CHAPTER 2

LITERATURE REVIEW

The available literature on the preparation, characterization, thermophysical properties of nanofluids, the heat transfer and pressure drop characteristics of the double pipe heat exchanger and shell and tube heat exchanger using mono/hybrid nanofluids are discussed in five sections. In the first and second sections, it summarizes the preparation, characterization and thermophysical properties of nanofluids. Exclusive reviews on the heat transfer, pressure drop characteristics and energy performance of both double-tube and shell-tube heat exchangers using nanofluids are presented in the third and fourth sections. The last section summarizes the researches on various engineering applications of tubular heat exchanger using nanofluids.

2.1 Preparation and Characterization of Nanofluids

2.1.1 Preparation of mono/hybrid nanofluids

The preparation method is a key step for nanofluids to get a homogeneous and stable suspension. Two methods are generally used to prepare nanofluids: one-step and two-step methods **(Sidik et al., 2014; Haddad et al., 2014)**. Preparation and dispersion of nanoparticles in the base fluid are simultaneously done for a one-step technique. This method is used to reduce the nanoparticle's agglomeration by avoiding the drying processes, storing processes, transportation, and distribution of nanoparticles and hence the stability of nanofluids is also improved. Suitable reducing agents (sodium borohydride and hydrazine) and surfactants (e.g., polyvinylpyrrolidone) are used in this method, which can help to get stable suspension even with high dense nanoparticle (e.g., silver) and improve the thermal conductivity even with a lower concentration of nanoparticles **(Salehi et al., 2013)**.

The two-step method is used to engineer the nanofluids by mixing base fluids with nanoparticles, which can be manufactured by different physical and chemical processes such as grinding, milling and vapor-phase methods. The mixture of nanopowder with base fluid is first stirred for proper mixing and then sonicated by using an ultrasonic vibrator for reducing particle agglomeration to get a stable and uniform suspension. The two-step method has been mostly used for nanofluids preparation **(Sidik et al., 2014; Haddad et al., 2014)**. **Hu et al. (2008)** prepared ethanol-based aluminum nitride (AlN) nanofluid by a two-step method followed by first magnetic striation and then ultrasonic agitation. **Yu et al. (2011)** prepared AlN/EG and AlN/PG nanofluids by the two-step method, and the nanofluid was stirred and sonicated for three hours.

Hybrid nanofluids may also be prepared by dispersing nanoparticles mixture or nanocomposites in a base fluid using a one-step or two-step method. Hybridization is needed to a settlement between several properties in many practical applications, and good hybridization will lead to the heat transfer improvement using hybrid nanofluids **(Sarkar et al., 2015)**. Most of the nanoparticles used in the synthesis of hybrid nanofluid were hydrophobic in nature and their characteristics in some instances were affected while making them hydrophilic **(Sidik et al., 2017)**. The two-step method has been mostly used for the preparation of hybrid nanofluids. **Yarmand et al. (2015)** engineered GNP–Ag nanocomposite by using a chemical process and dispersed in distilled water without any dispersant. **Toghraie et al. (2016)** prepared ZnO–TiO_2/EG hybrid nanofluid by dispersing an equal amount of ZnO and TiO_2 nanoparticles in pure EG and mixed in magnetic stirrer for 2.5 h and then ultrasonicated for 6–7 h. For hybrid nanofluids also, ultrasonication and surfactant improve the homogeneity and stability.

2.1.2 Characterization of mono/hybrid nanofluids

Nanofluid's characterization mainly consists of (i) the nanoparticle's characterization to measure the shape, size and agglomeration's size and (ii) analysis of homogeneity and stability of the suspension. Nanoparticle characterization methods include TEM, XRD, VSM, EDX, thermal analysis TG-DTA, UV–Vis spectroscopy, FTIR, infrared absorption spectroscopy, SEM, and (ICP-OES) **(Kumar et al., 2016)**. The stability of nanofluids can be examined by using zeta potential analysis, sedimentation method, UV–vis spectroscopy, electron microscopy, etc. **(Babita et al., 2016)**. **Nabil et al. (2017)** characterized TiO_2 and SiO_2 nanofluids by TEM techniques. Both TiO_2 and SiO_2 nanoparticles were observed to be almost spherical with an average size of 50 nm, 22 nm, respectively. **Fule et al. (2017)** characterized the morphology of CuO nanoparticles by SEM and TEM analyses and detected uniform particle distribution from the TEM image. Similarly, many nanoparticle characterization results have been reported for both mono and hybrid nanofluids.

2.2. Thermophysical Properties of Nanofluids

2.2.1 Thermal Conductivity

Studies reveal that the addition of nanoparticles in the conventional fluid leads to increase thermal conductivity. The four possible mechanisms, e.g., nanoparticle Brownian motion, particle interface liquid layering, heat transport between nanoparticles and nanoparticle clustering have been explored and investigated the effects of different mechanisms and found that the Brownian motion effect is most important when compared to thermophoresis and osmophoresis.

Recently, many experimental studies have been conducted on thermal conductivity on hybrid nanofluids. **Harandi et al. (2016)** experimentally showed that the thermal conductivity of MWCNT–Fe_3O_4/EG hybrid nanofluid increases with an augmentation in temperature and solid volume fraction. **Shahsavar and Bahiraei (2017)** also observed that thermal conductivity enhances with the temperature due to the rise of disordered particle motion. **Esfe et al. (2017)** also observed similar behavior for CNT-MgO/EG hybrid nanofluids with an increase in particle concentration and operating temperature. **Nabil et al. (2017)** studied the thermal conductivity of EG brine-based TiO_2-SiO_2 nanofluids and demonstrated that the thermal conductivity enhances up to 22.8% for 3.0% volume concentration at a temperature of 80°C. **Yarmand et al. (2016)** examined the thermal conductivity of GNP/Pt hybrid nanofluid in the range of temperature 20^{o}C-40^{o}C with a weight concentration of 0-0.1%. The result revealed that the enhancement of thermal conductivity was 17.77% at 40^{o}C and 0.1% wt concentration. **Afrand (2017)** investigated thermal conductivity of MgO-MWCNT hybrid nanofluids and exhibited that the enhancement at low solid volume fractions (0.05–0.2%) is higher than that at higher solid volume fractions (0.2–0.6%) as the average dimension of the clusters increases at higher solid volume fraction. Composite dispersed hybrid nanofluid showed better improvement than mono nanofluid; however, mixture dispersed hybrid nanofluid showed similar behavior. Empirical thermal conductivity models are summarized in **Table 2.1**, which are nanoparticle specific. For the generalized model, many researchers have used the conventional nanofluid model by inserting average solid particle thermal conductivity, applicable for similar size nanoparticles.

Table 2.1: Summary of experimental thermal conductivity correlations of hybrid nanofluids

References	**Correlation**	**Nanofluid Vol. concentration Temperature range**
Esfe et al. (2015a)	$\frac{k_{nf}}{k_{bf}} = 1.07 + 0.000589T - \frac{0.000184}{T\phi} + 4.44 \times T\phi \times \cos\left(6.11 + 0.00673T + 4.41T\phi - 0.0414 \times \sin(T)\right)$	Cu-TiO_2/Water+EG (60:40) 0.1-2% 30^oC-60^oC
Esfe et al. (2015b)	$\frac{k_{nf}}{k_{bf}} = 1.085\exp(0.001351T + 0.13\phi^2) + 0.0288 \times \ln(\phi)$	DWCNT-ZnO/Water+EG (60:40) 0.025-1% 25^oC -50^oC
Esfe et al. (2015c)	$\frac{k_{nf}}{k_{bf}} = \frac{0.1747 \times 10^5 + \phi}{0.1747 \times 10^5 - 0.1498 \times 10^6 \times \phi + 0.1117 \times 10^7 \times \phi^2 + 0.1997 \times 10^8 \times \phi^3}$	Ag-MgO/Water 0-3% 25^oC -60^oC
Toghraie et al. (2016)	$\frac{k_{nf}}{k_{bf}} = 1 + 0.004503\phi^{0.8717}T^{0.7972}$	ZnO-TiO_2/EG 0-3.5% 25^oC -50^oC
Harandi et al. (2016)	$\frac{k_{nf}}{k_{bf}} = 1 + 0.0162\phi^{0.7038}T^{0.6009}$	FMWCNT-Fe_3O_4/EG 0.1-2.3% 25^oC -50^oC
Rostamian et al. (2017)		SWCNT-CuO/ Water+EG

	$$\frac{k_{nf}}{k_{bf}} = 1 + 0.04056(\phi T) - 0.003252(\phi T)^2 + 0.0001181(\phi T)^3 - 0.000001431(\phi T)^4$$	0.02-0.75% 20°C -50°C
Vafaei et al. (2017)	$$\frac{k_{nf}}{k_{bf}} = 0.9787 + \exp\left(0.3081\phi^{0.3097} - 0.002T\right)$$	MgO-MWCNT/EG 0.05-0.6% 25°C -50°C
Esfe et al. (2017a)	$$\frac{k_{nf}}{k_{bf}} = 0.90844 - 0.06613\phi^{0.3}T^{0.7} + 0.01266\phi^{0.31}T$$	SWCNT-MgO(20:80)/EG 0.05-2% 30°C -50°C
Esfe et al. (2017b)	$$\frac{k_{nf}}{k_{bf}} = 1.024 + 0.5988\phi^{0.6029}\exp\left(\frac{\phi}{T}\right) - \frac{8.059\phi T^{0.2} + 2.24}{6.052\phi^{0.2} + T}$$	ZnO-MWCNT/Water+EG (50:50) 0.02-1% 30°C -50°C
Akilu et al. (2017)	$$\frac{k_{nf}}{k_{bf}} = 1 + 6.2299\left(\frac{\phi}{100}\right)^{0.9371}\left(\frac{T}{333}\right)^{10.2685}$$	TiO_2-CuO/C-EG 0.5-2% 25°C -60°C
Afrand (2017)	$$\frac{k_{nf}}{k_{bf}} = 0.8341 + 1.1\phi^{0.243}T^{-0.289}$$	MgO-FMWCNT/EG 0.05-0.6% 25°C -50°C
Nabil et al. (2017)	$$\frac{k_{nf}}{k_{bf}} = \left(1 + \frac{\phi}{100}\right)^{5.5}\left(\frac{T}{80}\right)^{0.01}$$	SiO_2-TiO_2/Water+EG (60:40) 0.5-3% 30°C -80°C

Esfahani et al. (2018)	$\frac{k_{nf}}{k_{bf}} = 1 + 0.0008794\phi^{0.5899}T^{1.345}$	ZnO-Ag/water 0.125-2% 25°C -50°C
Hamid et al. (2018)	$\frac{k_{nf}}{k_{bf}} = 1.17(1+R)^{-0.1151}\left(\frac{T}{80}\right)^{0.0437}$ Where R is the mixture ratio	SiO_2-TiO_2/Water+EG (60:40) 20:80-VR-80:20 30°C -80°C
Moldoveanu et al. (2018)	$k_{hnf} = 0.607 - 0.005\varphi_1 + 0.009\varphi_1{}^2 + 0.109\varphi_2 - 0.059\phi_2{}^2 + 0.013\phi_2{}^3$	Al_2O_3-SiO_2 1-3% 25°C -50°C
Safaei et al. (2018)	$\frac{k_{nf}}{k_{bf}} = 0.9789 + 0.0389T^{0.4917}wt^{0.7182}$	$CoFe_2O_4/SiO_2/$ Water+EG $0.1<wt<1.5$ 15°C -65°C

2.2.2 Dynamic viscosity

In general, the viscosity and rheological behavior of nanofluids depend on particle concentration, shape and size, and operating temperature. **Mostafizur et al. (2016)** measured the viscosity of CH_3OH based SiO_2 nanofluids at different volume concentrations and temperatures and showed that viscosity increases with nanoparticle concentration due to the higher internal shear force among the nanoparticles and decreases with rising in temperature due to a weakening of intermolecular and inter-particle adhesion forces of fluids. Also, it was found that the nanofluids behaved as a non-Newtonian fluid with a shear thickening. The nanofluid viscosity was found a maximum 1.13 times more than that of methanol at a particle concentration of 0.15 vol% and a temperature of 25 °C. **Sundar et al. (2016)** experimentally studied the viscosity of nanodiamond–water nanofluids and observed that the enhancement of viscosity with respect to water is more at a higher temperature. **Abdollahi et al. (2018)** studied the effects of different types of base fluids (DI, EG and Ethanol) on the viscosity of CuO loaded nanofluid. The result implied that the viscosity shows the maximum for CuO/Ethanol and minimum for CuO/DI at a higher mass fraction. Many theoretical model-based equations for predicting the viscosity of nanofluids have been proposed; however, the predicted viscosity data from those models highly deviate from the experimental data. Hence, various empirical relations of nanofluid viscosity have also been proposed **(Akilu et al., 2016; Raja et al., 2016; Azmi et al., 2016; Bashirnezhad et al., 2016)**.

Rheological behavior of similar particle mixture or composite dispersed hybrid nanofluid is similar to mono nanofluid, although it yields slightly higher viscosity. **Esfe et al. (2019)** studied the rheological behavior of MWCNT-TiO_2/EG-water hybrid nanofluid and found a negligible effect on viscosity with the addition of nanoparticles at low volume concentration. **Goodarzi et al. (2018)** used ZnO-MWCNT nanoparticles dispersed in engine oil (SAE 10W40) and reported a Newtonian behavior. For the hybrid nanofluids, all the empirical correlations are summarized in **Table 2.2**.

Table 2.2: Summary of dynamic viscosity correlations of hybrid nanofluids

References	**Correlation**	**Nanofluid Vol. concentration Temperature range**
Soltani et al. (2016)	$\frac{\mu_{nf}}{\mu_{bf}} = \left[0.191\phi + 0.240\left(T^{-0.342}\phi^{-0.473}\right)\right] \times \exp\left(1.45T^{0.120}\phi^{0.158}\right)$	MWCNT-MgO/EG 0.1% - 1.0% 30 °C - 60 °C

Dardan et al. (2016)	$\frac{\mu_{nf}}{\mu_{bf}}=1.123+0.3251\phi-0.08994T+0.002552T^2-0.00002386T^3+0.9695\left(\frac{T}{\phi}\right)^{0.01719}$	MWCNT-Al_2O_3(25-75)/Engine oil 0% -2.0% 25 °C-50 °C,
Asadi et al. (2016)	$\mu_{nf}=796.8+76.26\phi+12.88T+0.7965\phi T-196.9\sqrt{T}-16.53\phi\sqrt{T}$	MWCNT-ZnO (15%-85%)/ Engine oil 0.125% - 1% 5 °C-55 °C
Akilu et al. (2017)	$\frac{\mu_{nf}}{\mu_{bf}}=0.9653+77.4567\left[\frac{\varphi_v}{100}\right]^{1.1558}\left[\frac{T}{333}\right]^{0.6881}$	TiO_2-CuO/ EG 0.5%-2% 303.15K-333.15K
Esfe et al. (2018)	$\mu_{nf}=1731.14+245.35\varphi-88.14T-0.028\gamma-8.94\varphi T-0.00078\varphi\gamma+0.00094T\gamma-8.77\varphi^2$ $+1.65T^2+1.26\times10^{-6}\gamma^2+0.091\varphi T^2-1.07\times10^{-5}T^2\gamma-0.010T^2-6\times10^{-11}\gamma^3$ Where ϒ= shear stress	MWCNT-TiO_2/Engine oil 0.0625%-1% 25 °C-50 °C
Esfe et al. (2019)	$\mu_{nf}=6.35+2.56\phi-0.24T-0.068\phi T+0.905\phi^2+0.0027T^2$	MWCNT-TiO_2/EG-water 0.05%-0.85% 10°C-50°C

2.2.3 Density and specific heat

Density is a basic property of nanofluid, which depends on nanoparticle volume concentration. In general, the density of nanofluid is higher as compared to base fluid due to the higher density of solid (nanoparticle) than the liquid (base fluid). The density of the mono nanofluids, as well as hybrid nanofluids (containing particle mixture or composite particle), can be obtained using mixing rule **(Pak and Cho, 1998)**. Nanofluid specific heat can be expressed as a blend of heat capacities of base fluid and nanoparticle when both are in thermal equilibrium. Specific heat of the nanofluid with mono-nanoparticles or nanocomposites can be calculated using energy balance. Density and heat capacity of mono and hybrid nanofluids can be expressed as:

$$\rho_{nf} = \left(1 - \sum \phi_{np}\right) \rho_{bf} + \sum \phi_{np} \rho_{np} \tag{2.1}$$

$$\rho_{nf} c_{p,nf} = \left(1 - \sum \phi_{np}\right) \rho_{bf} c_{p,bf} + \sum \phi_{np} \rho_{np} c_{p,np} \tag{2.2}$$

Due to the paucity of experimental data on their temperature dependence, the specific heat and density of nanofluids are supposed to be a linear function of volume fraction. The density of nanofluids decreases with an increase in temperature. The heat capacity may also be dependent on temperature and particle size; it increases with a decrease in temperature as well as particle size (**Akilu et al., 2016)**. Due to the lower heat capacity of solid compared to liquid, the heat capacity of nanofluids generally reduces, which can be avoided by using phase change materials **(Fazeli et al., 2012)**.

2.3 Nanofluids in Double-Tube Heat Exchangers

2.3.1. Heat transfer characteristics

Studies on double tube heat exchanger using nanofluids are summarized in **Table 2.3**. Research works on heat transfer characteristics of nanofluids in a double tube heat exchanger can be divided into two parts: (i) Heat exchanger with straight tube configuration without any enhancer, e.g., Refs. **(Sarafraz and Hormozi, 2015; Goodarzi et al., 2016; Sarafraz et al., 2016; Jafarimoghaddam et al., 2017; El-Maghlany et al., 2016; Sozen et al., 2016a; Sozen et al., 2016b)** (ii) Heat exchanger with straight tube configuration with an enhancer such as twisted tape, wire coil and louvered strip, e.g., Refs. **(Mohammed et al., 2013; Prasad et al., 2014)**. In most of the studies, the nanofluids have been used in the inner tube.

Goodarzi et al. (2016) examined the convective heat transfer behavior of the nitrogen-doped graphene nanofluids in a double pipe heat exchanger and reported an average heat transfer coefficient increment of 16.2%. The causes for such high heat transfer coefficient are Brownian motion effects, increase in thermal conductivity and effective heat transfer surface area with the addition of nanosheets to water. **Huminic and Huminic (2011)** studied the heat transfer characteristics of water-based CuO and TiO_2 nanofluids in double-tube helical heat exchangers for laminar flow and reported 14% improvement of heat transfer rate for CuO nanofluid of 2% particle volume concentration, and found that heat transfer coefficient of the nanofluids enhances with the increase in mass flow rate and Dean Number. **Wu et al. (2016)** experimentally studied the convective heat transfer characteristic of Al_2O_3/Water nanofluids flowing in a double-tube helically coiled heat exchanger under laminar as well as turbulent flow and reported negligible heat transfer enhancement at constant flow velocity. **Hussein (2017)** experimentally studied the thermal performance of Aluminum Nitride-EG hybrid nanofluid for laminar flow and reported a 35% enhancement of Nusselt number. **Bahmani et al. (2018)** numerically observed the heat transfer behavior of Al_2O_3/Water nanofluid in a double tube heat exchanger and reported maximum Nusselt number enhancements of 31.85% for parallel flow and 32.7% for counter-flow. They reported the following reasons for the enhancement: the Brownian motion of the particles that increases the thermal diffusion and therefore, energy transfer within the fluid, and the existence of nanoparticles in the base fluid, which improve nanofluid thermal conductivity.

Maddah et al. (2014) experimentally observed the heat transfer of alumina nanofluid for turbulent flow condition in a double pipe heat exchanger equipped with modified twisted tape and reported 1.4 to 2.8 times heat transfer rate compared to plain tube depending on geometrical progression ratio. **Prasad et al**. **(2014)** experimentally performed the heat transfer analysis of Al_2O_3/water based nanofluid in a double tube U-bend heat exchanger by inserting a trapezoidal-cut twisted tape and showed 34.2% average Nusselt number enhancement at 0.03% particle concentration. Since, inserted trapezoidal-cut twisted tape generates swirl flow, which offers better fluid mixing and the long flowing path leading to thinner thermal boundary layer over the tube wall and thus enhances convective heat transfer. **Naik et al. (2014)** experimentally found that the performance enhancement of CuO nanofluid with coil insert is more than that with twisted tape. **Akyurek et al. (2018)** conducted an experimental study on heat transfer of Al_2O_3/Water nanofluid in a coaxial double tube heat exchanger with a two-wire coil tarbulator having 25 and 39 mm pitches. They reported that the Nusselt number and h increase 35.67% and 3.58% with a 25 mm wire coil pitch and 19.24 % and 2.24 % with a 39 mm pitch at 1.6 % vol concentration, respectively. **Hosseinian et al. (2018)** experimentally observed the heat transfer of MWCNT/Water nanofluid in a DTHX by imposing vibration and reported 100% heat transfer coefficient enhancement with 9 m/s^2 vibration level. **Khoshvaght-Alabadi et al. (2018)** examined the hydrothermal characteristics of a U-tube heat exchanger inserting spiky twisted tapes using Cu/water, Fe/water and Ag/water nanofluids. They found that Ag/water nanofluid shows the maximum heat transfer coefficient enhancement of about 18.2% as compared to the base fluid. **Kumar et al. (2017)** observed the heat transfer behavior of magnetic Fe_3O_4 nanofluid flowing in double tube U-bend heat exchanger with longitudinal strip inserts and showed the Nusselt number enhancement of 14.7% without inserts and 41.3% with an insert respectively, compared to base fluid without inserts. Inserting a longitudinal strip augments the turbulence, which yields an increased heat transfer coefficient. Irrespective of enhancer used in the double tube heat exchanger, all studies reported the enhancements of the heat transfer coefficient. **Hamid et al. (2019a and 2019b)** numerically as well as experimentally evaluated the hydrothermal performance of TiO_2+SiO_2 nanofluid with wire inserted in a circular tube and reported the heat transfer augmentation up to 254%.

Table 2.3: Heat transfer characteristics of double tube heat exchanger using nanofluids

Investigators	**Particles/ Base fluids**	**Tube layout, Enhancer**	**Important Findings**
Chun et al. (2008)	Alumina/ Transformer oil	Straight	Addition of nanoparticles in the fluid increases the average heat transfer coefficient in laminar flow
Huminic and Huminic (2011)	CuO/Water TiO_2/Water	Coiled	Heat transfer rate of the nanofluid is approximately 14% and 19% greater than of pure water for annulus and inner flow, respectively
Zamzamian et al. (2011)	Al_2O_3/EG CuO/EG	Straight	Heat transfer enhances 26% for 1.0% weight Al_2O_3/EG and 37% for 1.0% weight CuO/EG.
Kumaresan et al. (2012)	MWCNT/water -EG mixture	Straight	Convective heat transfer coefficient is enhanced to a maximum of 160% for 0.45 vol. % MWCNT
Wu et al. (2013)	Al_2O_3 / water	Coiled	Heat transfer enhancement of the nanofluids compared to water is from 0.37% to 3.43%
Darzi et al. (2013)	Al_2O_3/Water	Straight	Heat transfer increases with concentration of nanofluid
Mohammed et al.	Al_2O_3/W,		Louvered strip arrangement can

(2013)	CuO/W, SiO_2/W, ZnO/W	Straight, louvered strip	promote the heat transfer by approximately 350% to 411% by using nanofluids
Kumaresan et al. (2013)	MWCNT/ water–ethylene glycol mixture	Straight	Enhancement in heat transfer coefficient for nanofluid with 0.15 vol.% MWCNT is 92%.
Sonawane et al. (2013)	Al_2O_3/Distilled water	Straight	Heat transfer enhancement over the water is about 16 %
Maddah et al. (2014)	Al_2O_3/water	Straight, twisted tape	Heat transfer increases by 12% to 52% as compared with the tube with typical twisted tapes
Rao and Reddy (2014)	TiO_2/EG-Water	Helical coiled	Heat transfer coefficient enhances by 10.73% for 0.02% volume concentration of nanofluid
Kumar et al. (2014)	Al_2O_3 / water	Helically coiled	Maximum Nusselt number improvement is 56%
Prasad et al. (2014)	Al_2O_3 / water	U-tube, twisted tape	Nusselt number for 0.03% concentrations of nanofluid with trapezoidal-cut twisted tape inserts is enhanced by 34.24%
Sarafraz and Hormozi (2015)	Biological silver–/EG-water	Straight	Addition of nanoparticles at volume fractions 0.1-1% enhances the heat transfer coefficient by 22-67%

Goodarzi et al. (2016)	Graphene-based nanofluids	Straight	The average increase in heat transfer coefficient is 16.2%
Sarafraz et al. (2016)	COOH-CNT/water	Straight	Thermal performance enhancement in comparison with water is up to 44% at maximum concentration of 0.3%
Jafarimoghaddam et al. (2016)	Cu/Oil	Straight	Heat transfer coefficients have a 7.33-17.32% enhancement as compared to the base fluid
El-Maghlany et al. (2016)	Cu/Water	Straight	The NTU is enhanced by 23.4% and the effectiveness by 16.5%
Sozen et al. (2016a) and (2016b)	Fly-ash/Water	Straight	Efficiency improvements of 31.2% and 6.9% are obtained for parallel and cross flows, respectively
Wu et al. (2016)	MWCNT/water	Helically coiled	No heat transfer enhancement based on fixed flow velocity and fixed pumping power
Huminic and Huminic (2016)	CuO/Water TiO_2/Water	Coiled	Entropy generation due to heat transfer decreases with increase in volume fraction, whereas that due to pressure drop is negligible

Kumar et al. (2017)	Fe_3O_4/Water	U-bend, Longitudinal strip inserts	For the 0.06% nanofluid at a Reynolds number of 28954, the Nusselt number enhancement is 14.7% without inserts and 41.29% with an insert
Bahiraei et al. (2017)	Ag/WEG50	Straight	Marginal decrease in entropy generation rate by using nanofluid,
Hussein (2017)	AlN/EG	Straight	The Nusselt number values enhance up to 35%.
Shirvan et al. (2017)	Al_2O_3 nanofluid	Straight	Mean Nusselt number enhanced in the vicinity of 57.70% for the case with Re=50 to 150 and ϕ = 0.03
Bahmani et al. (2018)	Al_2O_3/ water	Straight	For Re=105 and ϕ = 10%, Maximum average Nusselt number enhancement is 31.85% for parallel low and 32.7% for counter flow
Hosseinian et al. (2018)	MWCNT/water	Straight	Heat transfer coefficient enhances 100% for lowest mass fraction (0.04%)with the highest vibration level (9 m/s^2)

Akyurek et al. (2018)	Al_2O_3/ water	Wire-coil turbulator	The addition of wire coil resulted in increased Nusselt Number and the total heat transfer coefficient
Khoshvaght-Aliabadi et al. (2018)	Cu/water Fe/water Ag/water	Agitated U-tube heat exchanger spiky twisted tape	Using spiky twisted tapes leads to an increase in the range of 11%–67% for the heat transfer coefficient
Hamid et al. (2019)	TiO_2-SiO_2	Wire coil inserts	The heat transfer augmentation was up to 254%.
Chaurasia and Sarviya (2020)	CuO/water	Single and double strip helical screw tape	Nusselt number enhances by 182% and 170% for double strip and single strip helical screw tape inserts, respectively, at a twist ratio of 1.5.

2.3.2 Pressure drop characteristics

Research works on the pressure drop characteristic of nanofluids in the double tube heat exchanger are summarized in **Table 2.4**. The pressure drop of nanofluid is generally more than that of base fluid due to an increase in viscosity and nano-fin induced turbulence. **Darzi et al. (2013)** conducted an experimental study on the pressure drop of Al_2O_3 nanofluid in a DTHX and observed higher pressure drop at higher volume concentration. **Sarafraz and Hormozi (2015)** experimentally quantified the pressure drop of biologically produced Ag–EG/water nanofluid in a counter flow DTHX and showed that the friction factor of silver–EG nanofluids is 11.3% higher than that of base fluids due to the presence of Ag nanoparticles inside the base fluid. **Wu et al. (2016)** experimentally examined the pressure drop characteristic of aqueous MWCNT nanofluids inside the double-tube helically coiled heat exchanger. Their results exhibited that the apparent friction factor for the 0.1 wt% nanofluid is the highest among the studied fluids mainly because of viscosity increase. For the turbulent flow, the apparent friction factor increases with an increase in weight fraction. **Raei et al. (2017)** experimentally studied the pressure drop behavior of Al_2O_3/water nanofluid in the double-tube heat exchanger and found that the friction factor is about 25 % higher than that of pure water at the particle volume fraction of 0.15 vol%. It was observed that the friction factor increases with an increase in the volume concentration at low Reynolds number. This is due to the fact that the ratio of the viscous force to the inertia force is higher; therefore, adding nanoparticles to the base fluid leads to an increase in shear stress and hence increases the friction factor. In-overall, contradictory conclusions are found in the literature related to the increase in heat transfer and pumping power by using nanofluids. Some authors concluded that the nanofluid sustains with a low penalty of pumping power and could be suitable for practical application **(El-Maghlany et al., 2016)**, whereas some authors concluded negligible heat transfer augmentation for the fixed fluid velocity or pumping power.

Table 2.4: Summary of the pressure drop for double pipe heat exchanger

References	Particles/Base fluid	Important Finding
Darzi et al. (2013)	Al_2O_3/Water	The pressure drop increases by increasing the concentration of nanoparticles due to the rise of the viscosity of working fluid
Kumar et al. (2014)	Al_2O_3/Water	The pressure drop of 0.1%, 0.4% and 0.8% are found to be 4%, 6%, and 9%, respectively higher than water.

Sarafraz and Hormozi (2015)	Biological silver–EG/Water	The values of friction factors related to silver–EG nanofluids (at vol.% = 1) are 11.3% higher than that of base fluid
Goodarzi et al. (2016)	Graphene-based nanofluids	Increase of pressure drop using nanofluids is found significant on for high Reynolds number
Sarafraz et al. (2016)	CNT/water	Increased the friction factor and pressure drop up to 9% and 11% respectively for 0.3 wt.%
El-Maghlany et al. (2016)	Cu/Water	The pressure drop of the nanofluid is around 36% as those of water in the given conditions
Wu et al. (2016)	MWCNT/DI Water	The apparent friction factor for the 0.1 wt% nanofluid is the largest among the four fluids mainly due to its 25% increase in viscosity
Hussein (2017)	AlN/EG	The friction factor values increased to 12.5%.
Raei et al. (2017)	γ-Al_2O_3/water nanofluid	Maximum friction factor was about 25 % greater than that of pure water which was occurred at the highest volume fraction of nanofluid (0.15 vol%)
Baba et al. (2018)	Fe_3O_4/water	Pressure drop is more in finned tube heat exchanger compared to the plain tube heat exchanger due to the resistance offered by fin geometry.
Dalkilic et al. (2019)	Graphite-SiO_2	Pressure drop increases with increasing Reynolds number and it is always larger for higher concentrations and longer tape inserts expectedly.

2.3.3 Energy Performance

Kumar et al. (2017) experimentally studied the effectiveness of Fe_3O_4 nanofluid in DTHX with return bend and showed that the number of transfer units is enhanced from 0.429 to 0.469 and the effectiveness varied from 0.293 to 0.339 for 0.06% nanofluid at Reynolds number ranging from 16554 to 28970. Optimum flow velocity has to be maintained to minimize the total cost of double tube heat exchanger operation, which is dependent on the nanofluids used **(Dalkilic et al. 2017)**. **Huminic and Huminic (2016)** reported the decrease of entropy generation by using nanofluids in the coiled double tube heat exchanger. **Bahiraei et al. (2017)** numerically investigated the entropy generation rate considering heterogeneous particle distribution in a mini double tube heat exchanger using biological silver nanofluid as the coolant in the tube side and reported that at high concentration and Reynolds number, particle migration disturbs the particle distribution and alters the thermophysical properties, which subsequently affect the entropy generation. The influence of friction on the entropy generation of nanofluid was found greater than that of heat transfer.

2.4 Nanofluids in Shell-Tube Heat Exchangers

2.4.1. Heat transfer characteristics

Experimental and numerical studies on heat transfer characteristics of nanofluids in Shell-Tube Heat Exchanger (STHX) are summarized in **Table 2.5**. **Shahrul et al. (2014)** theoretically investigated the thermal performance of STHX using ZnO/Water, CuO/Water, Fe_3O_4/Water, TiO_2/Water and Al_2O_3/Water nanofluids at 0.03 volumetric fraction and found highest heat transfer coefficient for Al_2O_3/Water nanofluid and the lowest for CuO/Water nanofluid. The thermal conductivity of Al_2O_3 is lower than that of Fe_3O_4 and ZnO, but the specific heat of Al_2O_3 is higher than that of Fe_3O_4 and ZnO. That is why the Al_2O_3/Water has the highest heat transfer coefficient than the other nanofluids. However, the highest enhancement in the energy effectiveness of 43% was observed for ZnO/Water nanofluid and minimum enhancement of 31% was observed for Al_2O_3/Water nanofluid because energy effectiveness greatly depends on the specific heat of the nanofluids. **Ghozatloo et al. (2014)** experimentally studied the convective heat transfer behavior of graphene nanofluids flowing in the STHX under laminar flow and reported a 35.6% improvement in convective heat transfer coefficient as compared with pure water. **Farajollahi et al. (2010)** experimentally studied the heat transfer behavior of water-based γ-Al_2O_3 and TiO_2 nanofluids in a STHX for turbulent flow condition and reported higher heat transfer coefficient for TiO_2/Water nanofluid at optimum concentration, while better heat transfer behavior for γ-Al_2O_3/Water nanofluid at higher concentration. The main source of this difference might be a clash of thermal conductivity and the size of nanoparticles for heat transfer performances. **Lotfi et al. (2012)** experimentally studied the heat transfer behavior of water-based MWCNT nanofluid in a horizontal STHX and reported comparatively less improvement of heat transfer coefficient (about 7%). **Kumar and Sonawane (2016)** experimentally studied the heat transfer behavior of Fe_2O_3/Water and Fe_2O_3/EG in STHX and showed that the enhancements of both convective heat transfer coefficient and Nusselt number increase with the increase in nanoparticle volume concentration for given flow rate. **Kumar et al. (2018)** experimentally examined the heat transfer enhancement of water, EG and paraffin-based Al_2O_3 nanofluids in the shell and tube heat exchanger for the laminar and turbulent flows and found the maximum enhancement of heat transfer coefficient of 28%, 26% and 25%, for Al_2O_3/Water, Al_2O_3/EG and Al_2O_3/paraffin, respectively. **Said et al. (2019)** investigated the performance of shell and tube heat exchanger using CuO/water nanofluids of volume concentration ranging from 0.05% to 0.3%. The result highlighted that the overall heat transfer coefficient and convective heat transfer increase by 7% and 11.39%, respectively. In addition, the possible reduction in the area of shell and tube heat exchanger of 6.81% was observed.

Barzegarian et al. (2017) experimentally studied the effect on the thermal performance of STHX with segmental baffles using Al_2O_3/Water nanofluid and reported the overall heat transfer coefficient enhancement up to 19.1%. Due to some desirable reasons, i.e., the higher thermal conductivity of nanofluid, reduction of boundary layer thickness and nanoparticle Brownian motion, this enhancement may occur. **Haque et al. (2018)** experimentally studied the heat transfer performance of aqueous Al_2O_3 nanofluids in a vertical shell and tube heat exchanger under laminar flow regime showed that the heat transfer coefficient increases significantly (up to 49%) with an increase in concentration. **Naik and Vinod (2018)** carried out the experimental investigation to determine the heat transfer using aqueous carboxymethyl cellulose (CMC) based Fe_2O_3, Al_2O_3 and CuO nanofluids in a helical coil and shell heat exchanger and showed that the CuO/CMC based nanofluid offers better heat transfer than the other types of nanofluids (Fe_2O_3/CMC and Al_2O_3/CMC). Also, it was found that the overall heat transfer coefficient enhanced 26% and 29%, respectively for Al_2O_3/CMC and CuO/CMC nanofluids as CuO nanoparticles have higher thermal conductivity than Al_2O_3 nanoparticles.

Aghabozorg et al. (2016) experimentally investigated the convective heat transfer enhancement of Fe_2O_3-CNT/water nanofluids in laminar, transient and turbulent flows in shell and tube heat exchanger and found more heat transfer coefficient as compared to the base fluid. They reported the heat transfer coefficient improvements of 13.54% and 27.69% at 0.1% concentration and 34.02% and 37.50% at 0.2% concentration under laminar and turbulent flows, respectively. The highest heat transfer coefficient occurs in the turbulent flow regime because of the fact that the thermal boundary layer absorbs the magnetism particles and creates turbulence, which leads to an increase in the heat transfer coefficient.

Table 2.5: Studies on heat transfer characteristics for shell and tube heat exchanger

Investigators	Particles/base fluids	Important findings
Farajollahi et al. (2010)	Al_2O_3/Water, TiO_2/water	Heat transfer characteristics of TiO_2/water at its optimum nanoparticle concentration are greater than those of Al_2O_3/water
Lotfi et al. (2012)	MWNT/Water	About 6.7% improvement of overall heat transfer coefficient was observed for 0.015% weight concentration
Leong et al. (2012)	Cu/EG-Water	Heat transfer enhances about 7.8% and 4.5% for EG and water, respectively, based nanofluids containing 1% nanoparticles
Raja et al. (2012)	Al_2O_3/Water	Overall heat transfer coefficient increased by 12.6-25% when the particle volume concentrations varied from 0.5 to 1.5%
Akhtari et al. (2013)	γ-Al_2O_3/Water	Heat transfer performance of 0.5% and 0.2% nanofluid are 26.2% and 17.1% higher than the double pipe heat exchanger.
Albadr et al. (2013)	Al_2O_3/Water	Overall heat transfer coefficient of nanofluid is 57% greater than that of distilled water at the particle volume concentration of 2%.
Elias et al. (2013)	Boehmite alumina (γ-AlOOH)/EG-Water	Highest heat transfer coefficient was obtained for cylindrical shape whereas the lowest heat transfer coefficient for platelet shape of nanoparticles

Anoop et al. (2013)	SiO_2/Water	2% and 4% nanofluids show higher heat transfer enhancement than 6% nanofluids.
Shahrul et al. (2014)	ZnO, CuO, Fe_3O_4, TiO_2, and Al_2O_3/Water	Effectiveness improvement was maximum (43%) for ZnO nanofluid and minimum (31%) for Al_2O_3 nanofluid at 0.03 volumetric fraction.
Ghozatloo et al. (2014)	Graphene/Water	Convective heat transfer coefficient of graphene nanofluids enhanced up to 35.6% at 0.1 wt% concentration compared with pure water.
Godson et al. (2014)	Ag/Water	The percentage increase in heat transfer coefficient of 0.01%, 0.03% and 0.04% are respectively 9.2%, 10.87% and 12.4%.
Salem et al. (2015)	γ-Al_2O_3/Water	When $\emptyset$ increases from 0% to 2%, the average increase in Nusselt Number is 59.4–81% at studied Reynolds number range.
Dharmalingam et al. (2015)	Al_2O_3/Water	Up to 17% overall heat transfer coefficient improvement was reported
Aghabozorg et al. (2016)	Fe_2O_3-CNT/Water	Heat transfer coefficient enhanced 34.02% and 37.50% for laminar flow and turbulent flow, respectively, at 0.2% weight concentration in comparison with distilled water.
Shahrul et al.	ZnO, CuO, Fe_3O_4,	Energy effectiveness enhances about 27.9–

(2016a) and (2016b)	TiO_2, Al_2O_3 and SiO_2 /Water	51.7, 26.80–47.22, 25.31–41.22, 24.34–37.39, 23.78–35.07 and 22.25–29.02 % for ZnO. CuO, Fe_3O_4, TiO_2, Al_2O_3 and SiO_2 nanofluids, respectively
Srinivas and Vinod (2016)	Al_2O_3/Water, CuO/Water, TiO_2/Water	For CuO/water nanofluid the heat transfer rate increased maximum by 32.7% when compared to base fluid
Kumar and Sonawane (2016)	Fe_2O_3/Water Fe_2O_3/EG	Maximum convective heat transfer coefficient enhancements were 20% and 13% for Fe_2O_3/water and Fe_2O_3/EG nanofluids, respectively
Hosseini et al. (2016)	CNT/Water	Overall heat transfer coefficient and heat transfer rate increased by about 14.5% and 10.3% respectively, compared to water
Barzegarian et al. (2017)	Al_2O_3- gamma/Water	Heat transfer coefficient enhanced around 5.4, 10.3 and 19.1%, respectively at 0.03, 0.14 and 0.3 vol%, respectively.
Tan et al. (2017)	MWCNT/DI Water	The heat transfer coefficient augmented by 24.3, 13.2 and 4.7% at 1.0, 0.5 and 0.2 wt%, respectively.
Nallusamy and Prabu (2017)	Al_2O_3 /Water	The average increase in Nu of nanofluid was about 10% in parallel-flow heat exchanger and was about 6.5% in counter-flow heat exchanger with same pipe length and diameter.

Ling (2017)	MWCNTs/Xanthan Gum (XG)	For 0.2, 0.5 and 1.0 wt % MWCNTs, Nusselt number, increases by about 11%, 21% and 35%, respectively, at the same Reynolds number compared with that of base fluid
Haque et al. (2018)	Al_2O_3 /DI Water	For 1 wt% and 2 wt%, heat transfer coefficient increases by 25.70% and 49.04%, respectively, as compared to that of DI Water
Naik and Vinod (2018)	Fe_2O_3/aqueous carboxymethyl cellulose (CMC), Al_2O_3/(CMC), CuO/(CMC)	CuO/CMC nanofluid shows better heat transfer than the other fluids. Enhancements in overall heat transfer coefficient for 1.0 wt% Al_2O_3 and CuO nanofluids are 26 and 29%, respectively
Kumar et al. (2018)	Al_2O_3/water Al_2O_3/ EG Al_2O_3/ paraffin	Maximum enhancement of convective heat transfer coefficient of Al_2O_3-water, Al_2O_3/ EG and Al_2O_3/ paraffin nanofluids at 5lpm and 0.8% vol% is 28%, 26% and 25%, respectively.
Said et al. (2019)	CuO/water	Overall heat transfer coefficient enhanced by 7%, convective heat transfer increased by 11.39%
Fares et al. (2020)	Graphene/water	A maximum increase in the heat transfer coefficient of 29% is achieved.

2.4.2. Pressure drop characteristics

Investigations related to the pressure drop characteristics of nanofluids in STHX are summarized in **Table 2.6**. **Godson et al. (2014)** investigated the pressure drop characteristics of Ag/water nanofluids in STHX and observed a 16.2% increase in pressure drop compared with that of water. **Anoop et al. (2013)** also found that the pressure drop enhances more than 10% for SiO_2/water nanofluids in industrial type heat exchangers as compared to water. This can be attributed to the fact that the viscosity, as well as wall roughness, increases by adding nanoparticles. Most of the studies showed much less increase in pressure drop by using nanofluids. It is widely accepted that both heat transfer and pressure drop increase by using nanofluids. The heat transfer rate to pumping power ratio (performance index) and heat transfer coefficient to pressure drop ratio have been used to judge whether the use of nanofluids in heat exchange devices are favorable or not.

Table 2.6: Summary of the pressure drop for shell and tube Heat exchanger

Investigators	**Particles/base fluids**	**Findings**
Albadr et al. (2013)	Al_2O_3/Water	Friction factor increases with the increase in particle volume concentration. The nanofluid suffer little penalty in pressure drop
Anoop et al. (2013)	SiO_2/water	Pressure drop increases more than 10% for nanofluids compared to that of pure water
Godson et al. (2014)	Ag/Water	The percentage increase in pressure drop for 0.04% concentration was 16.22% for Re=25,000 when compared with that of pure water
Shahrul et al. (2016)	ZnO, Al_2O_3 and SiO_2 /Water	Pressure drop increased 9% for ZnO–Water and 6.48% for SiO_2–Water

Tan et al., (2017)	MWCNT/DI Water	Pressure drop of nanofluids with 0.2, 0.5, and 1.0 wt% of MWCNTs increased 9.5, 44.2, and 52.0% as compared to that of the base fluid.

2.4.3 Energy Performance

Researchers showed that the heat transfer rate, effectiveness and performance index of STHX increase by using nanofluids with the negligible increase in pumping power. **Shahrul et al. (2014)** concluded that the energy effectiveness of the STHX could be increased by using metal oxide nanofluids. This is due to the fact that the increase in the heat transfer coefficient decreases the temperature difference. **Elshazly et al. (2017)** showed that the thermal performance index increases with an increase in nanoparticle concentration, coil torsion and flow rate for shell- helically coiled tube heat exchanger. **Esfahani et al. (2017)** experimentally measured the exergy performance of STHX using graphene oxide nanofluid and found that under laminar flow condition, the exergy loss of distilled water is about 22% at 0.01 wt. % and 109% at 0.1 wt. %, respectively, greater as compared to graphene oxide nanofluids. **Singh and Sarkar (2018)** investigated numerically the exergy performance of shell and tube condenser using four different hybrid nanofluids as coolant ranging from 0-1% vol concentration. The results revealed that among four hybrid nanofluids (Al_2O_3+MWCNT, Al_2O_3+Cu, Al_2O_3+Ag, Al_2O_3+TiO_2), Al_2O_3+Ag hybrid nanofluid showed maximum second law efficiency of 29.97% and minimum irreversibility at 1% vol concentration.

2.5 Energy Applications

Studies on tubular (double tube and shell and tube) heat exchangers using nanofluids have been done for many engineering applications such as power plants, refrigeration and air conditioning, renewable energy, domestic cooling or heating, etc. **Tora et al. (2013)** studied the performance of a Rankine power cycle condenser using Al_2O_3-water nanofluid as a cooling agent at various volumetric concentrations. The results showed that the area of the heat exchanger decreases linearly with nanoparticles volumetric concentration at concentrations of 0.1% and onward. It was found that approximately 4% area reduction is attained at 5vol.% nanoparticle concentration. Pumping power was increased linearly with nanoparticle concentration and up to 14% at 5vol.%. In power plants, the cooling tower, a specialized heat and mass exchanger, is used to release waste heat and nanofluids can be used for performance improvement. **Askari et al. (2016)** experimentally investigated the thermal performance of a mechanical counter flow wet cooling tower by using MWCNTs and graphene nanofluids and found the thermal conductivity enhancements by 20% and 16%, respectively, compared to the base fluid. It was also observed that the efficiency, cooling range and tower characteristic are enhanced by using nanofluids in the cooling tower as compared to the base fluid.

Sarkar (2011) modeled and simulated the shell-tube type gas cooler of a CO_2 refrigeration system using water-based Al_2O_3, TiO_2, CuO and Cu nanofluids as a coolant. It was observed that the maximum cooling COP improvement of the CO_2 system for Al_2O_3/Water is 26.0%, whereas that for TiO_2/Water, CuO/Water and Cu/Water are 24.4%, 20.7% and 16.5%, respectively, for studied ranges. **Sarkar (2013 and 2015)** has also observed the improvements in effectiveness and cooling capacity for double tube gas cooler with a negligible change of pumping power. **Kolhapure and Patil (2016)** experimentally investigated the refrigeration system performance using Al_2O_3/H_2O nanofluids as a cooling medium and found maximum percentage increase in the amount of heat absorbed in the condenser by 37.4% and actual coefficient of performance of the refrigeration system by 87% at the nanoparticle concentration of 0.3%. **Vasconcelos et al. (2017)** reported enhanced cooling capacity and system performance by using water-based CNT nanofluids in the tubular evaporator of the refrigeration system.

Hamdeh and Almitani (2016) constructed and tested a solar regeneration desiccant evaporative cooling system using various oxide nanofluids. They showed that the convective heat transfer coefficient enhances by 7.20–14.40%, 6.20–12.30%, and 5.50–9.01% for Al_2O_3/Water, Fe_3O_4/Water, and ZnO/Water nanofluids, respectively. **Lu et al. (2011)** experimentally investigated the thermal performance of evacuated tube solar collector with a natural circulation loop using water and CuO/water nanofluids and found maximum enhancement of heat transfer at 1.2% nanoparticle concentration. **Boyaghchi et al. (2015)** analyzed the combined solar and geothermal CCHP-ORC system with an ejector refrigeration cycle and water-based CuO nanofluid was used in the solar collector subsystem. It has been found that using the CuO/water nanofluid increases the daily thermal efficiency and daily exergy efficiency as compared to water and decreases total production cost. **Sui et al. (2017)** studied the potential of utilizing nanofluids as a working fluid that extracts more geothermal energy compared to conventional fluid and improves the exploitation of the geothermal resources. They demonstrated the importance of viscosity, specific heat capacity as well as the fluid mass flow rate in the geothermal well production. **Beydokhti and Heris (2012)** experimentally examined the use of CuO and Al_2O_3 nanofluids as heat transfer fluid in a CHP system to enhance the performance and showed that the thermal efficiency of the unit increases by about 17% and 11% using CuO and Al_2O_3 nanofluids, respectively. **Bozorgan (2016)** studied the helical coil heat recovery exchanger numerically using γ- Al_2O_3/ n-decane nanofluid (particle size of 20 nm) with volume concentrations up to 7% in a biomass heating plant under turbulent flow conditions. The hot n-hexane flows through the shell and the nanofluid flow through the tubes. The results showed that using γ- Al_2O_3/ n-decane nanofluid as a coolant in the heat exchanger can reduce the total heat transfer area and length of the helical coil, which leads to reducing the manufacturing cost of the heat exchanger.

Hosseini et al. (2016) utilized CNT/water nanofluid as a coolant in a shell-tube-type intercooler of LPG absorber tower and reported the overall heat transfer coefficient enhancement by about 14.5% and heat transfer rate by about 10.3%, respectively as compared to the base fluid. **Huang et al. (2016)** used water-based graphene nanoparticles and carbon nanotubes nanofluids for engine heat recovery and showed 4% increase in net power production. In the field of thermal processing of liquid food products, the tubular heat exchanger can be utilized. **Jafari et al. (2018)** designed a STHX using alumina nanofluids through the Kern method for food applications. They observed that by using 2% nanofluid as a heating medium, about 47% reduction in energy consumption for the liquid food product processing is achieved.

2.6 Research Gaps

From the above literature survey, it has been observed that different types of mono/hybrid nanofluids have been prepared by mixing of different nanoparticles comprising different oxides and metals of different shapes in a base fluid using one-step and two-step methods. Prepared nanofluids have been characterized and various thermophysical properties were measured based on which some correlations were also proposed to predict the properties of nanofluids. Experimental and theoretical investigations with nanofluids in the double pipe heat exchangers with/without enhancer and shell and tube heat exchanger to enhance their performance are reviewed extensively. Studies on various energy applications of tubular heat exchanger using nanofluids are reviewed as well.

From the above literature survey, following research gaps have been observed:

1. No work has been performed on hybrid nanofluid flow in the tubular heat exchanger with modified twisted tape inserts.
2. The experimental study on hybrid nanofluid in a double pipe heat exchanger equipped with a modified wire coil is not reported in earlier works.

3. No study is available on tubular heat exchanger with inserts for PCM dispersed mono/ hybrid nanofluids.
4. No literature is available on the effects of various geometric parameters of modified twisted tape and wire coil on the heat transfer and friction factor characteristics.
5. Studies on the shell and tube heat exchanger using hybrid nanofluid are very limited.
6. No economic study has been performed on the existing industrial heat exchanger with hybrid nanofluids to check the replacement feasibility

2.7 Objectives of the present study

In order to fulfill the research gaps, the main objectives of the present study are given as:

1. Preparation and characterization of different hybrid nanofluids.
2. Measurement of thermophysical properties of different hybrid nanofluids.
3. Experimental investigation on hydrothermal characteristics of the double pipe heat exchanger with V-cut twisted tapes inserts and different mono/hybrid nanofluids for various geometric and operating conditions.
4. Experimental investigation of heat transfer and pressure drop characteristics in a double pipe heat exchanger with different mono/hybrid nanofluids and modified coil turbulator inserts (i) Convergent type, (ii) Divergent type and (iii) Convergent-Divergent type.
5. Experimental investigation on hydrothermal characteristics of shell and tube heat exchanger with different mono/hybrid nanofluids for various operating conditions.
6. Case study: Energy, exergy and economic feasibility study of existing power plant shell and tube condenser using hybrid nanofluids.