51].

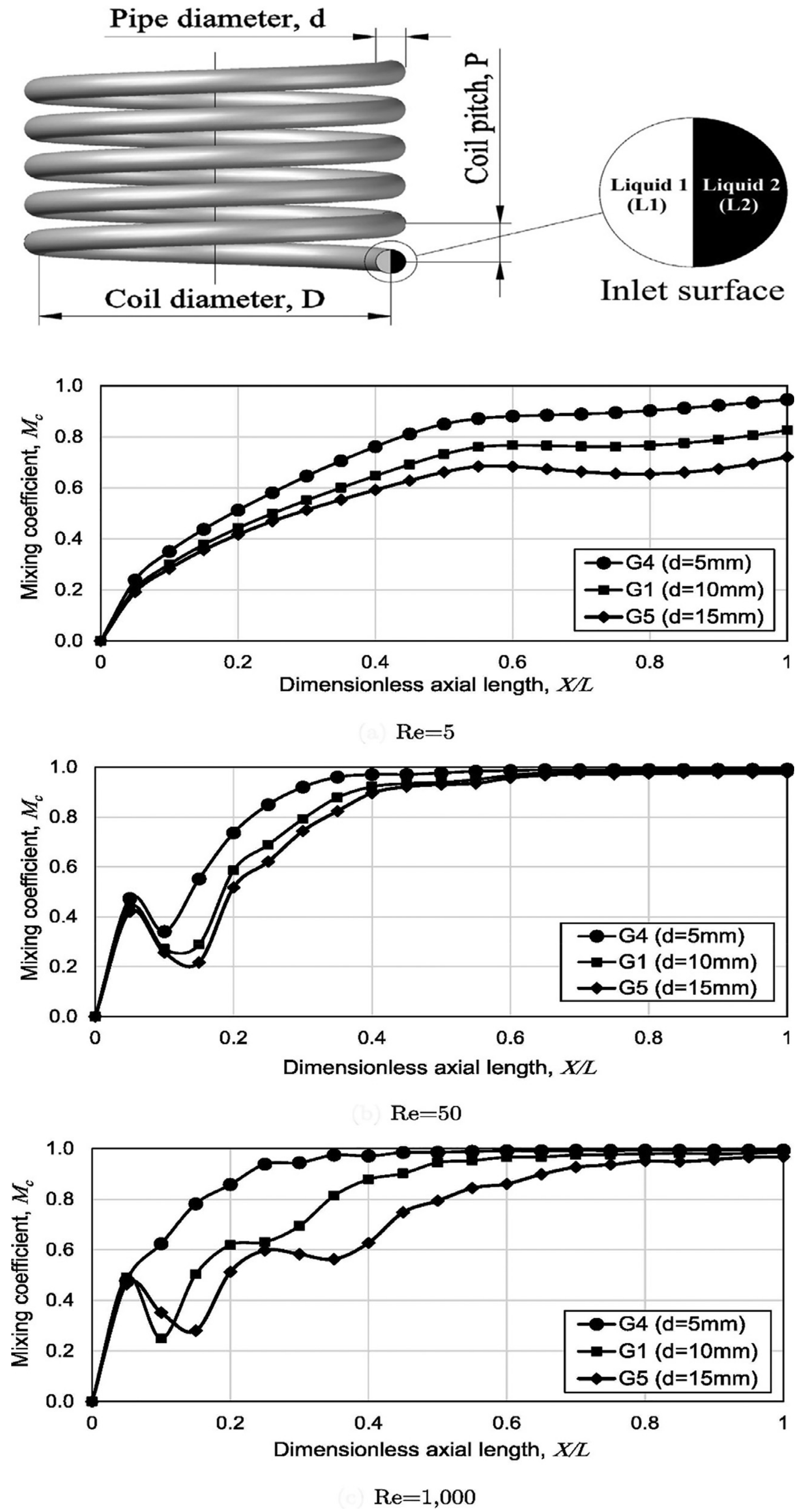

Fig. 5. Correlation between the pipe diameter and the mixing coefficient in the helical geometry pipe, adapted with permission from Elsevier [183].

Multiphysics to solve such complicated simultaneous heat transfer and fluid flow problems in complex structures and egometries over the constrained surface [139].

Two primary approaches are followed to simulate the HT properties of NFs, i.e., single- and two-phase models [136,140–143]. An assumption for continuity remains true for fluids having NPs for the first approach. The single-phase approach assumes the same governing equations as those for conventional fluids. The second approach involves the two-phase models such as the volume of fluid (VoF), mixed, Eulerian-Lagrangian, and

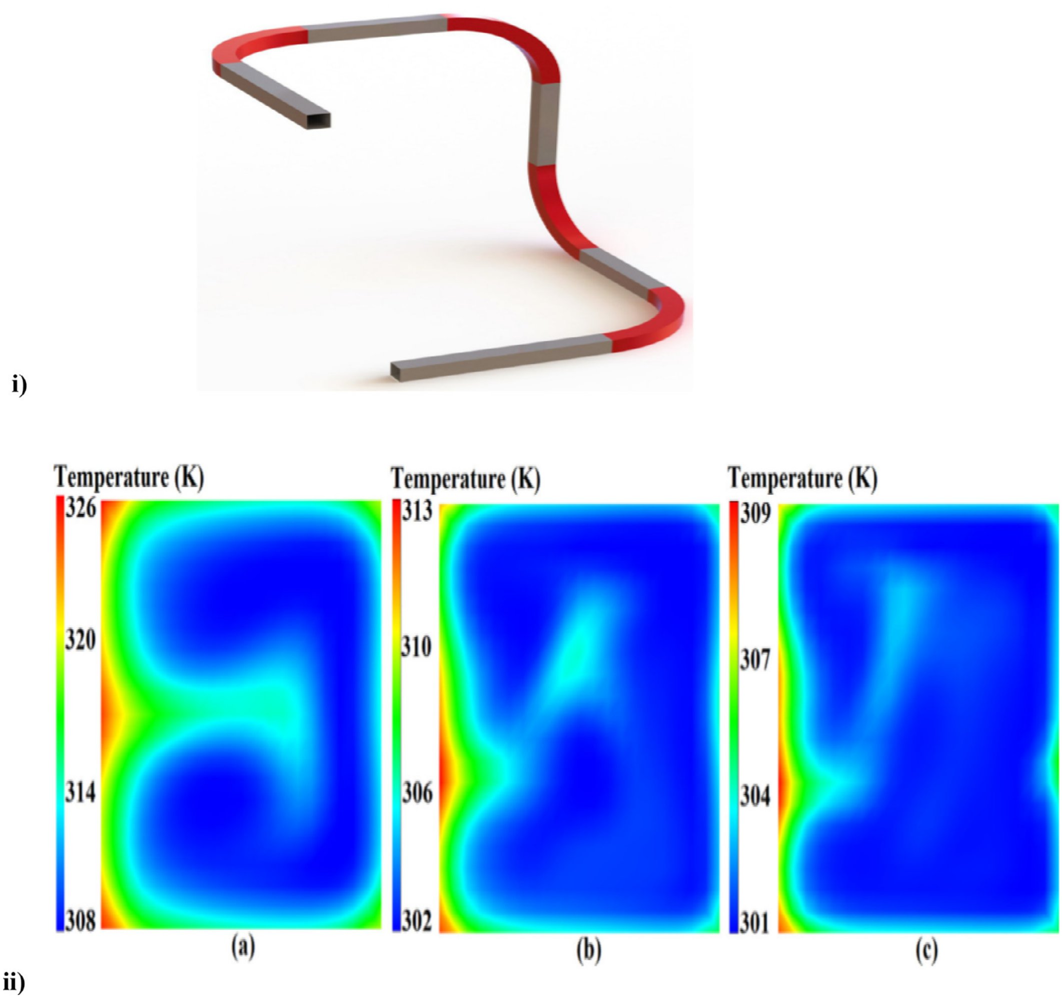

Fig. 6. (i) Chaotic geometry design studies, (ii) Temperature contours at Dean *De* number of (a) 100 (b) 300 (c) 500, adapted with permission from Elsevier [184].

Eulerian–Eulerian models. Determination of the flow regimes can be made possible provided the phases are identified. There are three ways to carry out the discrete multiphase flow model, but these are subjected to the type of flow, with the VoF being commonly used. This approach involves ensuring that the movement for the phases is carried out with simultaneous formulation of mass, energy, and momentum governing equations, which are solved with boundary conditions at the interface. However, liquid and solid phases in NF usually do not have a consistent interface, which generates lots of complex issues for the simulation. The VoF method captures the motion for all phases, with uniform variable forces swap the interfacial forces; thus, it is possible to estimate flow across the interfaces. Adhesion forces and superficial forces could be modeled using this technique. However, this technique is not ideal for the simulation of discrete multiphase flows for large size as huge computational resources are needed to calculate the flow surrounding the phase particles [78,144,145].

The Eulerian–Eulerian model assumes an intrusive continuity, with no calculations carried out for the pathlines and their averages on the computational surface. This technique is suitable for multiphase flow processes provided the governing equations are appropriately solved [145–148]. Explicit motion for the interface is not modeled under the Eulerian-Lagrangian technique, which implies that the movement of fluid surrounding dispersed phase particles is not factored into the modeling process, and modeling this phenomenon is conducted indirectly. The process involves modeling continuous phase motion captured in the Eulerian framework. The model takes an average for many pathlines to generate vital information to model the dispersed phase's impact on the continuous one. Therefore, it is possible to model mass transfer and heat transfer in a detailed manner. It is important for turbulent flow that simulation of many pathlines is conducted to obtain a reasonable average [149]. An increase in the number of simulated particles has a direct relation to the computational time and costs; hence it has been reported that this modeling technique is ideal for the simulation of discrete phase flows having volume fraction below 10% [150].

The reliability of the single-phase model, as well as the simplicity of the calculations, are key contributing factors to the single-phase methods being the predominantly used technique. The single-phase models have some limitations in terms of precision; hence capturing some important forces associated with the particles is sometimes a challenge. The model can support the prediction of liquid-solid flows, particularly for developed regions having volume fractions greater than 1% [74]. The single-phase model does not capture salient information on the movement of the solid phase particles and the motion [151–154]. The two-phase models' accuracy is higher compared to that of the single-phase for the simulating NFs. However, the single-phase models have been widely used due to their simplicity, relative to the two-phase model due to its high accuracy adopted in some investigations [155–159].

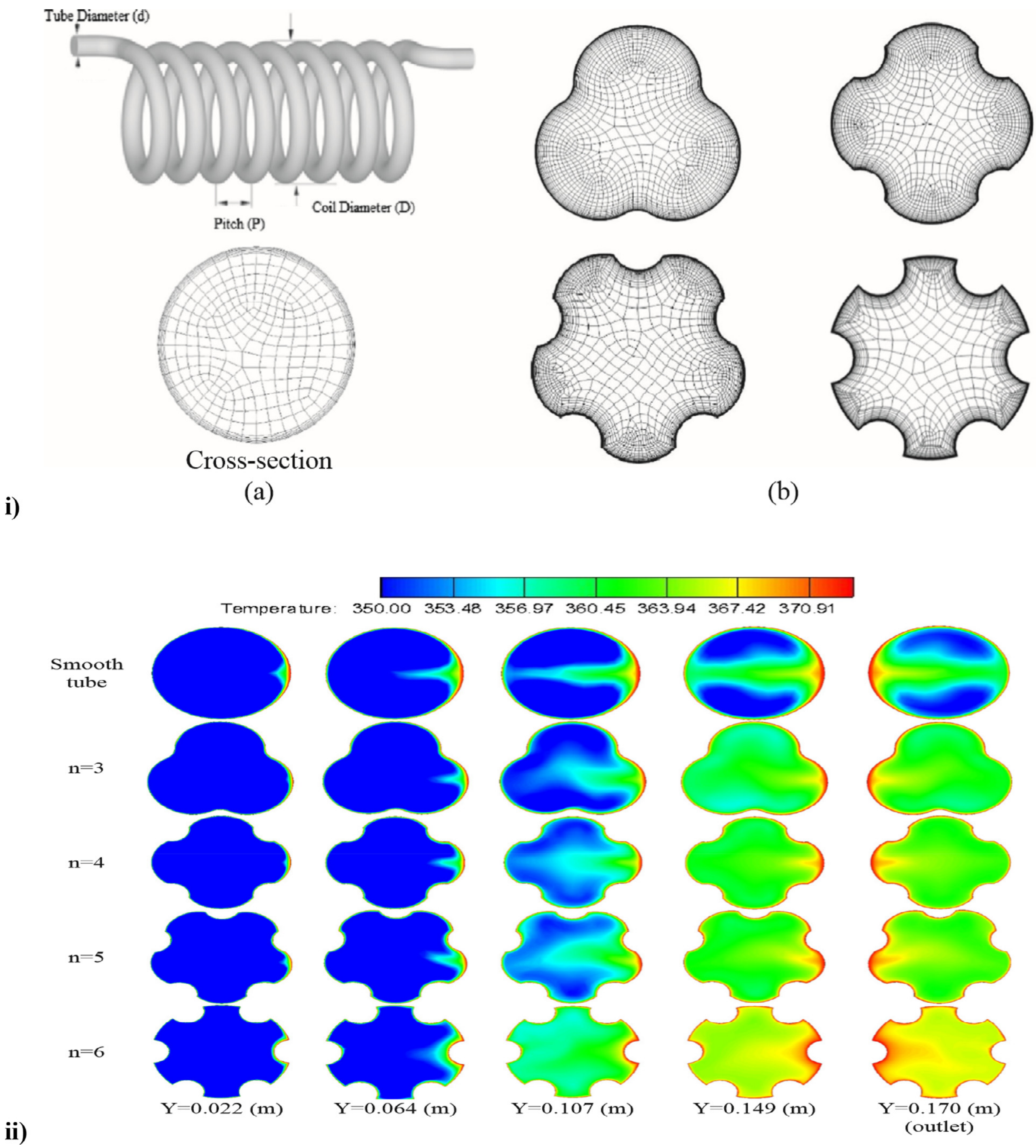

Fig. 7. (i) Geometry (a) Helical coil geometry design (b) Discretization carried out for the various geometry designs, (ii) Temperature contours of various cross-sections, adapted with permission from Elsevier [185].

3.3. Heat exchangers employing nanofluids for waste heat recovery

Nanofluids as the HTF in standard HExs have been widely studied for the specific application of waste heat recovery. Many economic, technical, environmental, and sustainable drivers have been pushing in such directions [5,82,160,161]. From an economical standpoint of view the recovered waste heat can be utilized for heating other process streams, hence reducing the fuel bill, in a very volatile fossil fuel market. This also reduced the environmental impacts and more importantly the carbon footprint associated with fossil fuels, hence making the process more sustainable. From a technical point of view, NFs with improved thermophysical properties and heat transfer performance can better extract heat from low-grade waste heat sources, which present the major share of waste heat potential [162,163]. The worldwide primary energy consumption is about 474 PJ or 132 PWh ($P = 10^{12}$), with almost 70% is rejected as waste heat into the environment as exhaust loss, effluent loss, and other losses [164]. In the United States alone, industrial boiler holds 40% of the industrial energy consumption of 1,905 TWh/y, with about 340 TWh/y of low-medium grade waste heat, while 24 TWh of medium-high grade waste heat are produced from iron & steel and cement industries each [160]. In the European Union EU, it was shown that from annual primary energy consumption of 3.6 PWh there is a potential of about 366 TWh as recoverable waste heat [165]. Extensive literature work

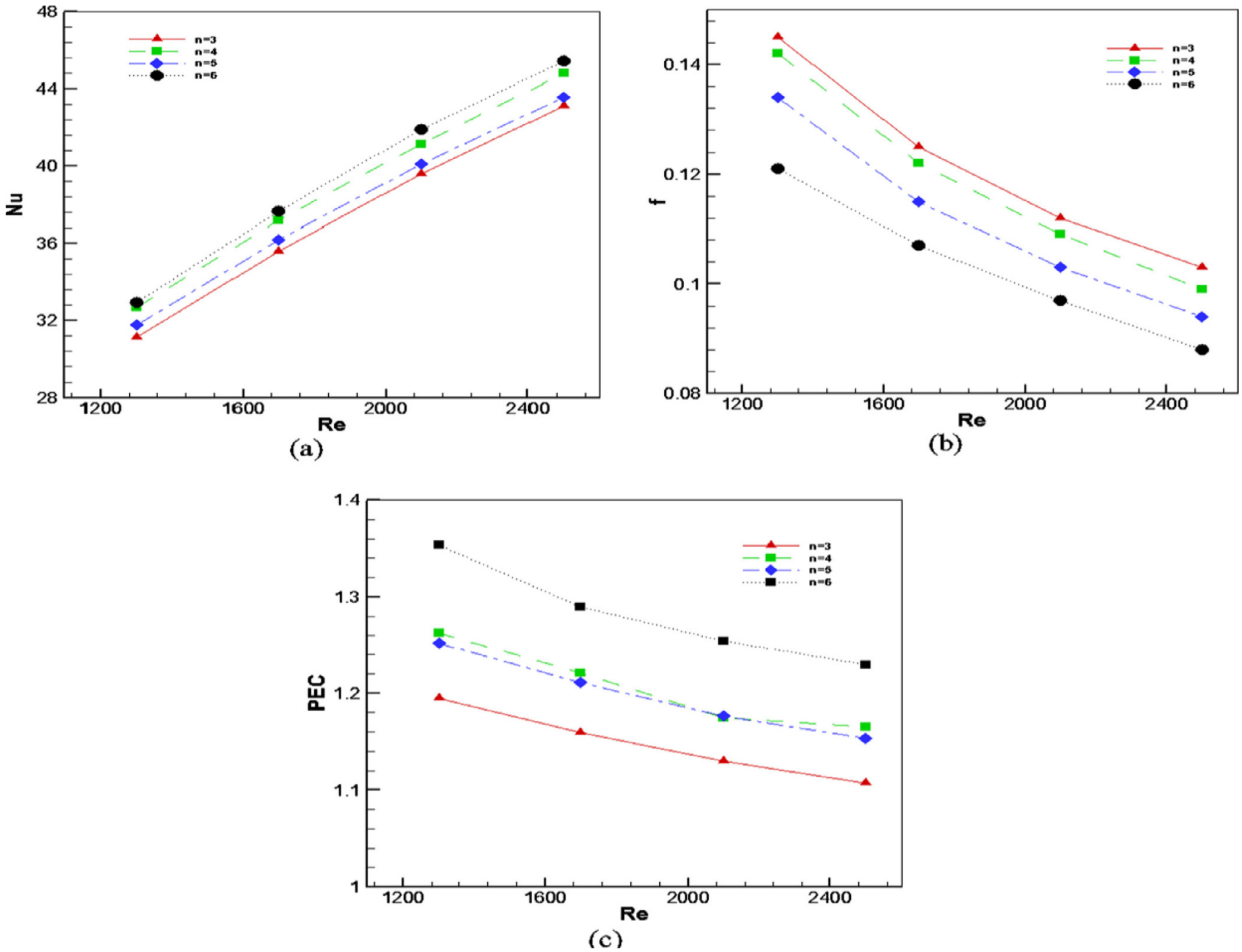

Fig. 8. Characteristics of flow in a helical coil subject to the number of lobes (a) *Nu* number (b) Friction factor, and (c) Performance evaluation criteria PEC, with permission from Elsevier [185].

has studied the effectiveness of employing NF for waste heat recovery as those by Poranjani et al. and others in different heat exchangers [166–169].

4. Effect of geometrical designs on the performance of heat exchangers

The flow within and outside the tubes of HExs is very crucial in the determination of the performance of the HEx. The fluid in contact with the heat exchange surface implies that the transfer of heat will be carried out at the interface surface; hence, the NF movement in these channels is very critical in enhancing the performance of the HEx [51,170–177].

4.1. Circular and triangular cross-section heat exchanger

The heat transfer and pressure drop in HEx employing NFs have been reported in the literature using experimental data for circular cross-section tubes [178]. It was shown that as the shear rate increases, the pressure drop increases, and as volume fractions of NF increases, the temperature uniformity increases, which lead to an increment in the HT coefficient. The laminar and turbulent flow of NFs in HEx with a triangular cross-section was also investigated, deducing that NF in the triangular channel led to an increment in the heat transfer rate [179]. HT augmentation and exergy loss in a pipe fixed with novel turbulators geometry, as shown in Fig. 1 was studied [180]. The results obtained, as shown in Fig. 1, indicating that as the pitch ratio (PR) was lowered, the rotating flow became stronger. A higher height ratio (BR), as well as a lower PR, improves the temperature gradient. Augments associated with the BR enhance the temperature gradient as the fluid mixing and the turbulent intensity were enhanced. In a nutshell, the investigation deduced that the efficiency is improved by increasing the BR and the *Re* number but decreases with augments associated with the PR. A reduction in the PR implies there will be chaotic fluid mixing, as the PR has a direct relation to the *Nu* number.

4.2. Helical coil tube heat exchanger

The performance of NF in a conical-helically coiled tube HEx, as shown in Fig. 2a was investigated [181]. As shown in Fig. 2b-e, it can be observed that generally, an increase in the Dean *De* number and NF volume fraction result in an increase in the *Nu* number, inner HT coefficient, and hence overall HT coefficient, but also increase the pressure drop. Overall HT coefficient improved by up to 52% at *De* of 4,200 and volume fraction of 0.5% for the NF. The inner HT was predominant due to the higher convection HT.

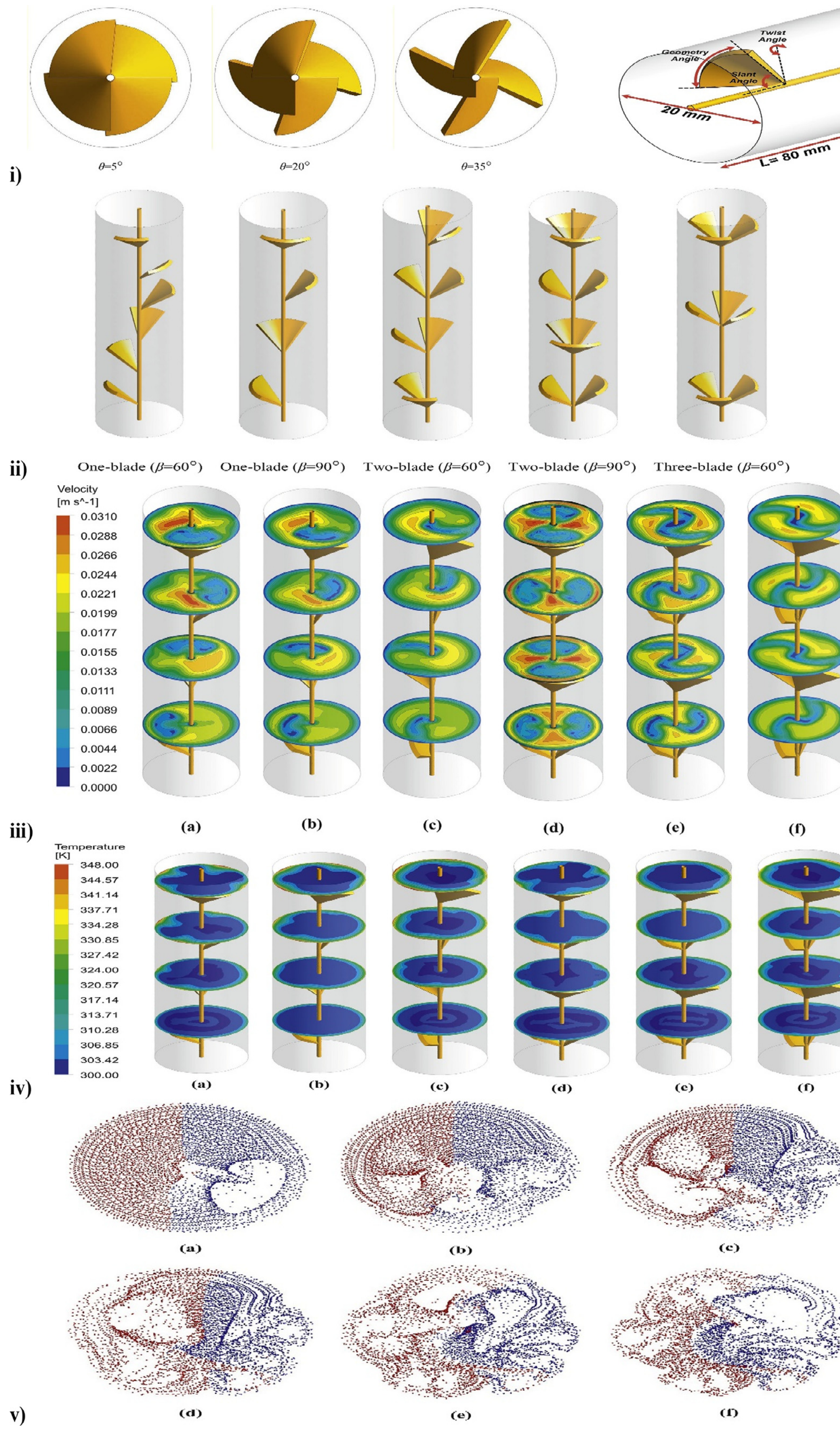

Fig. 9. (i) and (ii) geometry, (iii) velocity contours, (iv) temperature countours, (v) particles dispersion for various twist configurations: (a)1B, θ=5°, (b) 1B, θ=20°, (c)1B, θ=35°, (d) 2B, θ=5°, (e) 2B, θ= 20°, (f) 2B, θ = 35°, adapted with permission from Elsevier [187].

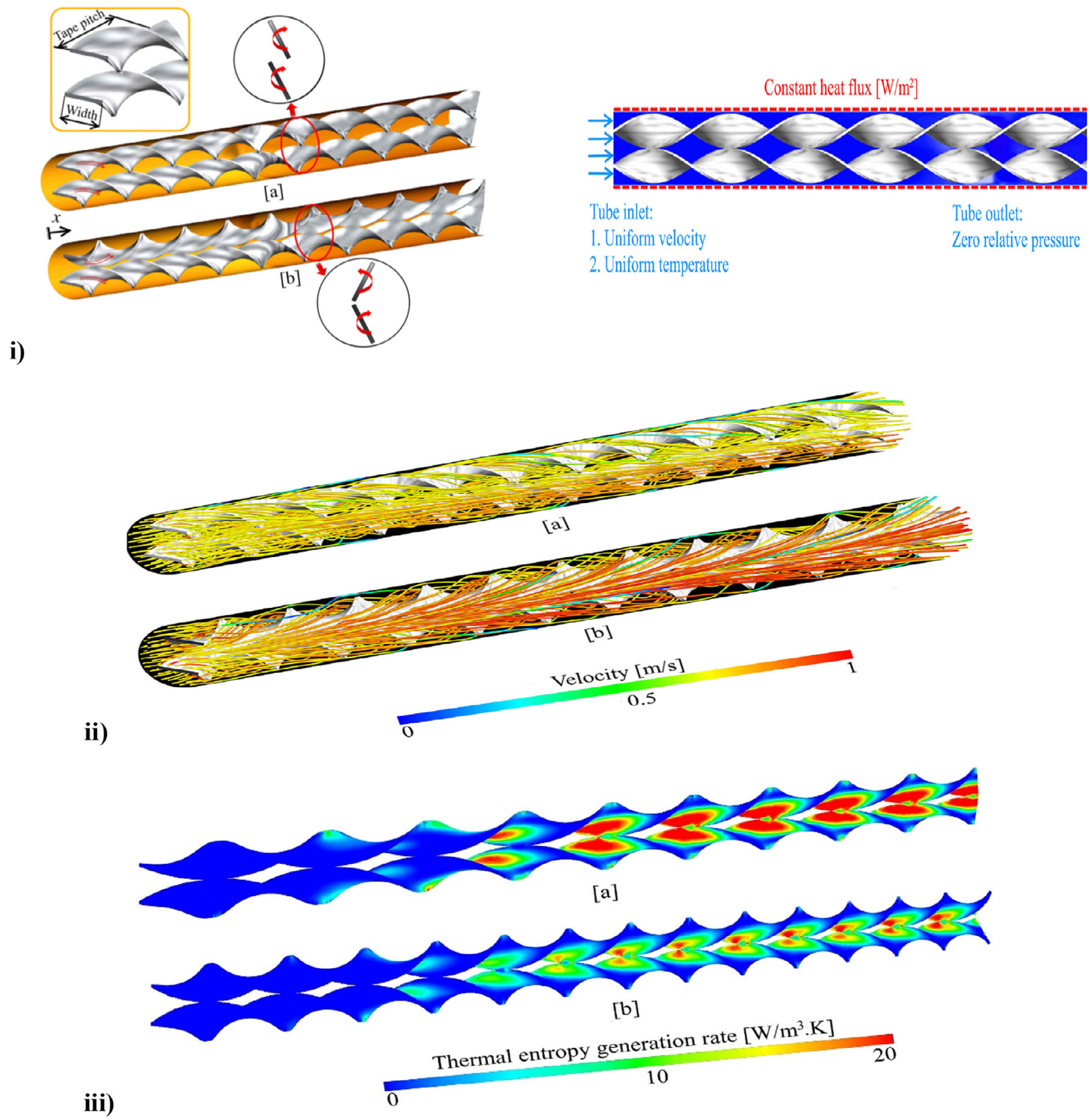

Fig. 10. Double twisted (i) geometry, (ii) flow pathlines, (iii) thermal entropy for (a) Co-twisted tapes (CoTs) (b) Counter twisted tapes (CTs), adapted with permission from Elsevier [188].

4.3. Twisted tape heat exchanger

Bahiraei et al. [51] explored the energy efficiency numerically for a new graphene-platinum NF with varying twisted tapes of single twisted tape (ST), twin co-twisted tape (CoTs), and counter twisted tape (CTs), as shown in Fig. 3i. The effect of the twisted tapes with respect to the flow pattern as represented by the velocity vector is captured in Fig. 3ii. The presence of the twisted tapes generated swirl flow leading to the development of radial velocities. It was further deduced that the tube having the single twisted tape led to the development of a single-swirl flow. Similarly, two-swirl flows were developed for the twin twisted tapes. However, reducing the twisted ratio led to augment the swirl flow, while the radial velocities improved significantly. In terms of the HT coefficient, it was deduced that an increment in the twist increased HT rate, as depicted in Fig. 4.

Mansour et al. carried out an investigation using CFD to ascertain the optimal mixing in a helical geometrical pipe, as shown in Fig. 5, at different geometry parameters and flow characteristics [183]. The study considered seven helical geometries considering the coil pitch, the pipe diameter, and the coil diameter, and their effect on the mixing profile and efficiency. It was reported that for low *Re* number, a higher coil pitch was needed to enhance the mixing. The study further highlighted that lower pitch generated a stronger secondary flow, which ensured good mixing efficiency at higher *Re* numbers. Smaller pipe and coil diameter also increased the rate of mixing, with a dominant effect for pipe diameter, as shown in Fig. 5. Again, the coil pitch and the diameter were observed to have an insignificant correlation to the pressure drop compared to the pipe diameter. An increase in the diameter of the pipe also caused the drop in pressure to decrease appreciably as well.

4.4. Chaotic twisted geometry

Bahiraei and Mazaheri [184] also studied the effect of chaotic twisted geometry with graphene-platinum NPs as shown in Fig. 6 and simple channel design. The HT coefficient and the pumping

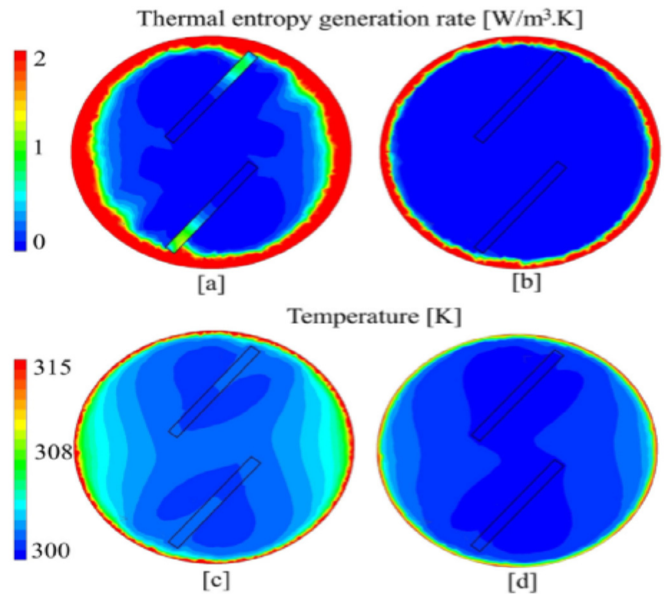

Fig. 11. Rate of thermal entropy generation for tube with co-twisted tapes [a] and [c] volume fraction $\varphi = 0$, [b] and [d] $\varphi = 0.1$, with permission from Elsevier [188].

power for chaotic and simple channels, increased with respect to the NF volume fraction and the Dean *De* number. The chaotic channel results in a higher HT coefficient and pressure drop compared to the simple straight design at the same flow conditions. Increasing distance from the bend also increased the velocity gradient. Again, an increment in thermal properties for the chaotic channel subject to an increase in the volume fraction of the NF was observed. While increasing the *De* number causes an irregularity in the flow. This causes a reduction in the temperature closer to the walls; hence the temperature eventually becomes uniformly distributed, as shown in Fig. 6.

4.5. Helical geometry

Omidi et al. numerically explored HT considering cross-sections in helical coil HExs that are lobbed, as shown in Fig. 7 [185]. They investigated the flow properties and the HT characteristics for four varying lobed cross-sections at laminar conditions. It was deduced that when the tubes are smooth, the flow usually does not mix properly compared to the others. It was further observed that after a few turns, the temperature difference within the coil became less, as depicted in Fig. 7. It was also deduced that as the number of lobes increased, the swirling flow increased, and the temperature distribution became more uniform.

Similarly, the more lobes result in a higher *Nu* number but lower friction factor coefficient as shown in Fig. 8, which was attributed to the flow field geometry. The number of lobes directly correlates to the HT but limited impact on the pressure drop compared to other techniques like the twisted tapes. The rate of HT similarly increased with the coil diameter; a decrement in the coil diameter resulted in an increment in the *Nu* number, and the friction factor coefficient. The Prandtl *Pr* number was also directly related to the *Nu* number [185]. Dbouk and Habchi performed a numerical investigation on three different pipes of straight, helical, and chaotic configuration, in which chaotic gave an excellent mixing performance [186]. Kodahbandeh et al. explored the thermal characteristics of NFs in a newly introduced conical strip with the aid of a two-phase model, as shown in Fig. 9, in which the intensity of mixing increased when the twist angle decreased [187]. An increase in the *Re* number and twist angle increases the *Nu* number. However, it results as well in increasing the friction factor. Similarly, a change in the angle for the geometry influenced the *Nu* number and the friction factor for the two-blades, but it was not the case for the one-blade, with the dispersion of the NPs was predominant when the twist angle was small.

Bahiraei et al. [188] explored NF with graphene-platinum NPs in a double twisted tape geometry as depicted in Fig. 10. It is observed that the twisted tape impacts the flow pathline for the counter twisted tapes compared to the Co-twisted one. Again, the same can be said of the path change. These variations between the counter twisted tapes and the co-twisted tapes in terms of the development of swirl flow with respect to the velocity and the temperature contours are crucial. They practically determine the thermal as well as frictional entropy generation rates [188]. It was further deduced that an increment in the volume fraction of NPs in the NF reduced thermal entropy generation rate, which can be attributed to the increased thermal conductivity, as captured in Fig. 11. It was further explained that reducing the twist ratio improved the flow mixing.

Another work studied the convective HT of Al_2O_3/water NF using numerical two-phase model technique [189]. The channel had two rows of twisted conical strip inserts having varying directions, namely inward Co-Conical inserts (CCI-inward), Counter-Conical inserts (CoCI), and outward Co-Conical inserts (CCI-outward) as shown in Fig. 12 below. It was deduced from the fluid streamlines that for all the three geometries, including the plane geometry, the twisted conical strip gave a better swirling in the fluid flow, and this was dependent on the direction of the two rows of the strip depicted in Fig. 12. The temperature profile results for the various cross-section for all the geometries demonstrated that the thermal boundary region developed at the lower section of the channel. The thermal boundary layer for the geometries was disturbed from the results generated, indicating mixing as well as a secondary flow for all the geometries under investigation. The heat flux for all the geometries explored under this investigation shows that the CCI-inward, CoCI, and the CCI-outward result in a good cooling of the heated wall. In summary, this investigation highlighted that the CCI-inward gave the highest heat transfer enhancement of 17% relative to the plain tube. It was further reiterated that an increase in the NF volume fraction directly affected the thermal characteristics at high *Re* number.

4.6. Twisted conical strip geometry in a circular pipe

Mashayekhi et al. carried detailed investigations using the two-phases Eulerian-Lagrangian technique for simulating NF flow in a circular tube with twisted conical strip inserts, as shown in Fig. 13 [75]. It was further highlighted that the twisted conical strip enhanced the *Nu* number, especially at high *Re* number. Increasing the volume fraction of NF also increased the *Nu* number due to the improved thermal conductivity, hence improves the HT rate. The temperature and velocity gradient near the wall increase because of the increase in *Re* number, which causes an improvement in the HT. It was further observed that when the *Re* number was low, the staggered alignment exhibited a higher *Nu* number compared to the non-staggered alignment. It highlighted that when the *Re*s number was high, the flow velocity next to the wall for the non-staggered design was good as well.

Guo et al. affirmed that the volume fraction of the NPs had an effect on the HT and the flow performance under different pulsations in helical coil [190]. Using the single-phase modeling technique, Bahiraei and Hangi explored NF's application in a C-shaped chaotic channel numerically [191]. The analyzed energy efficiency considering a straight channel and chaotic channel as shown in Fig. 14. The NF's hydrothermal properties were explored numerically with the aid of a C-shaped and straight channel for single- and two-phase approaches. It was found that the values for the HT coefficient and the pressure drop were higher for the C-shaped channel compared to the straight channel as mixing was intense in chaotic geometry. The uniformity of velocity and temperature profiles was observed in the

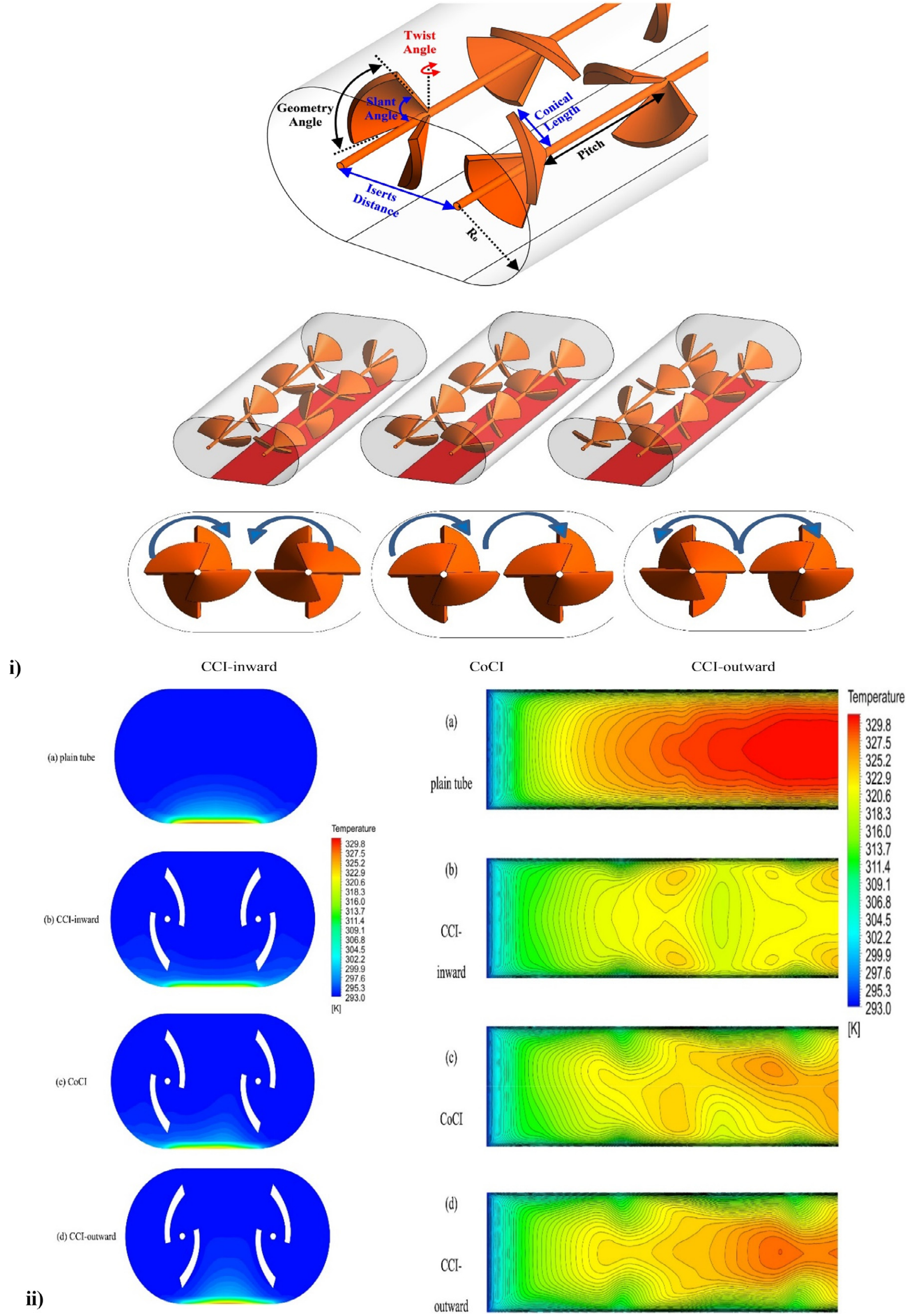

Fig. 12. (i) Geometrical structure of conical inserts, (ii) temperature contours, adapted with permission from Elsevier [189].

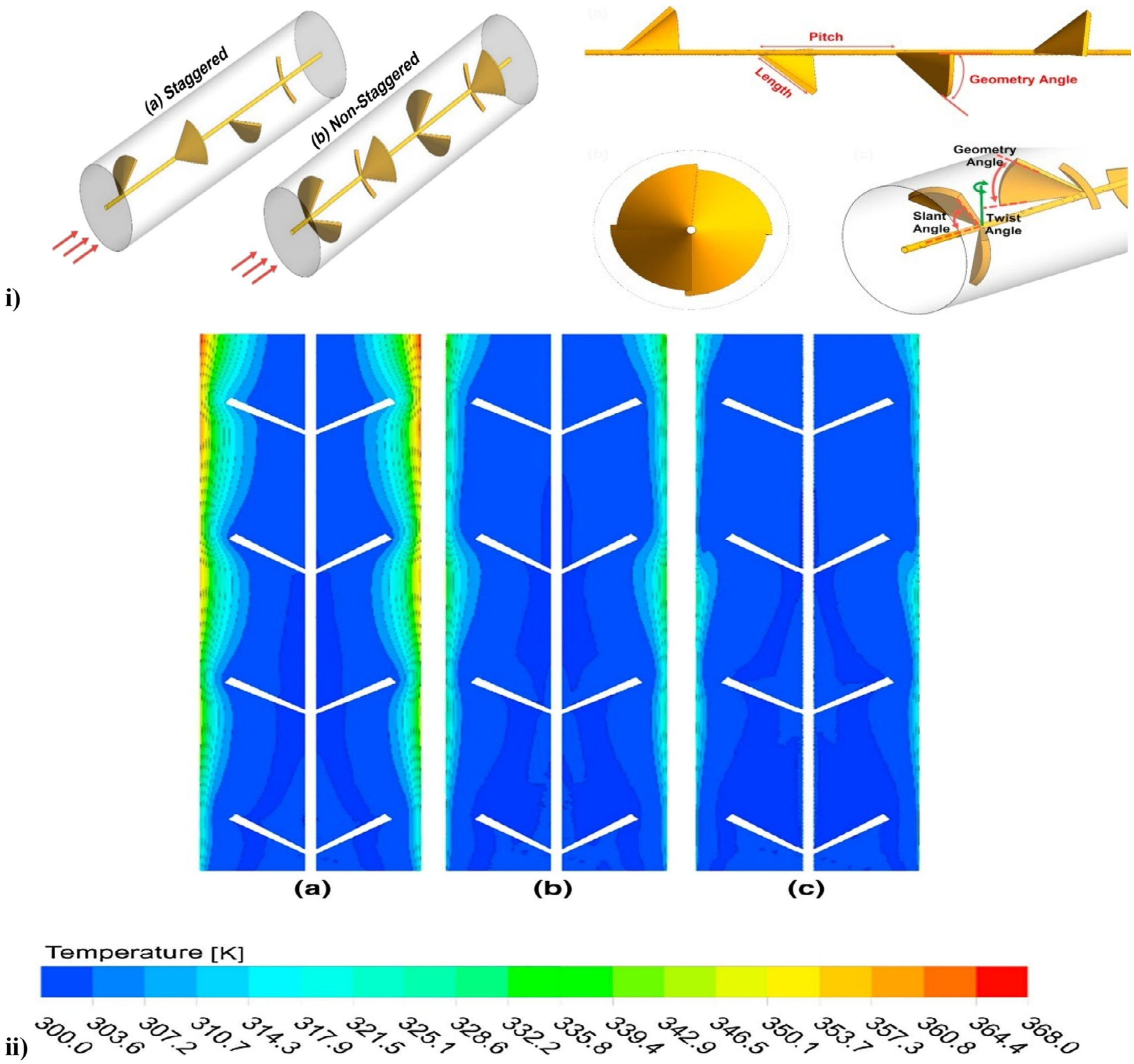

Fig. 13. (i) Geometry of twisted inserts, (ii) Temperature contours for non-staggered alignment at φ = 3% for: (a) Re = 100, (b) Re = 300, and (c) Re = 700, adapted with permission from Elsevier [75].

C-shaped channel, unlike the straight channel, and similarly for the particle distribution. The use of NF increased the rate of HT and the pressure drop compared to the BF, i.e., water. It, therefore, implies that both geometry and application of the NF had led to higher energy efficiency and curbed NPs agglomeration due to intensive mixing.

In another study, Xiong et al. numerically explored the performance of HEx having a turbulator [192]. The turbulent flow was simulated using the k-ε model, and it was deduced that a lower pitch ratio PR resulted in the development of a thinner boundary layer. The PR also influenced pressure loss, with a higher PR led to a lower pressure loss, with stronger eddy and turbulent intensity were created. The use of NF reduced the entropy generation. In a similar study, Sheikholeslami et al. explored turbulent Al_2O_3/water NF flow via a helical swirl flow in a pipe having insertion for the generation of secondary flows as shown in Fig. 15 [193]. The single-phase model was adopted, and the effect of the number of revolutions coupled with the turbulator diameter was also explored. However, it was deduced that the intensity for the velocity gradient for the NPs closer to the pipe was higher because of the backflow. Augmenting the number of revolutions enhanced the NF flow, which led to the development of thinner boundary layers. The flow disturbances from the investigation were also subject to the increase of the revolutions.

4.7. Summary for the geometrical effect

The previous sections have discussed the heat transfer enhancement due to different heat exchange geometries, more specifically in the case of using NFs as the HTF. It has been clearly shown the NF has improved the heat transfer characteristics and performance, which is mainly due to the improved thermophysical properties of NF relative to the BF. However, it has been shown as well, that this effect is also altered by the geometry of heat transfer. The geometrical effect can be summarized in two major aspects. First is the increased contact surface between the exchanging fluids, i.e., hot and cold fluids or streams. Second is the increased turbulence or eddies flow, which increases the convective heat transfer coefficient due to the local mixing and thermal homogeneity within the fluid component or

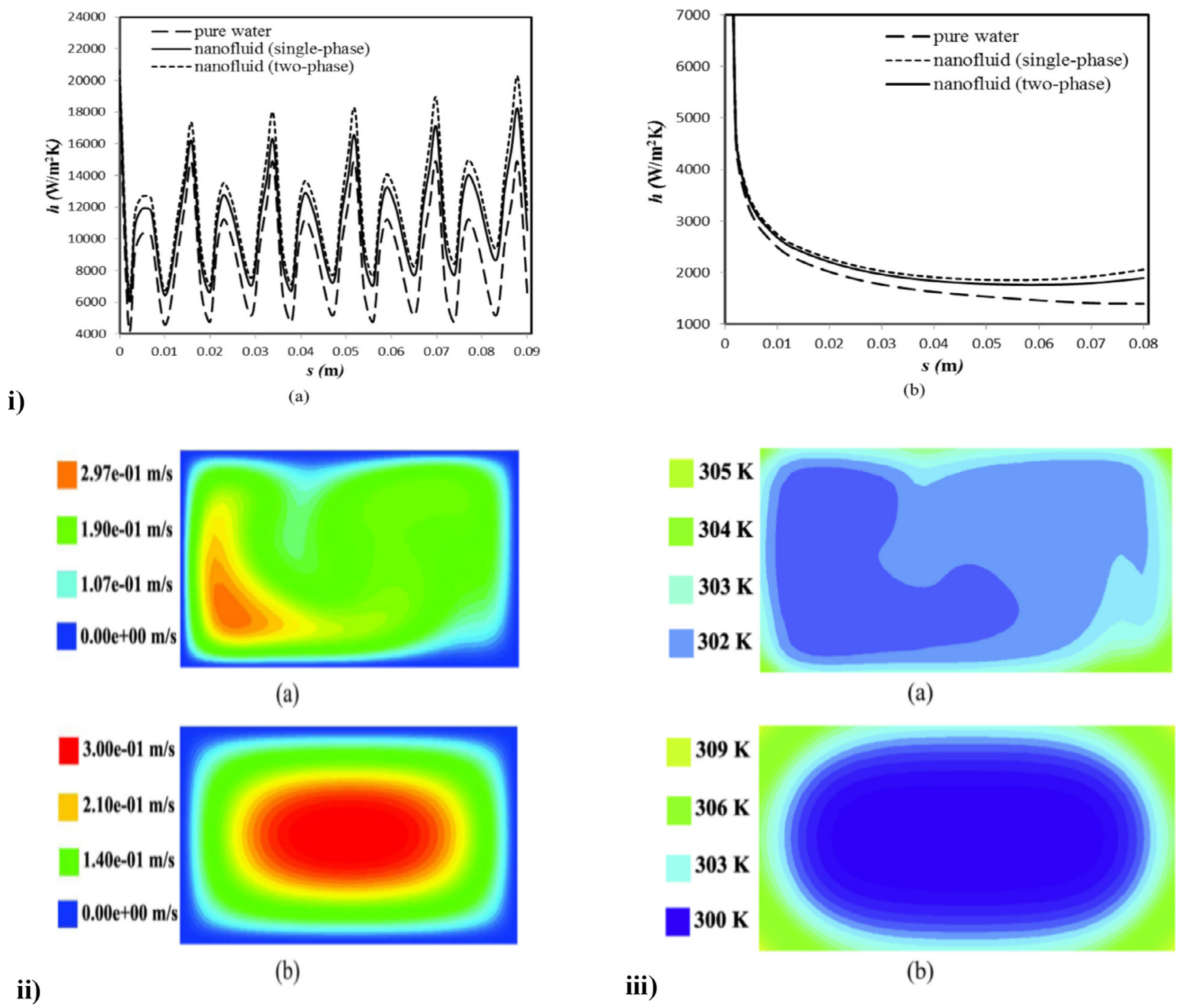

Fig. 14. (i) Convective heat transfer coefficient, (ii) Velocity countors, and (iii) Temperature countors for (a) C-shaped, and (b) Straight channel, adapted with permission from Elsevier [191].

element. However, the latter has to be handled and considered carefully when employing NF, due to the presence of NPs. Intercomparison among different geometrical designs for HEx was difficult to obtain as different geometries have been studied at different conditions of *Re, De*, and fluids which might bias the conclusions drawn from such comparison. However, a general conclusion was made that such geometries have significantly increased the thermal performance and efficiency of the HEx due to the aforementioned reasons.

5. Recommendations and future work

The previous discussion has confirmed the improvement in thermal performance and efficiency of HEx due to both the employment of NF as the HTF and the changed geometry from commonly used and studied flat surfaces, which together have further improved the heat transfer efficiency. At last, it ought to be said that with assist headway in HExs conjointly creating better NFs coupled with a novel geometrical design will significantly improve the heat transfer in many thermal engineering applications. Therefore, the following recommendations are suggested for future work:

- Ø Future work can be made to focus on the stability of NFs as well as their production cost. Furthermore, some detailed studies are required to investigate and minimize the pressure drop due to NF, which is vital for HEx operation.
- Ø The investigation into the transition region, especially for the turbulent flow conditions, needs to be further explored. Future research activities can also consider the NF as being non-Newtonian instead of the commonly used Newtonian fluid.
- Ø Prediction of HT numerically is also performed using temperature-independent models, which is less accurate. It is therefore recommended that temperature-dependent properties for NFs are considered for numerical studies.
- Ø Optimization of NFs in terms of size, volume fraction, and shape should be considered for the specific application under study.
- Ø The development of environmentally friendly NF is very essential for sustainable operation.
- Ø Energy management couple with the economic analysis of NFs and their effect on the immediate surrounding will also be another key research area that can be considered.
- Ø Corrosion, erosion and material integrity of HExs should be further discussed due to the friction effect caused by NPs in the NF, especially at high flow rates and long operation time.

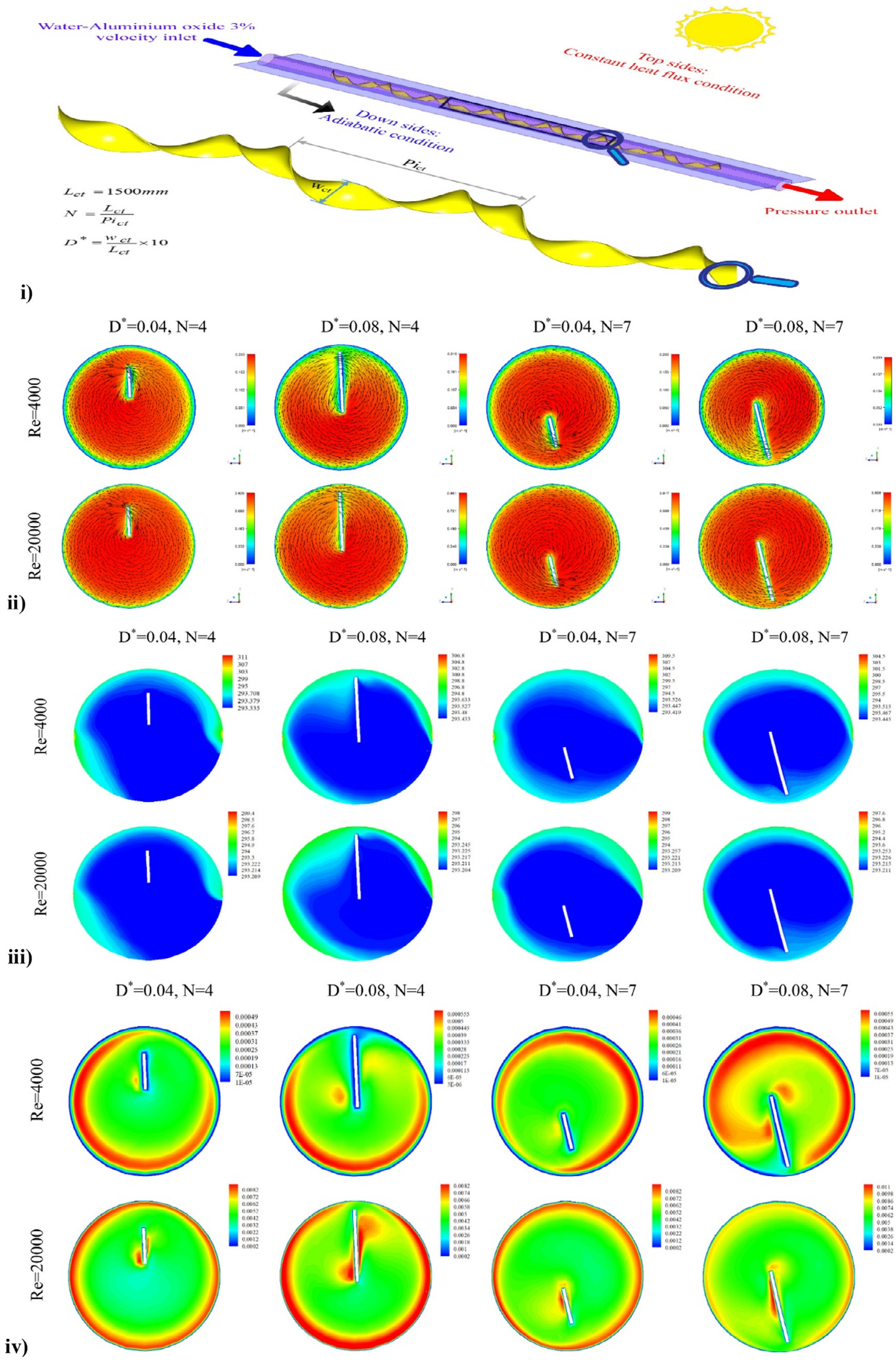

Fig. 15. (i) Geometry of the helical swirl, (ii) velocity countors, (iii) temperature contours, (iv) turbulence energy counters, adapted with permission from Elsevier [193].

Ø Although novel geometrical designs provide a significant enhancement in heat transfer, it adds complexity to the design and manufacturing activities. Hence, it has to be carefully considered both technically and economically.
Ø Although the proven performance improvements for the application of complex geometries and surface structures, which are further improved upon the employment of NF, still the application is limited to lab-scale, and no large-scale or industrial level applications have been realized yet. Hence it is very advisable to carry out further economical and technical feasibility studies for large-scale applications.

6. Conclusion

In summary, this review explored the characteristics of nanofluids NFs in heat exchangers HExs at varying geometrical designs. The improved thermal conductivity of NFs improved via the addition of nanoparticles NPs into base fluids BF has improved the thermal performance, more significantly for laminar flow. It has also been established that an increment in the volume fraction of the NP directly relates to the increased heat transfer HT coefficient for HExs subject to the geometry or design, although of the increased pumping power requirements. Increasing the ribs' height for HExs leads to even temperature distribution, although of the higher pressure drops. The review discussed the numerical investigation for the single- and two-phase model. Numerical studies using the single-phase model for NF was also effective in some research activity due to the nature of the NPs. However, the single-phase models neglect the slip forces between the NPs and the fluids. On the other hand, particles' Brownian motion coupled with the particle slip is considered for the two-phase model. The discussion included various HExs types of helical, double tube, shell, and tube, with different tube geometries and inserts. It was concluded that NF along with different geometries has resulted in a significant increase in heat transfer efficiency both individually and collectively. The major contribution of the geometrical effect is to increase the contact surface area between the hot and cold fluid, and to increase the local eddies, hence improving the heat transfer characteristics.

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.

References

[1] T. Wilberforce, A.G. Olabi, E.T. Sayed, K. Elsaid, M.A. Abdelkareem, Progress in carbon capture technologies, Sci. Total Environ. (2020) 143203.
[2] T. Wilberforce, A. Baroutaji, B. Soudan, A.H. Al-Alami, A.G. Olabi, Outlook of carbon capture technology and challenges, Sci. Total Environ. 657 (2019) 56–72.
[3] K. Elsaid, E. Taha Sayed, B.A.A. Yousef, M. Kamal Hussien Rabaia, M. Ali Abdelkareem, A.G. Olabi, Recent progress on the utilization of waste heat for desalination: a review, Energy Conv. Manag. 221 (2020) 113105.
[4] A.G. Olabi, K. Elsaid, M.K.H. Rabaia, A.A. Askalany, M.A. Abdelkareem, Waste heat-driven desalination systems: perspective, Energy 209 (2020) 118373.
[5] B. Egilegor, H. Jouhara, J. Zuazua, F. Al-Mansour, K. Plesnik, L. Montorsi, L. Manzini, ETEKINA: analysis of the potential for waste heat recovery in three sectors: aluminium low pressure die casting, steel sector and ceramic tiles manufacturing sector, Int. J. Thermofluids 1-2 (2020) 100002.
[6] P.K. Pandis, S. Papaioannou, V. Siaperas, A. Terzopoulos, V.N. Stathopoulos, Evaluation of Zn- and Fe- rich organic coatings for corrosion protection and condensation performance on waste heat recovery surfaces, Int. J. Thermofluids 3-4 (2020) 100025.
[7] A.G. Olabi, M.A. Abdelkareem, T. Wilberforce, E.T. Sayed, Application of graphene in energy storage device – a review, Renew. Sustain. Energy Rev. 135 (2021) 110026.
[8] T. Wilberforce, E.T. Sayed, M.A. Abdelkareem, K. Elsaid, A.G. Olabi, Value added products from wastewater using bioelectrochemical systems: current trends and perspectives, J. Water Process Eng. (2020) 101737.
[9] N. Shehata, E.T. Sayed, M.A. Abdelkareem, Recent progress in environmentally friendly geopolymers: a review, Sci. Total Environ. (2020) 143166.
[10] M.A. Ershov, E.V. Grigorieva, T.M.M. Abdellatief, V.M. Kapustin, M.A. Abdelkareem, M. Kamil, A.G. Olabi, Hybrid low-carbon high-octane oxygenated gasoline based on low-octane hydrocarbon fractions, Sci. Total Environ. (2020) 142715.
[11] M.K.H. Rabaia, M.A. Abdelkareem, E.T. Sayed, K. Elsaid, K.-J. Chae, T. Wilberforce, A.G. Olabi, Environmental impacts of solar energy systems: a review, Sci. Total Environ. 754 (2021) 141989.
[12] M. Milani, L. Montorsi, G. Storchi, M. Venturelli, D. Angeli, A. Leonforte, D. Castagnetti, A. Sorrentino, Experimental and numerical analysis of a liquid aluminium injector for an Al-H_2O based hydrogen production system, Int. J. Thermofluids 7-8 (2020) 100018.
[13] M.A.A. Waqas Hassan Tanveer, Ben W. Kolosz, Hegazy Rezk, John Andresen, S.W. Cha, E.T. Sayed, The role of vacuum based technologies in solid oxide fuel cell development to utilize industrial waste carbon for power production, Renew. Sustain. Energy Rev. (2021) in press.
[14] A.G. Olabi, T. Wilberforce, M. Ramadan, M.A. Abdelkareem, A.H. Alami, Compressed air energy storage systems: components and operating parameters – a review, J. Energy Storage (2020) 102000.
[15] A.G. Olabi, T. Wilberforce, M.A. Abdelkareem, Fuel cell application in the automotive industry and future perspective, Energy 214 (2021) 118955.
[16] A.H. Alami, Compressed-Air Energy Storage Systems, in: A.H. Alami (Ed.), Mechanical Energy Storage for Renewable and Sustainable Energy Resources, Springer International Publishing, Cham, 2020, pp. 67–85.
[17] A.H. Alami, Buoyancy Work Energy Storage (BAES) Systems, in: A.H. Alami (Ed.), Mechanical Energy Storage for Renewable and Sustainable Energy Resources, Springer International Publishing, Cham, 2020, pp. 87–92.
[18] H. Jouhara, N. Khordehgah, S. Almahmoud, B. Delpech, A. Chauhan, S.A. Tassou, Waste heat recovery technologies and applications, Therm. Sci. Eng. Progr. 6 (2018) 268–289.
[19] R. Agathokleous, G. Bianchi, G. Panayiotou, L. Aresti, M.C. Argyrou, G.S. Georgiou, S.A. Tassou, H. Jouhara, S.A. Kalogirou, G.A. Florides, P. Christodoulides, Waste Heat Recovery in the EU industry and proposed new technologies, Energy Procedia 161 (2019) 489–496.
[20] H. Jouhara, A.G. Olabi, Editorial: industrial waste heat recovery, Energy 160 (2018) 1–2.
[21] B. Delpech, M. Milani, L. Montorsi, D. Boscardin, A. Chauhan, S. Almahmoud, B. Axcell, H. Jouhara, Energy efficiency enhancement and waste heat recovery in industrial processes by means of the heat pipe technology: case of the ceramic industry, Energy 158 (2018) 656–665.
[22] H. Atwany, M.O. Hamdan, B.A. Abu-Nabah, A.H. Alami, M. Attom, Experimental evaluation of ground heat exchanger in UAE, Renew. Energy 159 (2020) 538–546.
[23] S. Almahmoud, H. Jouhara, Experimental and theoretical investigation on a radiative flat heat pipe heat exchanger, Energy 174 (2019) 972–984.
[24] D. Brough, J. Ramos, B. Delpech, H. Jouhara, Development and Validation of a TRNSYS type to simulate heat pipe heat exchangers in transient applications of waste heat recovery, Int. J. Thermofluids (2020) 100056.
[25] S. Agrawal, K. Nigam, Modelling of a coiled tubular chemical reactor, Chem. Eng. J. 84 (2001) 437–444.
[26] V. Kumar, M. Aggarwal, K.D. Nigam, Mixing in curved tubes, Chem. Eng. Sci. 61 (2006) 5742–5753.
[27] V. Kumar, S. Saini, M. Sharma, K. Nigam, Pressure drop and heat transfer study in tube-in-tube helical heat exchanger, Chem. Eng. Sci. 61 (2006) 4403–4416.
[28] S. Vashisth, V. Kumar, K.D. Nigam, A review on the potential applications of curved geometries in process industry, Ind. Eng. Chem. Res. 47 (2008) 3291–3337.
[29] T. Alam, M.-.H. Kim, A comprehensive review on single phase heat transfer enhancement techniques in heat exchanger applications, Renew. Sustain. Energy Rev. 81 (2018) 813–839.
[30] M. Awais, A.A. Bhuiyan, Heat transfer enhancement using different types of vortex generators (VGs): a review on experimental and numerical activities, Therm. Sci. Eng. Progr. 5 (2018) 524–545.
[31] M. Sheikholeslami, M. Gorji-Bandpy, D.D. Ganji, Review of heat transfer enhancement methods: focus on passive methods using swirl flow devices, Renew. Sustain. Energy Rev. 49 (2015) 444–469.
[32] N. Piriyarungrod, M. Kumar, C. Thianpong, M. Pimsarn, V. Chuwattanakul, S. Eiamsa-Ard, Intensification of thermo-hydraulic performance in heat exchanger tube inserted with multiple twisted-tapes, Appl. Therm. Eng. 136 (2018) 516–530.
[33] M. Nakhchi, J. Esfahani, Numerical investigation of rectangular-cut twisted tape insert on performance improvement of heat exchangers, Int. J. Therm. Sci. 138 (2019) 75–83.
[34] H. Rezk, E.T. Sayed, M. Al-Dhaifallah, M. Obaid, A.H.M. El-Sayed, M.A. Abdelkareem, A.G. Olabi, Fuel cell as an effective energy storage in reverse osmosis desalination plant powered by photovoltaic system, Energy 175 (2019) 423–433.
[35] L. Wang, S. Wang, F. Wen, X. Zhou, Z. Wang, Effects of continuous wavy ribs on heat transfer and cooling air flow in a square single-pass channel of turbine blade, Int. J. Heat Mass Transf. 121 (2018) 514–533.
[36] S. Alfarawi, S. Abdel-Moneim, A. Bodalal, Experimental investigations of heat transfer enhancement from rectangular duct roughened by hybrid ribs, Int. J. Therm. Sci. 118 (2017) 123–138.
[37] L. Wang, S. Wang, F. Wen, X. Zhou, Z. Wang, Heat transfer and flow characteristics of U-shaped cooling channels with novel wavy ribs under stationary and rotating conditions, Int. J. Heat Mass Transf. 126 (2018) 312–333.

[38] H. Fawaz, M. Badawy, M. Abd Rabbo, A. Elfeky, Numerical investigation of fully developed periodic turbulent flow in a square channel fitted with 45 in-line V-baffle turbulators pointing upstream, Alexandria Eng. J. 57 (2018) 633–642.
[39] W. Yang, S. Xue, Y. He, W. Li, Experimental study on the heat transfer characteristics of high blockage ribs channel, Exp. Therm. Fluid Sci. 83 (2017) 248–259.
[40] D. Jin, S. Quan, J. Zuo, S. Xu, Numerical investigation of heat transfer enhancement in a solar air heater roughened by multiple V-shaped ribs, Renew. Energy 134 (2019) 78–88.
[41] M. Bahiraei, H.K. Salmi, M.R. Safaei, Effect of employing a new biological nanofluid containing functionalized graphene nanoplatelets on thermal and hydraulic characteristics of a spiral heat exchanger, Energy Conv. Manag. 180 (2019) 72–82.
[42] A.A. Alrashed, M.S. Gharibdousti, M. Goodarzi, L.R. de Oliveira, M.R. Safaei, E.P. Bandarra Filho, Effects on thermophysical properties of carbon based nanofluids: experimental data, modelling using regression, ANFIS and ANN, Int. J. Heat Mass Transf. 125 (2018) 920–932.
[43] A. Karimipour, S.A. Bagherzadeh, M. Goodarzi, A.A. Alnaqi, M. Bahiraei, M.R. Safaei, M.S. Shadloo, Synthesized $CuFe_2O_4/SiO_2$ nanocomposites added to water/EG: evaluation of the thermophysical properties beside sensitivity analysis & EANN, Int. J. Heat Mass Transf. 127 (2018) 1169–1179.
[44] M. Turkyilmazoglu, Free and circular jets cooled by single phase nanofluids, Eur. J. Mech.-B/Fluids 76 (2019) 1–6.
[45] M. Turkyilmazoglu, Fully developed slip flow in a concentric annuli via single and dual phase nanofluids models, Comput. Methods Programs Biomed. 179 (2019) 104997.
[46] M. Turkyilmazoglu, Flow of nanofluid plane wall jet and heat transfer, Eur. J. Mech.-B/Fluids 59 (2016) 18–24.
[47] A.A. Alrashed, A. Karimipour, S.A. Bagherzadeh, M.R. Safaei, M. Afrand, Electro-and thermophysical properties of water-based nanofluids containing copper ferrite nanoparticles coated with silica: experimental data, modeling through enhanced ANN and curve fitting, Int. J. Heat Mass Transf. 127 (2018) 925–935.
[48] M. Bahiraei, N. Mazaheri, A. Rizehvandi, Application of a hybrid nanofluid containing graphene nanoplatelet−platinum composite powder in a triple-tube heat exchanger equipped with inserted ribs, Appl. Therm. Eng. 149 (2019) 588–601.
[49] E. Khodabandeh, M.R. Safaei, S. Akbari, O.A. Akbari, A.A. Alrashed, Application of nanofluid to improve the thermal performance of horizontal spiral coil utilized in solar ponds: geometric study, Renew. Energy 122 (2018) 1–16.
[50] M. Bahiraei, N. Mazaheri, Application of a novel hybrid nanofluid containing graphene−platinum nanoparticles in a chaotic twisted geometry for utilization in miniature devices: thermal and energy efficiency considerations, Int. J. Mech. Sci. 138 (2018) 337–349.
[51] M. Bahiraei, N. Mazaheri, S.M. Hassanzamani, Efficacy of a new graphene−platinum nanofluid in tubes fitted with single and twin twisted tapes regarding counter and co-swirling flows for efficient use of energy, Int. J. Mech. Sci. 150 (2019) 290–303.
[52] M.I. Afridi, I. Tlili, M. Goodarzi, M. Osman, N.A. Khan, Irreversibility analysis of hybrid nanofluid flow over a thin needle with effects of energy dissipation, Symmetry (Basel) 11 (2019) 663.
[53] M.R. Safaei, R. Ranjbarzadeh, A. Hajizadeh, M. Bahiraei, M. Afrand, A. Karimipour, Effects of cobalt ferrite coated with silica nanocomposite on the thermal conductivity of an antifreeze: new nanofluid for refrigeration condensers, Int. J. Refrigeration 102 (2019) 86–95.
[54] M. Goodarzi, M. Safaei, K. Vafai, G. Ahmadi, M. Dahari, S. Kazi, N. Jomhari, Investigation of nanofluid mixed convection in a shallow cavity using a two-phase mixture model, Int. J. Therm. Sci. 75 (2014) 204–220.
[55] H. Maleki, J. Alsarraf, A. Moghanizadeh, H. Hajabdollahi, M.R. Safaei, Heat transfer and nanofluid flow over a porous plate with radiation and slip boundary conditions, J. Central South Univ. 26 (2019) 1099–1115.
[56] F. Bazdidi-Tehrani, A. Khabazipur, S.I. Vasefi, Flow and heat transfer analysis of TiO_2/water nanofluid in a ribbed flat-plate solar collector, Renew. Energy 122 (2018) 406–418.
[57] T. Krishnakumar, A. Sheeba, V. Mahesh, M.J. Prakash, Heat transfer studies on ethylene glycol/water nanofluid containing TiO_2 nanoparticles, Int. J. Refrigeration 102 (2019) 55–61.
[58] M. Bahiraei, A.A. Ahmadi, Thermohydraulic performance analysis of a spiral heat exchanger operated with water−alumina nanofluid: effects of geometry and adding nanoparticles, Energy Conv. Manag. 170 (2018) 62–72.
[59] D.K. Devendiran, V.A. Amirtham, A review on preparation, characterization, properties and applications of nanofluids, Renew. Sustain. Energy Rev. 60 (2016) 21–40.
[60] W. Yu, H. Xie, L.-.H. Liu, A review on nanofluids: preparation, stability mechanisms, and applications, J. Nanomater. 2012 (2011) 128.
[61] R.B. Ganvir, P.V. Walke, V.M. Kriplani, Heat transfer characteristics in nanofluid—a review, Renew. Sustain. Energy Rev. 75 (2017) 451–460.
[62] J. Philip, P.D. Shima, Thermal properties of nanofluids, Adv. Colloid Interface Sci. 183-184 (2012) 30–45.
[63] M. Awais, N. Ullah, J. Ahmad, F. Sikandar, M.M. Ehsan, S. Salehin, A.A. Bhuiyan, Heat transfer and pressure drop performance of Nanofluid: a state-of- the-art review, Int. J. Thermofluids 9 (2021) 100065.
[64] Z. Alhajaj, A.M. Bayomy, M.Z. Saghir, A comparative study on best configuration for heat enhancement using nanofluid, Int. J. Thermofluids 7-8 (2020) 100041.
[65] Z. Alhajaj, A.M. Bayomy, M.Z. Saghir, M.M. Rahman, Flow of nanofluid and hybrid fluid in porous channels: experimental and numerical approach, Int. J. Thermofluids 1-2 (2020) 100016.
[66] S.A. Angayarkanni, J. Philip, Review on thermal properties of nanofluids: recent developments, Adv. Colloid Interface Sci. 225 (2015) 146–176.
[67] E. Sadeghinezhad, M. Mehrali, R. Saidur, M. Mehrali, S. Tahan Latibari, A.R. Akhiani, H.S.C. Metselaar, A comprehensive review on graphene nanofluids: recent research, development and applications, Energy Conv. Manag. 111 (2016) 466–487.
[68] Y. Li, J.e. Zhou, S. Tung, E. Schneider, S. Xi, A review on development of nanofluid preparation and characterization, Powder Technol. 196 (2009) 89–101.
[69] A.R.I. Ali, B. Salam, A review on nanofluid: preparation, stability, thermophysical properties, heat transfer characteristics and application, SN Appl. Sci. 2 (2020) 1636.
[70] S. Chakraborty, P.K. Panigrahi, Stability of nanofluid: a review, Appl. Therm. Eng. 174 (2020) 115259.
[71] A. Asadi, F. Pourfattah, I. Miklós Szilágyi, M. Afrand, G. Żyła, H. Seon Ahn, S. Wongwises, H. Minh Nguyen, A. Arabkoohsar, O. Mahian, Effect of sonication characteristics on stability, thermophysical properties, and heat transfer of nanofluids: a comprehensive review, Ultrason. Sonochem. 58 (2019) 104701.
[72] N. Sezer, M.A. Atieh, M. Koç, A comprehensive review on synthesis, stability, thermophysical properties, and characterization of nanofluids, Powder Technol. 344 (2019) 404–431.
[73] A. Nasiri, M. Shariaty-Niasar, A. Rashidi, A. Amrollahi, R. Khodafarin, Effect of dispersion method on thermal conductivity and stability of nanofluid, Exp. Therm. Fluid Sci. 35 (2011) 717–723.
[74] G. Liang, I. Mudawar, Review of single-phase and two-phase nanofluid heat transfer in macro-channels and micro-channels, Int. J. Heat Mass Transf. 136 (2019) 324–354.
[75] R. Mashayekhi, E. Khodabandeh, M. Bahiraei, L. Bahrami, D. Toghraie, O.A. Akbari, Application of a novel conical strip insert to improve the efficacy of water−Ag nanofluid for utilization in thermal systems: a two-phase simulation, Energy Conv. Manag. 151 (2017) 573–586.
[76] M. Hangi, M. Bahiraei, A. Rahbari, Forced convection of a temperature-sensitive ferrofluid in presence of magnetic field of electrical current-carrying wire: a two-phase approach, Adv. Powder Technol. 29 (2018) 2168–2175.
[77] M. Sheikholeslami, H.B. Rokni, Nanofluid two phase model analysis in existence of induced magnetic field, Int. J. Heat Mass Transf. 107 (2017) 288–299.
[78] M. Bahiraei, A comprehensive review on different numerical approaches for simulation in nanofluids: traditional and novel techniques, J. Dispers. Sci. Technol. 35 (2014) 984–996.
[79] M. Amani, P. Amani, A. Kasaeian, O. Mahian, W.-.M. Yan, Two-phase mixture model for nanofluid turbulent flow and heat transfer: effect of heterogeneous distribution of nanoparticles, Chem Eng Sci 167 (2017) 135–144.
[80] A.R. Gorjaei, M. Soltani, M. Bahiraei, F.M. Kashkooli, CFD simulation of nanofluid forced convection inside a three-dimensional annulus by two-phase mixture approach: heat transfer and entropy generation analyses, Int. J. Mech. Sci. 146 (2018) 396–404.
[81] K. Kerrigan, H. Jouhara, G.E. O'Donnell, A.J. Robinson, Heat pipe-based radiator for low grade geothermal energy conversion in domestic space heating, Simul. Model. Pract. Theory 19 (2011) 1154–1163.
[82] J.J. Fierro, A. Escudero-Atehortua, C. Nieto-Londoño, M. Giraldo, H. Jouhara, L.C. Wrobel, Evaluation of waste heat recovery technologies for the cement industry, Int. J. Thermofluids 7-8 (2020) 100040.
[83] M. Bayareh, A.H. Pordanjani, A.A. Nadooshan, K.S. Dehkordi, Numerical study of the effects of stator boundary conditions and blade geometry on the efficiency of a scraped surface heat exchanger, Appl. Therm. Eng. 113 (2017) 1426–1436.
[84] A. Zeiny, H. Jin, L. Bai, G. Lin, D. Wen, A comparative study of direct absorption nanofluids for solar thermal applications, Solar Energy 161 (2018) 74–82.
[85] L. Shi, Y. He, X. Wang, Y. Hu, Recyclable photo-thermal conversion and purification systems via Fe_3O_4@ TiO_2 nanoparticles, Energy Conv. Manag. 171 (2018) 272–278.
[86] X. Zheng, R. Wang, Y. Tu, Investigation on energy consumption of desiccant coated heat exchanger based heat pump: limitation of adsorption heat of desiccant, Energy Conv. Manag. 188 (2019) 473–479.
[87] M. Holik, M. Živić, Z. Virag, A. Barac, Optimization of an organic Rankine cycle constrained by the application of compact heat exchangers, Energy Conv. Manag. 188 (2019) 333–345.
[88] F. Tang, H. Nowamooz, Factors influencing the performance of shallow Borehole Heat Exchanger, Energy Conv. Manag. 181 (2019) 571–583.
[89] N. Kayaci, H. Demir, B.B. Kanbur, Ş.O. Atayilmaz, O. Agra, R.C. Acet, Z. Gemici, Experimental and numerical investigation of ground heat exchangers in the building foundation, Energy Conv. Manag. 188 (2019) 162–176.
[90] H. Mroue, J.B. Ramos, L.C. Wrobel, H. Jouhara, Experimental and numerical investigation of an air-to-water heat pipe-based heat exchanger, Appl. Therm. Eng. 78 (2015) 339–350.
[91] S. Aghakhani, A.H. Pordanjani, A. Karimipour, A. Abdollahi, M. Afrand, Numerical investigation of heat transfer in a power-law non-Newtonian fluid in a C-Shaped cavity with magnetic field effect using finite difference lattice Boltzmann method, Comput. Fluids 176 (2018) 51–67.
[92] A.I. Alsabery, M.S. Ishak, A.J. Chamkha, I. Hashim, Entropy generation analysis and natural convection in a nanofluid-filled square cavity with a concentric solid insert and different temperature distributions, Entropy 20 (2018) 336.
[93] S. Bhowmick, S.C. Saha, M. Qiao, F. Xu, Transition to a chaotic flow in a V-shaped triangular cavity heated from below, Int. J. Heat Mass Transf. 128 (2019) 76–86.
[94] N.S. Bondareva, M.A. Sheremet, H.F. Öztop, N. Abu-Hamdeh, Transient natural convection in a partially open trapezoidal cavity filled with a water-based nanofluid under the effects of Brownian diffusion and thermophoresis, Int. J. Numer. Methods Heat Fluid Flow (2018).

[95] M.D. Garmroodi, A. Ahmadpour, F. Talati, MHD mixed convection of nanofluids in the presence of multiple rotating cylinders in different configurations: a two-phase numerical study, Int. J. Mech. Sci. 150 (2019) 247–264.
[96] A. Dogonchi, A.J. Chamkha, D. Ganji, A numerical investigation of magneto-hydrodynamic natural convection of Cu−water nanofluid in a wavy cavity using CVFEM, J. Therm. Anal. Calorim 135 (2019) 2599–2611.
[97] H. Karatas, T. Derbentli, Natural convection in differentially heated rectangular cavities with time periodic boundary condition on one side, Int. J. Heat Mass Transf. 129 (2019) 224–237.
[98] A. Karimipour, M.H. Esfe, M.R. Safaei, D.T. Semiromi, S. Jafari, S. Kazi, Mixed convection of copper−water nanofluid in a shallow inclined lid driven cavity using the lattice Boltzmann method, Physica A: Stat. Mech. Appl. 402 (2014) 150–168.
[99] A. Rahimi, M. Sepehr, M.J. Lariche, M. Mesbah, A. Kasaeipoor, E.H. Malekshah, Analysis of natural convection in nanofluid-filled H-shaped cavity by entropy generation and heatline visualization using lattice Boltzmann method, Physica E: Low-Dimension. Syst. Nanostruct. 97 (2018) 347–362.
[100] A. Raisi, The effect of conductive baffles on natural convection in a power-law fluid-filled square cavity, J. Brazil. Soc. Mech. Sci. Eng. 40 (2018) 33.
[101] A. Rashad, T. Armaghani, A.J. Chamkha, M. Mansour, Entropy generation and MHD natural convection of a nanofluid in an inclined square porous cavity: effects of a heat sink and source size and location, Chin. J. Phys. 56 (2018) 193–211.
[102] M.R. Safaei, A. Karimipour, A. Abdollahi, T.K. Nguyen, The investigation of thermal radiation and free convection heat transfer mechanisms of nanofluid inside a shallow cavity by lattice Boltzmann method, Physica A: Stat. Mech. Appl. 509 (2018) 515–535.
[103] H. Sajjadi, A.A. Delouei, M. Atashafrooz, M. Sheikholeslami, Double MRT Lattice Boltzmann simulation of 3-D MHD natural convection in a cubic cavity with sinusoidal temperature distribution utilizing nanofluid, Int. J. Heat Mass Transf. 126 (2018) 489–503.
[104] F. Selimefendigil, H.F. Öztop, Corrugated conductive partition effects on MHD free convection of CNT-water nanofluid in a cavity, Int. J. Heat Mass Transf. 129 (2019) 265–277.
[105] F. Selimefendigil, H.F. Öztop, Role of magnetic field and surface corrugation on natural convection in a nanofluid filled 3D trapezoidal cavity, Int. Commun. Heat Mass Transf. 95 (2018) 182–196.
[106] M. Sheikholeslami, Z. Li, M. Shamlooei, Nanofluid MHD natural convection through a porous complex shaped cavity considering thermal radiation, Phys. Lett. A 382 (2018) 1615–1632.
[107] M. Sheikholeslami, S. Shehzad, Z. Li, Water based nanofluid free convection heat transfer in a three dimensional porous cavity with hot sphere obstacle in existence of Lorenz forces, Int. J. Heat Mass Transf. 125 (2018) 375–386.
[108] M.A. Sheremet, I. Pop, O. Mahian, Natural convection in an inclined cavity with time-periodic temperature boundary conditions using nanofluids: application in solar collectors, Int. J. Heat Mass Transf. 116 (2018) 751–761.
[109] A.H. Pordanjani, A. Jahanbakhshi, A.A. Nadooshan, M. Afrand, Effect of two isothermal obstacles on the natural convection of nanofluid in the presence of magnetic field inside an enclosure with sinusoidal wall temperature distribution, Int. J. Heat Mass Transf. 121 (2018) 565–578.
[110] M. Sheikholeslami, M. Seyednezhad, Simulation of nanofluid flow and natural convection in a porous media under the influence of electric field using CVFEM, Int. J. Heat Mass Transf. 120 (2018) 772–781.
[111] M. Sheikholeslami, Numerical investigation of nanofluid free convection under the influence of electric field in a porous enclosure, J. Mol. Liq. 249 (2018) 1212–1221.
[112] M. Sheikholeslami, S. Soleimani, D. Ganji, Effect of electric field on hydrothermal behavior of nanofluid in a complex geometry, J. Mol. Liq. 213 (2016) 153–161.
[113] K.-.L. Hsiao, Stagnation electrical MHD nanofluid mixed convection with slip boundary on a stretching sheet, Appl. Therm. Eng. 98 (2016) 850–861.
[114] S.U. Choi, J.A. Eastman, Enhancing Thermal Conductivity of Fluids With Nanoparticles, Argonne National Lab., ILUnited States, 1995.
[115] S. Lee, S.-.S. Choi, S. Li, and, J. Eastman, Measuring thermal conductivity of fluids containing oxide nanoparticles, (1999).
[116] X. Wang, X. Xu, S.U. Choi, Thermal conductivity of nanoparticle-fluid mixture, J. Thermophys. Heat Transf. 13 (1999) 474–480.
[117] K. Thulukkanam, Heat Exchanger Design Handbook, CRC press, 2013.
[118] A.P. Fraas, Heat Exchanger Design, John Wiley & Sons, 1989.
[119] B. Linnhoff, D.R. Mason, I. Wardle, Understanding heat exchanger networks, Comput. Chem. Eng. 3 (1979) 295–302.
[120] T.L. Bergman, F.P. Incropera, D.P. DeWitt, A.S. Lavine, Fundamentals of Heat and Mass Transfer, John Wiley & Sons, 2011.
[121] K.-.M. Björk, R. Nordman, Solving large-scale retrofit heat exchanger network synthesis problems with mathematical optimization methods, Chem. Eng. Process.: Process Intensif. 44 (2005) 869–876.
[122] B. Farajollahi, S.G. Etemad, M. Hojjat, Heat transfer of nanofluids in a shell and tube heat exchanger, Int. J. Heat Mass Transf. 53 (2010) 12–17.
[123] G. Huminic, A. Huminic, Application of nanofluids in heat exchangers: a review, Renew. Sustain. Energy Rev. 16 (2012) 5625–5638.
[124] T. Gundersen, L. Naess, The synthesis of cost optimal heat exchanger networks: an industrial review of the state of the art, Heat Recov. Syst. CHP 10 (1990) 301–328.
[125] A. Mueller, J. Chiou, Review of various types of flow maldistribution in heat exchangers, Heat Transf. Eng. 9 (1988) 36–50.
[126] D.t. Weaver, J. Fitzpatrick, A review of cross-flow induced vibrations in heat exchanger tube arrays, J. Fluids Struct. 2 (1988) 73–93.
[127] A. Iqbal, M.S. Mahmoud, E.T. Sayed, K. Elsaid, M.A. Abdelkareem, H. Alawadhi, A.G. Olabi, Evaluation of the nanofluid-assisted desalination through solar stills in the last decade, J. Environ. Manag. 277 (2021) 111415.
[128] K. Somasekhar, K.M. Rao, V. Sankararao, R. Mohammed, M. Veerendra, T. Venkateswararao, A CFD investigation of heat transfer enhancement of shell and tube heat exchanger using Al_2O_3-water nanofluid, Mater. Today: Proc. 5 (2018) 1057–1062.
[129] R. Ganvir, P. Walke, V. Kriplani, Heat transfer characteristics in nanofluid—a review, Renew. Sustain. Energy Rev. 75 (2017) 451–460.
[130] L.S. Sundar, K. Sharma, M.K. Singh, A. Sousa, Hybrid nanofluids preparation, thermal properties, heat transfer and friction factor−a review, Renew. Sustain. Energy Rev. 68 (2017) 185–198.
[131] A. Bhattad, J. Sarkar, P. Ghosh, Discrete phase numerical model and experimental study of hybrid nanofluid heat transfer and pressure drop in plate heat exchanger, Int. Commun. Heat Mass Transf. 91 (2018) 262–273.
[132] A.A. Baloch, H.M. Bahaidarah, P. Gandhidasan, F.A. Al-Sulaiman, Experimental and numerical performance analysis of a converging channel heat exchanger for PV cooling, Energy Conv. Manag. 103 (2015) 14–27.
[133] G.L. Morini, Single-phase convective heat transfer in microchannels: a review of experimental results, Int. J. Therm. Sci. 43 (2004) 631–651.
[134] G. Florides, S. Kalogirou, Ground heat exchangers—a review of systems, models and applications, Renew. Energy 32 (2007) 2461–2478.
[135] T.S. Bisoniya, A. Kumar, P. Baredar, Experimental and analytical studies of earth−air heat exchanger (EAHE) systems in India: a review, Renew. Sustain. Energy Rev. 19 (2013) 238–246.
[136] A.A. Al-Rashed, A. Shahsavar, S. Entezari, M. Moghimi, S.A. Adio, T.K. Nguyen, Numerical investigation of non-Newtonian water-CMC/CuO nanofluid flow in an offset strip-fin microchannel heat sink: thermal performance and thermodynamic considerations, Appl. Therm. Eng. 155 (2019) 247–258.
[137] D. Purbia, A. Khandelwal, A. Kumar, A.K. Sharma, Graphene-water nanofluid in heat exchanger: mathematical modelling, simulation and economic evaluation, Int. Commun. Heat Mass Transf. 108 (2019) 104327.
[138] R.D. Plant, M.Z. Saghir, Numerical and experimental investigation of high concentration aqueous alumina nanofluids in a two and three channel heat exchanger, Int. J. Thermofluids 9 (2021) 100055.
[139] X. Shi, S. Li, Y. Wei, J. Gao, Numerical investigation of laminar convective heat transfer and pressure drop of water-based Al_2O_3 nanofluids in a microchannel, Int. Commun. Heat Mass Transf. 90 (2018) 111–120.
[140] M. Shirzad, S.S.M. Ajarostaghi, M.A. Delavar, K. Sedighi, Improve the thermal performance of the pillow plate heat exchanger by using nanofluid: numerical simulation, Adv. Powder Technol. 30 (2019) 1356–1365.
[141] N. Moghaddaszadeh, J.A. Esfahani, O. Mahian, Performance enhancement of heat exchangers using eccentric tape inserts and nanofluids, J. Therm. Anal. Calorim. 137 (2019) 865–877.
[142] R. Hosseinnejad, M. Hosseini, M. Farhadi, Turbulent heat transfer in tubular heat exchangers with twisted tape, J. Therm. Anal. Calorim. 135 (2019) 1863–1869.
[143] S.M. Vanaki, P. Ganesan, H. Mohammed, Numerical study of convective heat transfer of nanofluids: a review, Renew. Sustain. Energy Rev. 54 (2016) 1212–1239.
[144] M. Rashidi, A. Hosseini, I. Pop, S. Kumar, N. Freidoonimehr, Comparative numerical study of single and two-phase models of nanofluid heat transfer in wavy channel, Appl. Math. Mech. 35 (2014) 831–848.
[145] R. Davarnejad, M. Jamshidzadeh, CFD modeling of heat transfer performance of MgO-water nanofluid under turbulent flow, Eng. Sci. Technol. Int. J. 18 (2015) 536–542.
[146] M. Kalteh, A. Abbassi, M. Saffar-Avval, J. Harting, Eulerian−Eulerian two-phase numerical simulation of nanofluid laminar forced convection in a microchannel, Int. J. Heat Fluid Flow 32 (2011) 107–116.
[147] H. Bahremand, A. Abbassi, M. Saffar-Avval, Experimental and numerical investigation of turbulent nanofluid flow in helically coiled tubes under constant wall heat flux using Eulerian−Lagrangian approach, Powder Technol. 269 (2015) 93–100.
[148] H. Aminfar, R. Motallebzadeh, Investigation of the velocity field and nanoparticle concentration distribution of nanofluid using Lagrangian−Eulerian approach, J. Dispers. Sci. Technol. 33 (2012) 155–163.
[149] C. Li, C. Crua, K. Vogiatzaki, Effect of the scale resolution on the two phase coupling characteristics of high speed evaporating sprays using LES/Eulerian-Lagrangian methodologies, Int. J. Multiphase Flow 120 (2019) 103060.
[150] M. Mahdavi, M. Sharifpur, J.P. Meyer, CFD modelling of heat transfer and pressure drops for nanofluids through vertical tubes in laminar flow by Lagrangian and Eulerian approaches, Int. J. Heat Mass Transf. 88 (2015) 803–813.
[151] M. Akbari, N. Galanis, A. Behzadmehr, Comparative analysis of single and two-phase models for CFD studies of nanofluid heat transfer, Int. J. Therm. Sci. 50 (2011) 1343–1354.
[152] J. Lee, I. Mudawar, Assessment of the effectiveness of nanofluids for single-phase and two-phase heat transfer in micro-channels, Int. J. Heat Mass Transf. 50 (2007) 452–463.
[153] M.H. Fard, M.N. Esfahany, M. Talaie, Numerical study of convective heat transfer of nanofluids in a circular tube two-phase model versus single-phase model, Int. Commun. Heat Mass Transf. 37 (2010) 91–97.
[154] A. Behzadmehr, M. Saffar-Avval, N. Galanis, Prediction of turbulent forced convection of a nanofluid in a tube with uniform heat flux using a two phase approach, Int. J. Heat Fluid Flow 28 (2007) 211–219.
[155] A. Alsabery, M. Sheremet, A. Chamkha, I. Hashim, Conjugate natural convection of Al_2O_3−water nanofluid in a square cavity with a concentric solid insert using Buongiorno's two-phase model, Int. J. Mech. Sci. 136 (2018) 200–219.

[156] A. Jafarimoghaddam, Two-phase modeling of magnetic nanofluids jets over a Stretching/shrinking wall, Therm. Sci. Eng. Progr. 8 (2018) 375–384.

[157] A.I. Alsabery, E. Gedik, A.J. Chamkha, I. Hashim, Effects of two-phase nanofluid model and localized heat source/sink on natural convection in a square cavity with a solid circular cylinder, Comput. Methods Appl. Mech. Eng. 346 (2019) 952–981.

[158] S. Siddiqa, N. Begum, M. Hossain, R.S.R. Gorla, A.A. Al-Rashed, Two-phase natural convection dusty nanofluid flow, Int. J. Heat Mass Transf. 118 (2018) 66–74.

[159] A. Rahimi, A. Surendar, A. Kasaeipoor, P. Hooshmand, E.H. Malekshah, Lattice Boltzmann simulation of nanofluid flow and heat transfer in a hollow multipipe heat exchanger considering nanoparticles' shapes, Powder Technol. 339 (2018) 974–984.

[160] A.G. Olabi, K. Elsaid, E.T. Sayed, M.S. Mahmoud, T. Wilberforce, R.J. Hassiba, M.A. Abdelkareem, Application of nanofluids for enhanced waste heat recovery: a review, Nano Energy (2021) 105871.

[161] D. Brough, H. Jouhara, The aluminium industry: a review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery, Int. J. Thermofluids 1-2 (2020) 100007.

[162] H. Huang, J. Zhu, B. Yan, Comparison of the performance of two different Dual-loop organic Rankine cycles (DORC) with nanofluid for engine waste heat recovery, Energy Conv. Manag. 126 (2016) 99–109.

[163] R. Kong, A. Asanakham, T. Deethayat, T. Kiatsiriroat, Heat transfer characteristics of deionized water-based graphene nanofluids in helical coiled heat exchanger for waste heat recovery of combustion stack gas, Heat Mass Transf. 55 (2019) 385–396.

[164] C. Forman, I.K. Muritala, R. Pardemann, B. Meyer, Estimating the global waste heat potential, Renew. Sustain. Energy Rev. 57 (2016) 1568–1579.

[165] G.P. Panayiotou, G. Bianchi, G. Georgiou, L. Aresti, M. Argyrou, R. Agathokleous, K.M. Tsamos, S.A. Tassou, G. Florides, S. Kalogirou, Preliminary assessment of waste heat potential in major European industries, Energy Procedia 123 (2017) 335–345.

[166] A.H. Pordanjani, S. Aghakhani, M. Afrand, B. Mahmoudi, O. Mahian, S. Wongwises, An updated review on application of nanofluids in heat exchangers for saving energy, Energy Conv. Manag. 198 (2019) 111886.

[167] N.S. Pandya, H. Shah, M. Molana, A.K. Tiwari, Heat transfer enhancement with nanofluids in plate heat exchangers: a comprehensive review, Eur. J. Mech.-B/Fluids 81 (2020) 173–190.

[168] V. Kumar, A.K. Tiwari, S.K. Ghosh, Application of nanofluids in plate heat exchanger: a review, Energy Conv. Manag. 105 (2015) 1017–1036.

[169] H. Mohammed, G. Bhaskaran, N. Shuaib, R. Saidur, Heat transfer and fluid flow characteristics in microchannels heat exchanger using nanofluids: a review, Renew. Sustain. Energy Rev. 15 (2011) 1502–1512.

[170] K. Wongcharee, S. Eiamsa-ard, Heat transfer enhancement by using CuO/water nanofluid in corrugated tube equipped with twisted tape, Int. Commun. Heat Mass Transf. 39 (2012) 251–257.

[171] S. Hashemi, M. Akhavan-Behabadi, An empirical study on heat transfer and pressure drop characteristics of CuO−base oil nanofluid flow in a horizontal helically coiled tube under constant heat flux, Int. Commun. Heat Mass Transf. 39 (2012) 144–151.

[172] S.E.B. Maïga, C.T. Nguyen, N. Galanis, G. Roy, Heat transfer behaviours of nanofluids in a uniformly heated tube, Superlattices Microstruct. 35 (2004) 543–557.

[173] T. Kim, W. Song, D.-Y. Son, L.K. Ono, Y. Qi, Lithium-ion batteries: outlook on present, future, and hybridized technologies, J. Mater. Chem. A 7 (2019) 2942–2964.

[174] X. Zhai, C. Qi, Y. Pan, T. Luo, L. Liang, Effects of screw pitches and rotation angles on flow and heat transfer characteristics of nanofluids in spiral tubes, Int. J. Heat Mass Transf. 130 (2019) 989–1003.

[175] G. Huminic, A. Huminic, The influence of hybrid nanofluids on the performances of elliptical tube: recent research and numerical study, Int. J. Heat Mass Transf. 129 (2019) 132–143.

[176] S. Mei, C. Qi, T. Luo, X. Zhai, Y. Yan, Effects of magnetic field on thermo-hydraulic performance of Fe_3O_4-water nanofluids in a corrugated tube, Int. J. Heat Mass Transf. 128 (2019) 24–45.

[177] F. Liu, D. Zhang, Y. Cai, Z. Qiu, Q. Zhu, J. Zhao, L. Wang, H. Tian, Multiplicity of forced convective heat transfer of nanofluids in curved ducts, Int. J. Heat Mass Transf. 129 (2019) 534–546.

[178] E. Shahsavani, M. Afrand, R. Kalbasi, Using experimental data to estimate the heat transfer and pressure drop of non-Newtonian nanofluid flow through a circular tube: applicable for use in heat exchangers, Appl. Therm. Eng. 129 (2018) 1573–1581.

[179] C. Qi, M. Liu, G. Wang, Y. Pan, L. Liang, Experimental research on stabilities, thermophysical properties and heat transfer enhancement of nanofluids in heat exchanger systems, Chin. J. Chem. Eng. 26 (2018) 2420–2430.

[180] M. Sheikholeslami, M. Jafaryar, S. Saleem, Z. Li, A. Shafee, Y. Jiang, Nanofluid heat transfer augmentation and exergy loss inside a pipe equipped with innovative turbulators, Int. J. Heat Mass Transf. 126 (2018) 156–163.

[181] K. Palanisamy, P.C. Mukesh Kumar, Experimental investigation on convective heat transfer and pressure drop of cone helically coiled tube heat exchanger using carbon nanotubes/water nanofluids, Heliyon 5 (2019) e01705.

[182] T.L. Coggan, D. Moodie, A. Kolobaric, D. Szabo, J. Shimeta, N.D. Crosbie, E. Lee, M. Fernandes, B.O. Clarke, An investigation into per-and polyfluoroalkyl substances (PFAS) in nineteen Australian wastewater treatment plants (WWTPs), Heliyon 5 (2019) e02316.

[183] M. Mansour, P. Khot, D. Thévenin, K.D. Nigam, K. Zähringer, Optimal Reynolds number for liquid-liquid mixing in helical pipes, Chem. Eng. Sci. 214 (2020) 114522.

[184] M. Bahiraei, N. Mazaheri, Application of a novel hybrid nanofluid containing graphene−platinum nanoparticles in a chaotic twisted geometry for utilization in miniature devices: thermal and energy efficiency considerations, Int. J. Mech. Sci. 138-139 (2018) 337–349.

[185] M. Omidi, M. Farhadi, A.A.R. Darzi, Numerical study of heat transfer on using lobed cross sections in helical coil heat exchangers: effect of physical and geometrical parameters, Energy Conv. Manag. 176 (2018) 236–245.

[186] T. Dbouk, C. Habchi, On the mixing enhancement in concentrated non-colloidal neutrally buoyant suspensions of rigid particles using helical coiled and chaotic twisted pipes: a numerical investigation, Chem. Eng. Process.-Process Intensif. 141 (2019) 107540.

[187] E. Khodabandeh, M. Bahiraei, R. Mashayekhi, B. Talebjedi, D. Toghraie, Thermal performance of Ag−water nanofluid in tube equipped with novel conical strip inserts using two-phase method: geometry effects and particle migration considerations, Powder Technol. 338 (2018) 87–100.

[188] M. Bahiraei, N. Mazaheri, F. Aliee, Second law analysis of a hybrid nanofluid in tubes equipped with double twisted tape inserts, Powder Technol. 345 (2019) 692–703.

[189] R. Mashayekhi, H. Arasteh, D. Toghraie, S.H. Motaharpour, A. Keshmiri, M. Afrand, Heat transfer enhancement of Water-Al_2O_3 nanofluid in an oval channel equipped with two rows of twisted conical strip inserts in various directions: a two-phase approach, Comput. Math. Appl. 79 (2020) 2203–2215.

[190] W. Guo, G. Li, Y. Zheng, C. Dong, The effect of flow pulsation on Al_2O_3 nanofluids heat transfer behavior in a helical coil: a numerical analysis, Chem. Eng. Res. Des. 156 (2020) 76–85.

[191] M. Bahiraei, M. Hangi, Numerical simulation of nanofluid application in a C-shaped chaotic channel: a potential approach for energy efficiency improvement, Energy 74 (2014) 863–870.

[192] Q. Xiong, M. Ayani, A.A. Barzinjy, R.N. Dara, A. Shafee, T. Nguyen-Thoi, Modeling of heat transfer augmentation due to complex-shaped turbulator using nanofluid, Physica A: Stat. Mech. Appl. 540 (2020) 122465.

[193] M. Sheikholeslami, S.A. Farshad, A. Shafee, I. Tlili, Modeling of solar system with helical swirl flow device considering nanofluid turbulent forced convection, Physica A: Stat. Mech. Appl. 550 (2020) 123952.