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Thermohydraulic behavior of concentric tube heat exchanger inserted with conical wire coil using mono/hybrid nanofluids

Sumit Kumar Singh, Jahar Sarkar *

Department of Mechanical Engineering, Indian Institute of Technology (B.H.U.), Varanasi, UP-221005, India

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ABSTRACT

The experimental studies with a new type of enhancer, conical wire coil insertion in the concentric tube heat exchanger using water-based mono (Al_2O_3 and CNT) and hybrid (Al_2O_3 + CNT) nanofluids, flowing in the inner tube, are conducted to examine the effect on thermohydraulic performance. The thermohydraulic performances are studied with various conical wire coil configurations (converging, diverging and converging-diverging coils). The outcomes indicate that the diverging wire coil insert exhibits better thermohydraulic performance as compared to other wire coil arrangements. In comparison to DI water in the plain tube (without insert), the maximum Nusselt number enhancements for diverging, converging-diverging and converging wire coil inserts are 171%, 152% and 139%, respectively. Similarly, the friction factor is increased up to 106%, 92% and 72%, respectively, for diverging, converging-diverging and converging wire coil inserts. In all conditions, it is found that the entropy generation of DI water is higher than that of mono/hybrid nanofluids. The thermal performance factor is observed more than one with all mono/hybrid nanofluids and wire coil inserts, indicating a promising combination.

1. Introduction

For in-tube flow, the augmentation of heat transfer can be attained by using turbulent enhancers inserted inside the tube and numerous investigators studied the heat transfer augmentation of heat exchanger using various inserts, such as twisted tapes and helical coil [1]. Twisted tape inserts provide superior heat transfer enhancement than wire coil inserts; however, in the situation where pressure drop is a crucial constraint, wire coil inserts may become more effective due to less pressure drop penalty [2]. Many investigations on twisted tape insert are available in the literature using both mono nanofluids [3,4] and hybrid nanofluids [5]. The helical coil acts as a turbulence promoter, which increases turbulence flow intensity. Also, when helical coils are in interaction with the tube wall, they act as roughness elements and disrupt the boundary layer [6]. In the past decade, numerous experiments were accomplished to examine the thermohydraulic characteristics of water using helical coil inserts in a heat exchanger. Eren et al. [7] investigated the heat transfer by inserting a coil in a concentric tube. Eiamsa-ard et al. [8] experimented by periodically varying coil pitch ratio. Zohir et al. [9] studied heat transfer by inserting coils of different pitches in a double pipe heat exchanger. Panahi and Zamzamian [10] studied the heat transfer of shell-coil heat transfer by inserting wire coil. Khorasani et al. [11] studied the effect of spiral wire coil geometry on thermal performance.

Nowadays, the mono/hybrid nanofluid has been recently emerged as an advanced working fluid to improve the performance due to its enhanced thermophysical properties and slip mechanisms [12,13]. Hence, in view of the increasing demand for energy density, the use of both helical coil inserts and nanofluids can be a good combination to enhance the thermohydraulic characteristics of the tubular heat exchanger and several experiments have been performed in the last decade [14]. Related studies are summarized in Table 1. Chougule et al. [15] executed an experiment to study the thermohydraulic performance of CNT/water nanofluid in the tube with coil insert under laminar flow and stated that the Nusselt number augmentation up to 30.63%. Goudarzi and Jamali [16] experimented Al_2O_3/EG nanofluid under turbulent flow in car radiator using helical coil inserts and showed that Nusselt number and friction factor increases up to 13% and 47.5%, respectively. Naik et al. [17] used both twisted tape insert and coil insert and observed that helical coil inserts provide better heat transfer performance. Reddy and Rao [18] examined the heat transfer performance

Abbreviations: C, Convergence; C-D, Convergence-Divergence; CNT, Carbon Nanotube; D, Divergence; TPF, Thermal Performance Factor; SEM, Scanning Electron Microscope.

* Corresponding author.
E-mail address: jsarkar.mec@itbhu.ac.in (J. Sarkar).

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Nomenclatures

c_p	Specific heat capacity [J.kg^{-1}.K^{-1}]
d	Diameter [m]
D	Coil diameter [m]
f	Friction factor [−]
k	Thermal conductivity [W·K^{-1}.m^{-1}]
m	Mass flow rate [kg.s^{-1}]
Nu	Nusselt number [−]
P	Pitch of the coil [mm]
Pr	Prandtl number [−]
Q	Heat transfer rate [W]
Re	Reynolds number [−]
S	Entropy [W·K^{-1}]
T	Temperature [K]
Θ	Temperature difference [K]
ϕ	Particle volume concentration [%]
μ	Dynamic viscosity [Pa.s]
ρ	Density [kg.m^{-3}]

Subscripts

bf	Base fluid
c	Cold fluid (water)
f	Friction
gen	Generation
h,nf	Hot fluid, mono/hybrid nanofluid
ht	Heat transfer
i,o	Inner/outer
in,out	Inlet and outlet
np	Nanoparticle
it,ot	Inner tube, outer tube

Table 1
Summary of experimental studies using nanofluids and helical wire coil.

Investigators	Nanofluid	Coil geometry	Important Findings
Chougule et al. [15]	CNT/ Water	D = 4 mm, P/D = 2, 3	*Nu* augmentation up to 30.63%
Goudarzi and Jamali [16]	Al_2O_3/EG	D = 0.3 mm, Pitch = 11.7 and 6 mm	*Nu* and friction factor increase up to 13% and 47.5%, respectively
Naik et al. [17]	CuO/Water	P/D = 1.97 and 2.95	Nusselt number enhancement for 0.3% nanofluid with wire coil is 44.45%.
Rao and Reddy [18]	TiO_2/EG-Water	D = 2 mm, P/D = 1 and 2.5	Heat transfer coefficient enhances by 10.73% for 0.02% nanofluid
Akhavan-Behabadi et al. [19,20]	MWCNT / water	D = 8.82 mm, Pitch = 15, 20 and 25 mm	Heat transfer enhanced 85% and the thermal performance factor was found greater than one.
Mirzaei and Azimi [21]	Graphene oxide/Water	NA	Heat transfer enhances by adding nanoparticles
Sundar et al. [22]	Fe_3O_4/ Water	D = 14 mm, Pitch = 1, 1.34 and 1.79 mm	Nusselt number enhanced to 32.03% for 0.06% nanofluid with a wire coil of P/D = 1.
Akyurek et al. [23]	Al_2O_3/ Water	D = 12 mm, Pitch = 25 and 39 mm	Nur and heat transfer coefficient increase with decrease in coil pitch.

of the double tube heat exchanger and found a heat transfer improvement of 13.85%. Akhavan-Behabadi et al. [19,20] found 85% heat transfer enhancement with wire coil insert in a tube using multi-walled CNT (MWCNT) nanofluid and the thermal performance factor was found greater than one. Mirzaei and Azimi [21] experimentally studied the thermohydraulic characteristics with helical wire coil inserts using graphene oxide nanofluids and found 77% heat transfer coefficient augmentation. Sundar et al. [22] observed the heat transfer of Fe_2O_3 nanofluid in the tube bend equipped with coil insert and reported 32% Nusselt number enhancement. Akyurek et al. [23] did an experiment to investigate the heat transfer of Al_2O_3/water nanofluid with two wire-coil turbulators of different pitches. They found that the Nusselt number and heat transfer coefficient increase with a decrease in wire coil pitch.

However, the research work on the heat transfer improvement of the concentric tube heat exchanger with non-helical coil insertions using hybrid nanofluids is very rare. Sumit and Sarkar [24] used Al_2O_3 + MgO hybrid nanofluid as a hot fluid in a double pipe heat exchanger with tapered wire coil inserts and found that the heat transfer enhancement up to 84%. Karakaya and Durmus [25] used several discrete conical wire coil inserts in a tube and examined the thermal characteristics of air. However, as far as the authors know, none of the studies available with modified wire coil insertion using CNT dispersed mono/hybrid nanofluids as a coolant (cold fluid).

Hence, the present experimental study explores the improvement of thermohydraulic characteristics of the concentric tube heat exchanger with three proposed modified wire coil insertions, i.e., converging (C), diverging (D) and converging-diverging (C-D) coils as turbulator using water-based Al_2O_3 and CNT nanofluids, and Al_2O_3 + CNT hybrid nanofluids. The experiments were performed for different wire coil arrangements and nanofluid flow rates to study their effects on heat transfer and pressure drop behaviors. In addition, the impact of the conical coil on the heat transfer coefficient to pressure drop ratio (h/Δp) and the total entropy generation is also presented.

2. Experimental facility

2.1. Preparation of nanofluids and their properties

Both mono and hybrid nanofluids were synthesized by adding Al_2O_3 and CNT nanoparticles (chosen due to their low cost, easy availability and considerable thermal conductivity values) with equal volume ratio in base fluid (DI water) for 0.01% total volume concentration. After dispersing nanoparticles in DI water, it was sonicated for 3 h using an ultrasonic vibration bath to avoid the sedimentation of the nanoparticles. Fig. 1 displays SEM of Al_2O_3 + CNT hybrid nanofluid and found that the Al_2O_3 nanoparticles are in a spherical shape with particle size ranging between 10 and 100 nm and CNT particles are in a cylindrical shape. The visual observation of hybrid nanofluid was done to examine the stability, as shown in Fig. 2 and found that the hybrid nanofluid had sufficient stability (upto 10 days). Thermal conductivity and specific heat capacity were measured with Hot disk TPS 500 analyzer and viscosity was measured with Brookfield digital viscometer. Density was estimated by measuring the mass of a certain volume using high precision digital weighing balance. Moreover, obtained viscosity and thermal conductivity were compared with the models proposed by Sahu and Sarkar [26] and found good agreement. Table 2 shows the thermophysical properties DI water, Al_2O_3 nanofluid, CNT nanofluid and Al_2O_3 + CNT hybrid nanofluid, which have been measured at a mean temperature of 45 °C by considering the actual range (hot and cold fluid inlet temperatures of 60 °C and 30 °C, respectively).

2.2. Test setup and experimental procedure

The experiments were carried out in an experimental setup, which is schematically shown in Fig. 3. It contains the concentric tube heat

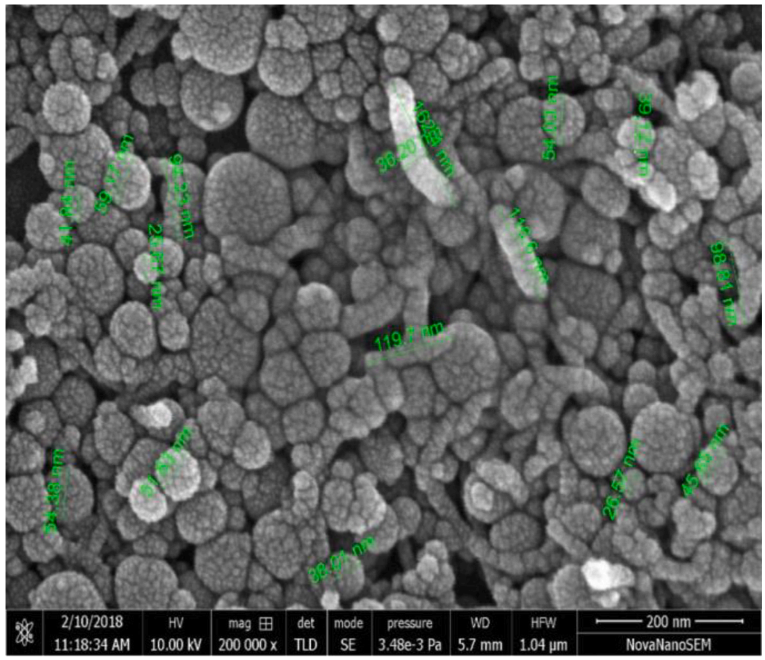

Fig. 1. SEM image of Al_2O_3 + CNT hybrid nanofluid.

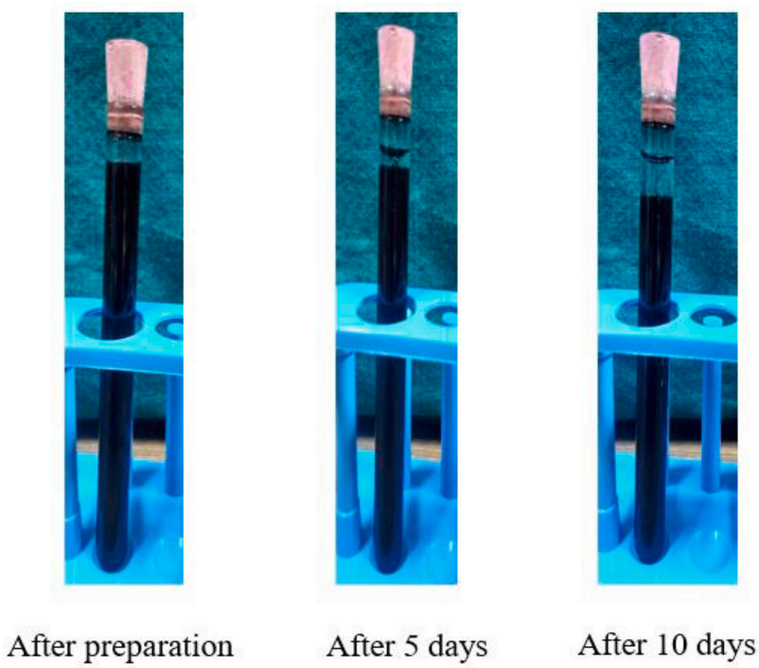

Fig. 2. Sedimentation observation of hybrid nanofluid.

exchanger, temperature-controlled heating tank with immersion heater, a cooling unit (chiller) with a temperature controller, having a cooling capacity of 4 kW, two flow meters, two magnetic drive pumps and a U-tube manometer. The concentric tube heat exchanger is made of double circular galvanized iron tubes (inner and outer tube). The inner tube has internal and external diameters of 20 and 24 mm, respectively, while the outer tube has an internal diameter of 47 mm and the length of the tube is 570 mm. Since the length-to-diameter ratio is 28, the entrance effect was considered and the Nusselt correlation [27] for the developing flow was used for validation. Mono/hybrid nanofluid was circulated through the inner tube and hot fluids through the outer tube with the help of pumps in the opposite direction. Table 3 presents the specifications and operating conditions of the concentric tube heat exchanger and designs of conical wire coils. The asbestos rope was wrapped over the annulus tube to diminish the heat losses to the external ambient. The calibrated PT-100 sensors were used for measuring the temperatures of both fluids. Two flow meters were fitted with control valves to determine the flow rates of the streams. Pressure drop was evaluated by using U-tube manometers inserted between the inlet and outlet of the tubes because of its simplicity and reliability in the operating conditions of the present study. A glass U-tube was fixed against a vertical scale board of length 30 cm and mercury was used as the manometric liquid. The inlet

Table 2
Thermophysical properties at mean temperature of 45 °C.

Materials	Thermal conductivity (W/m. K)	Density (kg/m^3)	Specific heat (J/kg.K)	Viscosity (Pa.s)
Water	0.6244	990.2	4182	0.0005963
Al_2O_3 particle	40	3900	880	–
CNT particle	3000	2660	740	–
Al_2O_3/water	0.6246	990.5	4180	0.0005965
CNT/water	0.6248	990.4	4181	0.0005971
Al_2O_3 + CNT/water	0.6247	990.4	4181	0.0005968

temperature of mono/hybrid nanofluid was maintained at 30 °C and the mass flow rate was varied from 0.08 to 0.42 kg/s (mean velocity of flow ranging from 0.34 to 1.67 m/s). The hot fluid was maintained at a uniform temperature of 60 °C with a constant mass flow rate of 0.25 kg/s. All the parameters, such as temperatures and pressure drops, were recorded after reaching the steady-state in every test run. All the wire coils were made of aluminum wire, having a diameter of 0.5 mm. Total three wire coil topologies were used in the experimentation: (i) convergence type (C), (ii) divergence type (D) and (iii) convergence-divergence type (C-D), as shown in Fig. 4. For all the conical wire coils, the largest diameter is 13 mm, the smallest diameter is 6.5 mm and the constant pitch is 10 mm.

2.3. Data reduction

Nanofluid heat transfer rate in the inner tube is calculated by,

$$Q_{nf} = \dot{m}_{nf} c_{pnf} \left(T_{nf,out} - T_{nf,in}\right) \tag{1}$$

Hot fluid (DI water) heat transfer rate in the outer tube is calculated by:

$$Q_h = \dot{m}_h c_{ph} \left(T_{h,in} - T_{h,out}\right) \tag{2}$$

Average heat transfer rate is determined by,

$$Q_{avg} = \left(Q_{nf} + Q_h\right)/2 \tag{3}$$

Eq. (4) is used to estimate the overall heat transfer coefficient for the inner tube side,

$$U_{in} = \frac{Q_{avg}}{A_{in} \times \Delta T_{lm}}, \Delta T_{lm} = \frac{\left(T_{h,in} - T_{nf,out}\right) - \left(T_{h,out} - T_{nf,in}\right)}{ln\left(\frac{T_{h,in} - T_{nf,out}}{T_{h,out} - T_{nf,in}}\right)} \tag{4}$$

Heat transfer coefficient (mono/hybrid nanofluid) without considering fouling is estimated by,

$$\frac{1}{U_{in}A_{in}} = \frac{1}{h_{in}A_{in}} + \frac{ln\left(\frac{d_o}{d_i}\right)}{2\pi kL} + \frac{1}{h_{out}A_{out}} \tag{5}$$

The Reynolds number in the inner tube is evaluated using,

$$Re = \frac{4\dot{m}_{nf}}{\pi d_{it,i} \mu_{nf}} \tag{6}$$

Nusselt number of annulus side is determined by (Dirker and Mayer [28] correlation),

$$Nu_{out} = 0.007435 Re^{0.91} \Pr^{1/3} \left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{7}$$

$$\text{Range}: 4000 < Re < 30000, 1.72 < d_{ot,i}/d_{it,o} < 3.2$$

Since the present annular diameter ratio ($d_{ot,i}/d_{it,o}$) (1.95) and Reynolds number (10000) are within the applicable ranges and also the insert in inner tube does not affect the annulus flow as separated by solid wall, above equation has been used.

From Eqs. (7) and (8), the heat transfer coefficient of the annulus flow is calculated.

Table 3
Details of experimental setup and operating conditions.

Parameter	Value
Inner tube internal diameter	20 mm
Inner tube external diameter	24 mm
Length of the tube	570 mm
Outer tube internal diameter	47 mm
Wire thickness	2 mm
Pitch of the tapered wire coil, P	10 mm
Larger end diameter of conical wire coil, D	13 mm
Smaller end diameter of conical wire coil, d	6.5 mm
Nanofluid Reynolds number	9000 to 45,000
Nanofluid inlet temperature	30 °C
Hot fluid inlet temperature	60 °C

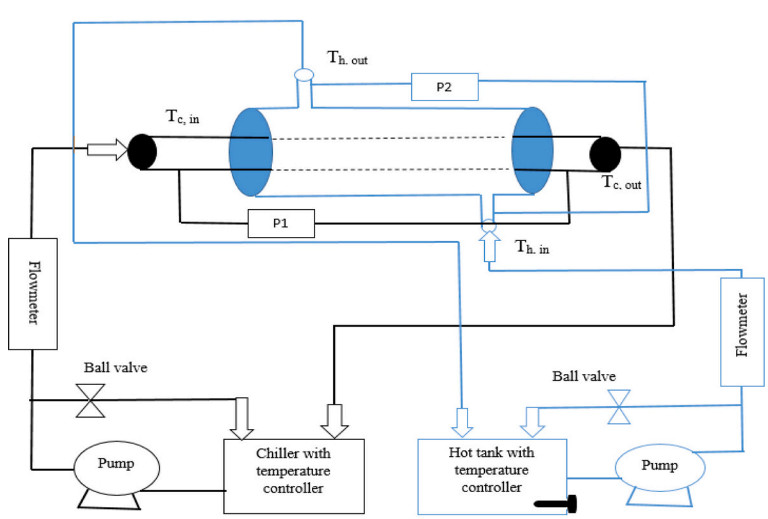

Fig. 3. Schematic diagram of experimental setup.

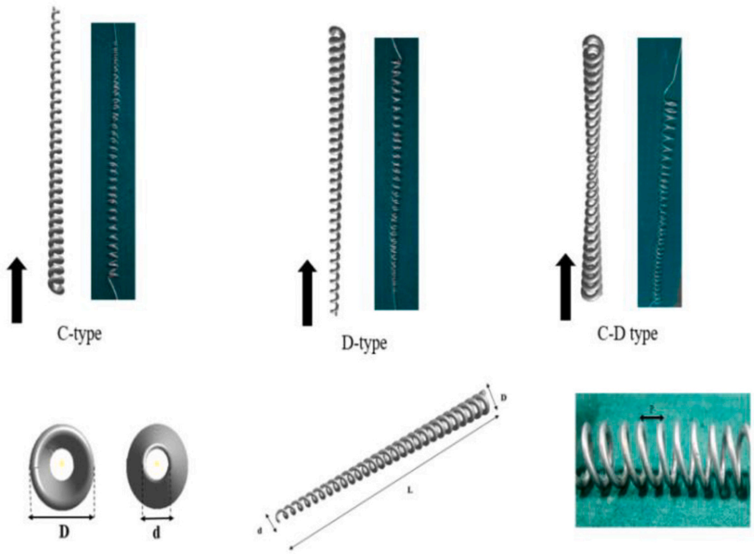

Fig. 4. Conical coil with different arrangements and geometries.

$$h_{out} = \frac{Nu_{out}k_{out}}{d_{eqv}} \tag{8}$$

Where d_{eqv} is determined by,

$$d_{eqv} = \left(d_{ot,i}{}^{2} - d_{it,o}{}^{2}\right)/d_{it,o} \tag{9}$$

From Eqs. (9) and (6), the inner tube side heat transfer coefficient (h_{nf}) is calculated. The Nusselt number of mono/hybrid nanofluid is evaluated by the following equation:

$$Nu_{nf} = h_{nf}d_{it,i}/k_{nf} \tag{10}$$

The friction factor for nanofluid is evaluated by the following expression,

$$f = \frac{\pi^2}{8}\Delta p\left(\frac{\rho_{nf}d_{it,i}{}^{5}}{\dot{m}_{nf}{}^{2}L}\right) \tag{11}$$

The thermal performance factor (TPF) represents the potential of enhancer in heat transfer augmentation, defined as the ratio of Nusselt number ratio to friction factor ratio at constant pumping power [24] and hence it is given by,

$$TPF = \left(\frac{Nu_{nf}}{Nu_{bf}}\right)\Big/\left(f_{nf}/f_{bf}\right)^{\left(1/3\right)} \tag{12}$$

There are two types of irreversibilities present in the heat exchanger, caused due to heat transfer and fluid friction (frictional pressure drop). By taking a heat exchanger as an adiabatic system, entropy generation is obtained as an entropy change of both fluids. Then, the second *Tds* equation ($Tds = dh - vdp$) is used for both fluids individually, which is applicable for both reversible and irreversible processes as all these quantities represent state variables. After taking the integration of *Tds* equation for both fluids and replacing in entropy generation equation, heat transfer and frictional pressure drop parts are separated.

The heat transfer related entropy generation is calculated by,

$$S_{gen_{ht}} = \dot{m}_{nf}c_{pnf}ln\left(\frac{T_{nf,out}}{T_{nf,in}}\right) + \dot{m}_{h}c_{ph}ln\left(\frac{T_{h,out}}{T_{h,in}}\right) \tag{13}$$

The pressure drop related entropy generation is calculated by,

$$S_{gen_f} = \frac{\dot{m}_{nf}\times\Delta p_{nf}}{\rho_{nf}\times T_{avg,nf}} + \frac{\dot{m}_{h}\times\Delta p_{h}}{\rho_{h}\times T_{avg,h}} \tag{14}$$

Hence, the total entropy generation is calculated by,

$$S_{gen_{tot}} = S_{gen_{ht}} + S_{gen_f} \tag{15}$$

2.4. Uncertainty analysis

The uncertainty values of all estimated parameters is evaluated based on the accuracies of measured parameters (temperature of 0.33%, pressure drop of 2.38% and volume flow rate of 0.67%) by using Kline and McClintock equation [29] and are presented in Table 4.

2.5. Validation

The experimental set up was validated by conducting the experiments with water in a plain tube. Initially, the cold water at 30 °C was delivered to the inner tube and hot water at 60 °C was supplied to the annular tube at the *Re* varying from 9000 to 45,000. The experimental result was validated with the correlations proposed by Nusselt [27] for developing flow (shown in Eq. (16)) and Bhuiya et al. [30], as depicts in Fig. 5. The experimental results well agreed with both correlations and showed a maximum deviation of 9.24% and 11.94%, respectively.

$$Nu = 0.036Re^{0.8}Pr^{1/3}\left(\frac{d}{L}\right)^{0.055} \text{ for } 10 < L\Big/d < 400 \tag{16}$$

3. Results and discussion

The effects of various conical wire coil enhancers and working fluids on heat transfer coefficient, Nusselt number, friction factor, heat transfer

Table 4
Uncertainty of the parameters.

Parameter	Uncertainty (%)
Mass flow rate (0.06–0.56 kg/s)	± 0.714
Density (kg/m^3)	± 1.00
Viscosity (Pa.s)	± 1.00
Thermal conductivity (W/m.K)	± 1.00
Reynolds number	± 1.23
Heat transfer coefficient	± 2.07
Nusselt number	± 2.29
Entropy generation	± 3.06
Friction factor	± 3.70
TPF	± 3.67

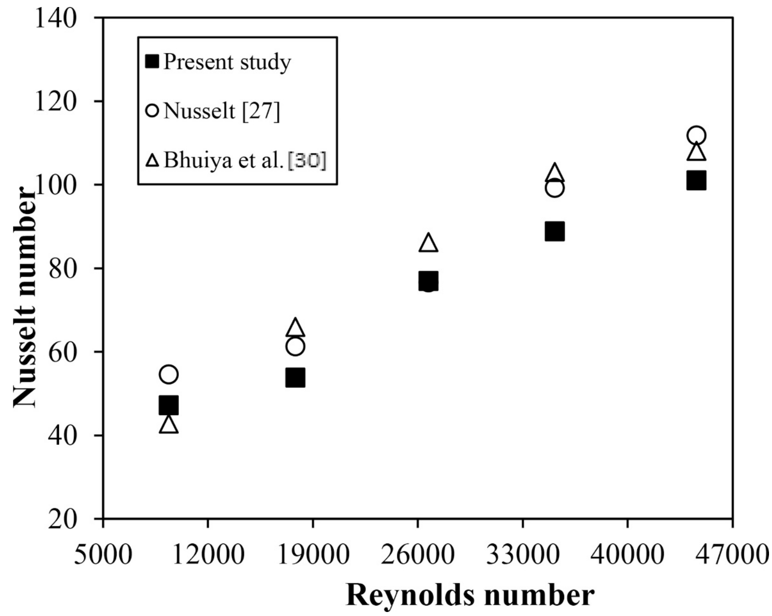

Fig. 5. Validation of Nusselt number for water without insert.

coefficient to pressure drop ratio, thermal performance factor and entropy generation are discussed.

3.1. Friction factor and Nusselt number

The effects of conical wire coils of different arrangements on the Nusselt number and friction factor are shown in Fig. 6. The outcomes show that with an increase in Reynolds number, Nusselt number increases and friction factor decreases. The boundary layer thickness weakens by inserting a conical wire coil, which raises the swirl flow at a different radial distance in the tube and promotes better heat transfer. The thermal conductivity of nanoparticles is higher than that of the base fluid and extra flow turbulence is created by nanoparticle due to various slip mechanisms, which leads to improving heat transfer. Similarly, the outcomes expose that diverging wire coil exhibits enhanced heat transfer than that of other coil arrangements due to an increase in residence time of flow and contact surface area when the fluid slows down from diverging wire coil. The friction factor increases by using a conical wire coil. Diverging wire coil illustrates a higher friction factor than that of the other coil arrangements due to the disturbing of the flow at the entrance of diverging wire coil inserts and leads to an increase in the pressure drop. In comparison to DI water in a smooth tube, the maximum Nusselt number and friction factor of hybrid nanofluid are enhanced for diverging, converging-diverging and converging wire coil inserts are 171%, 152% and 139%, and 106%, 92% and 72%, respectively. As shown in Fig. 7, the heat transfer coefficient increases with an increase in Reynolds number due to a similar trend of Nusselt number. The results imply that the D-type coil exhibits a higher heat transfer coefficient than that of other coil configurations. As compared to DI water without the insert, the maximum enhancements of heat transfer coefficient of hybrid nanofluid for diverging, converging-diverging and converging wire coil inserts are 171.2%, 152.6% and 139.6%, respectively.

Fig. 8 illustrates the comparisons of Nusselt number and friction

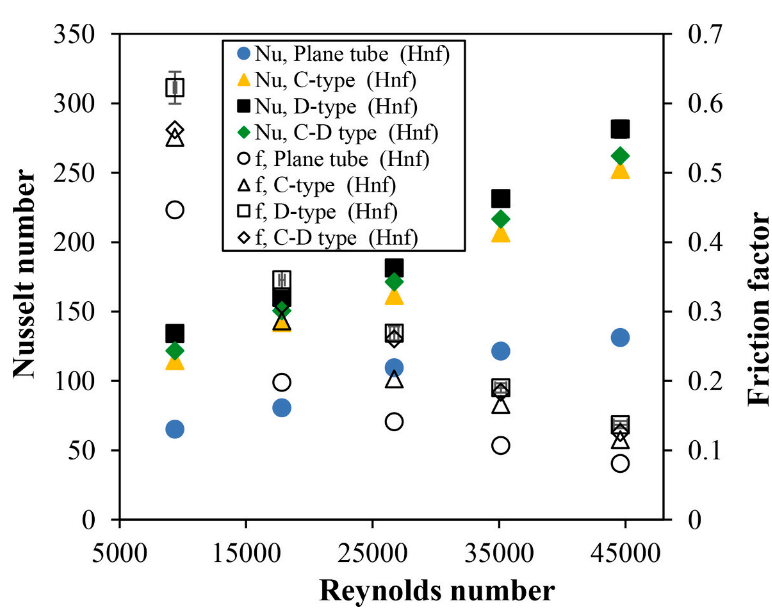

Fig. 6. Nusselt number and friction factor versus Reynolds number.

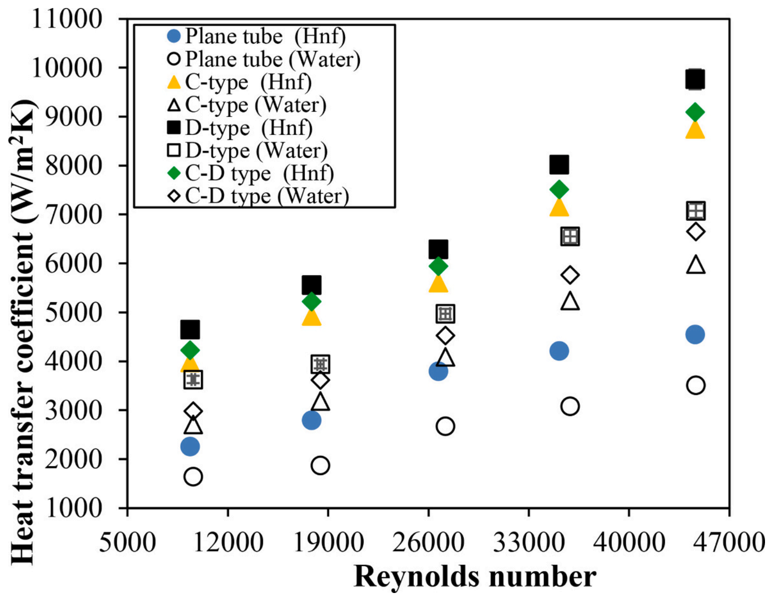

Fig. 7. Heat transfer coefficient versus Reynolds number.

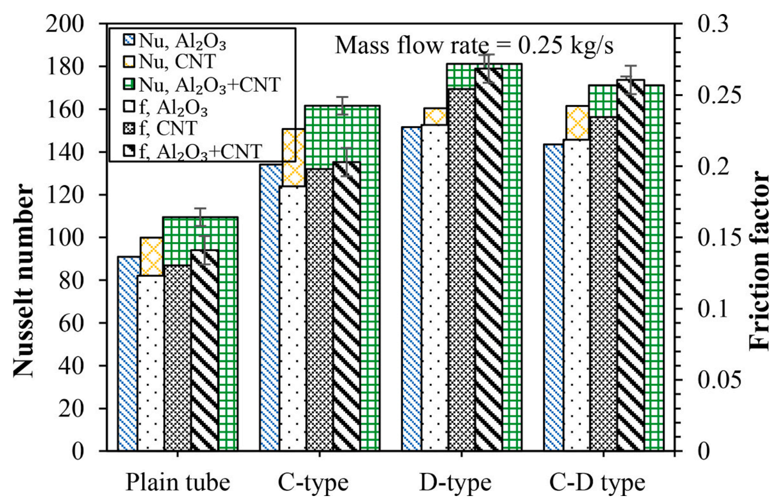

Fig. 8. Nusselt number and friction factor with different arrangements.

factor of different mono and hybrid (Al_2O_3, CNT and Al_2O_3 + CNT) nanofluids for different coil arrangements at a mass flow rate of 0.25 kg/s. Results expose that Al_2O_3 + CNT hybrid nanofluid shows a higher value of Nusselt number as well as friction factor as compared to that of CNT and Al_2O_3 nanofluids for different arrangements. The Nusselt number and friction factor increase due to combined effects of enhancements in thermal conductivity, viscosity (hybrid takes the advantages of both higher thermal conductivity of CNT and lower viscosity for Al_2O_3 dispersion) and heat capacity. The maximum values of the Nusselt number and friction factor show with the insertion of diverging coil followed by using converging-diverging and converging wire coil. By using the diverging coil, the augmentation of Nusselt number of the Al_2O_3 + CNT hybrid nanofluid is found about 26.50% more as compared to the DI water and about 12.95% more than that of CNT nanofluid and about 19.49% more that of Al_2O_3 nanofluid. Meanwhile, the friction factor of the Al_2O_3 + CNT hybrid nanofluid augments about 25.26% more than that of the DI water and 5.66% more than that of CNT nanofluid and 17.33% greater than that of Al_2O_3 nanofluids, using diverging wire coil.

3.2. Thermohydraulic performance (h/Δp and TPF)

The impacts of conical wire coils on the ratio of heat transfer coefficient and pressure drop (h/Δp) and TPF are depicted in Fig. 9. These two parameters are necessary to estimate the impact of modified helical coil inserts on the overall performance of the concentric tube heat exchanger. While increasing Reynolds number, the h/Δp deceases and TPF first increases and diminishes up to Reynolds number of 35,000 and then rises. This is due to the fact that, with the rise in Reynolds number, the pressure drop dominants over the heat transfer rate, which leads to a decrease in the value of h/Δp. This ratio is ranging from 1.94 to 4.64 for the diverging wire coil, 1.92 to 4.31 for the converging-diverging and 1.74 to 3.95 for the converging coil, respectively. The h/Δp using hybrid nanofluid is attained maximum for diverging wire coil, i.e., 15.11% more than that of DI water and about 34.69% more than the tube without the insert. TPF for all arrangements is higher than one, which indicates that both working fluid (nanofluid) and enhancer (conical wire coil) can be referred to as a fruitful option in practical application. The highest thermal performance factor of 1.39 is observed for diverging coil at Reynolds number of 18,000.

The effect of different mono and hybrid (Al_2O_3, CNT and Al_2O_3 +

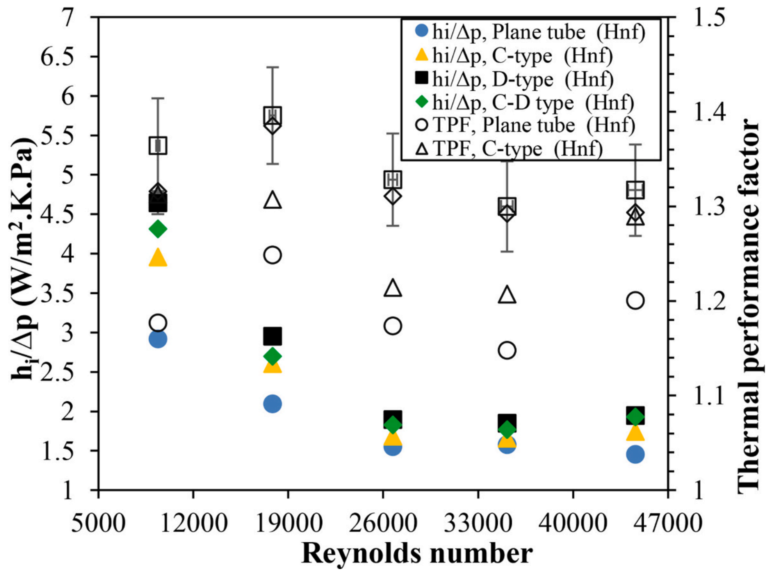

Fig. 9. h/Δp and TPF with Reynolds number.

CNT) nanofluids on heat transfer coefficient to pressure drop ratio (h/Δp) and thermal performance factor with various coil arrangements are depicted in Fig. 10. The outcomes expose that the h/Δp and TPF value of Al_2O_3 + CNT hybrid nanofluid exhibits greater than that of CNT and Al_2O_3 nanofluids. This is because of using Al_2O_3 + CNT hybrid nanofluid, the heat transfer dominants over the pressure drop at the mass flow rate of 0.25 kg/s. For example, the enhancement of h/Δp of the hybrid nanofluid is found around 4.57% more than that of CNT nanofluid and 8.43% more than that of Al_2O_3 nanofluid, with the use of diverging wire coil. However, the thermal performance factor of the hybrid nanofluid augments by 5.55% greater than that of CNT nanofluid and 7.46% more than that of Al_2O_3 nanofluid.

3.3. Entropy generation

The total entropy generation ($S_{gen,tot}$) of both water and hybrid nanofluid are depicted in Fig. 11 with respect to the mass flow rate for different coil arrangements. Likely, $S_{gen,tot}$ increases with a rise in mass flow rate. Since fluid friction irreversibility is found negligible in comparison to the heat transfer irreversibility, $S_{gen,tot}$ of mono/hybrid nanofluids is less than that of DI water. $S_{gen,tot}$ reduces by inserting the conical wire coil in the tube as it creates a strong mixing of fluids, which in results improves heat transfer. The maximum reduction in $S_{gen,tot}$ is observed as 8.92% for diverging wire coil, 3.53% for converging-diverging wire coil and 6.05% for converging wire coil, as compared to that of DI water at the mass flow rate of 0.25 kg/s.

Fig. 12 illustrates the total entropy generation with different wire coil arrangements for different mono and hybrid (Al_2O_3, CNT and Al_2O_3 + CNT) nanofluids at the constant mass flow rate of 0.25 kg/s. The outcome indicates that Al_2O_3 + CNT hybrid nanofluid shows a lower value of the $S_{gen,tot}$ than that of CNT and Al_2O_3 nanofluids for all types of wire coil arrangements. Due to the occurrence of nanoparticles in DI water, effective temperature difference reduces and viscosity increases. As a result, heat transfer irreversibility decreases and fluid friction irreversibility increases. In comparison to the tube without any insert using hybrid nanofluid, the reduction of 22.63% in $S_{gen,tot}$ is observed for diverging wire coil. Results show that the hybrid nanofluid performs better than the mono nanofluids for the same overall volume concentration due to the hybridization of individual advantages.

4. Conclusions

Experimental analysis on the hydrothermal performance of the concentric tube heat exchanger with novel conical coil insertions using

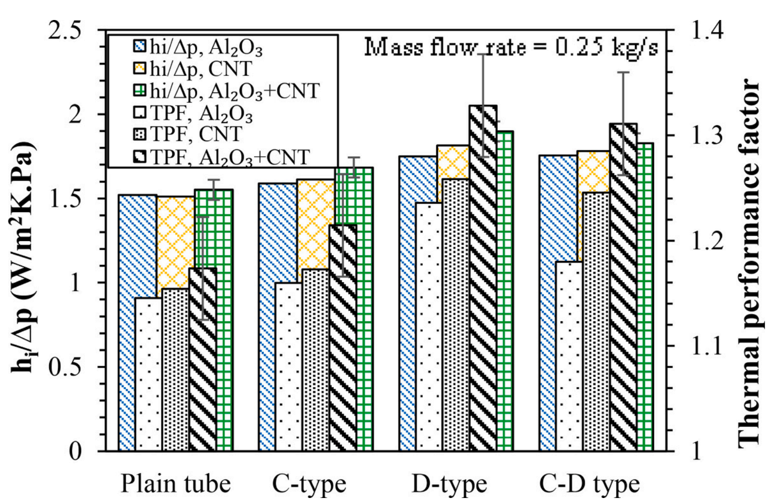

Fig. 10. h/Δp and TPF with different arrangements.

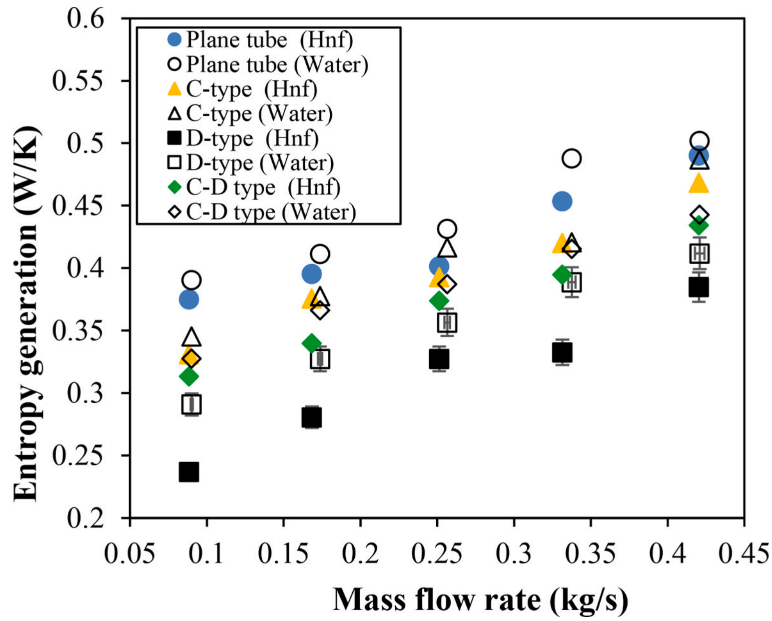

Fig. 11. Entropy generation with volume flow rate.

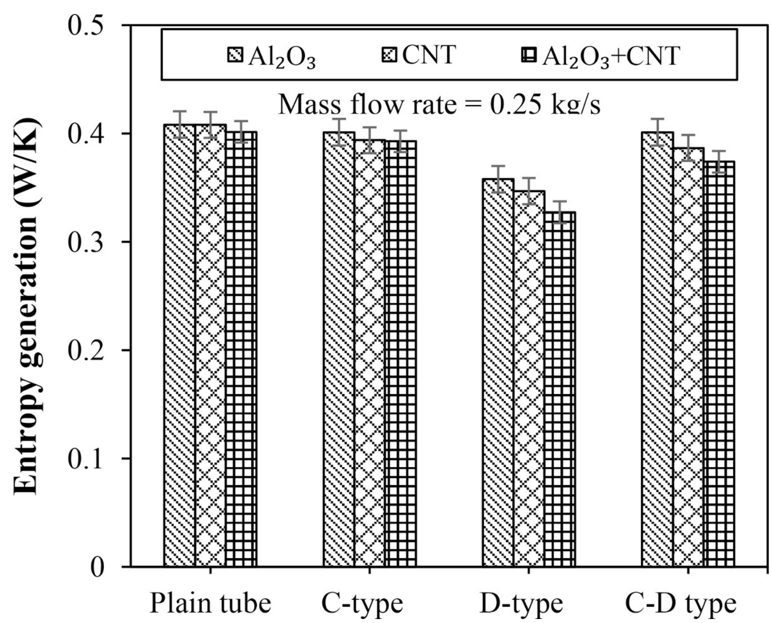

Fig. 12. Entropy generation with different arrangements.

different mono/hybrid nanofluids (Al_2O_3, CNT, and Al_2O_3 + CNT) at volume concentrations of 0.01% was conducted. The main results of this study are summed up below:

- ➢ Among all coil arrangements, diverging (D-type) wire coil exhibits higher heat transfer augmentation. In comparison to DI water without the coil, the maximum Nusselt number and friction factor of 0.01% hybrid nanofluid with diverging, converging-diverging and converging wire coil inserts are enhanced by 171%, 152% and 139%, and 106%, 92% and 72%, respectively.
- ➢ Al_2O_3 + CNT hybrid nanofluid exhibits better heat transfer than that of mono CNT and Al_2O_3 nanofluids. By using diverging coil, the augmentation of Nusselt number of the Al_2O_3 + CNT hybrid nanofluid is found about 26.50% more as compared to the DI water and about 12.95% more than that of CNT nanofluid and about 19.49% more than that of Al_2O_3 nanofluid.
- ➢ The h/Δp ratio using hybrid nanofluid is attained maximum for Diverging wire coil, ranging from 1.94 to 4.64, followed by 1.92 to 4.31 for Converging-Diverging coil and 1.74 to 3.95 for Converging coil. Meanwhile, the thermal performance factor is more than one, indicating that the use of both working fluid and conical wire coil insertions can be referred to as a good option for practical application.
- ➢ The total entropy generation of nanofluids is less than that of DI water. In comparison to DI water, the maximum drop in total entropy generation of hybrid nanofluid was found 8.92% for diverging, 3.53% for converging-diverging and 6.05% for converging coils, respectively, at the mass flow rate of 0.25 kg/s.

Declaration of Competing Interest

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

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