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Experimental investigation of Convective Heat Transfer of Carbon Nanotubes / Water Flow in a helical Triple tube Heat Exchanger

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In this work, the thermal performance of CNT/water nanofluid for the heat exchanger with helical triple tubes is investigated experimentally. The geometry of the tube, the volume percentage of nanoparticles, and Reynolds number are three key characteristics investigated. Two cases with different curvature ratios of 0.010 and 0.0167 are constructed and compared to investigate the impact of the curvature ratio on convection heat transfer. The results show that the Nusselt number of nanofluids is larger than the base fluid. In addition, maximum and minimum values of Nusselt number are found for Reynolds numbers of 1000 and 5000 correspondingly. The results show a slight reduction in pressure drop for pure water as the Dean number increased. Moreover, while the volume fraction of nanoparticles less than 0.1%, the Nusselt number increased with a shallow slope.

Keywords: helical triple tube, heat transfer, nanofluid, carbon nanotube

1 Introduction

With the growing need for energy consumption globally, optimizing the performance of energy exchange systems is essential. Heat exchangers are one of the most useful components in energy production systems. Different methods have been applied to improve heat transfer due to the low thermal conductivity of the cooling fluid (water or air). Additives such nanoparticles in the base fluid enhance the heat transfer of the fluid as a passive solution due to its high thermal conductivity. Although nanofluids have a higher thermal conductivity than the base fluid, nanofluids' utilization causes a higher pressure drop across the channels due to their high effective viscosity [1]. As mentioned below, several researchers carried out experimental and numerical studies to improve the thermal performance of nanofluids by enhancing the effective heat transfer coefficient and decreasing the pressure drop.

Amrollahi et al. [2] studied experimentally nanofluid performance in Carbon Nano Tube (CNT). Their obtained results show that using CNT-ethylene glycol as a nanofluid increases the thermal conductivity by 20%. Another research studied nanofluid flow's effect for enhancing heat transfer in a helical tube with a counter-current flow configuration. They found that adding nanoparticle to working fluid improves the thermal performance of heat exchangers.

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The influence of using nanofluid in helical tubes with counter-current flow configurations is investigated by Mukesh Kumar et al. [3]. They found a noticeable improvement in thermal performance of heat exchanger. [4] studied the helical tube's thermal performance using CuO/water nanofluid for two different positions (vertical and horizontal). According to their results, increasing the Dean number and volume fraction of nanoparticles increased the Nusselt number. Akbaridoust et al. [5] investigated CuO/water nanofluid's thermal performance in the tubes. They confirmed that a higher Reynold number corresponds to an improvement in thermal conductivity, and increasing the volume fraction of nanoparticles is linked to a higher pressure drop. Kannadasan et al. Kim et al. [6] investigated the influence of nanoparticles and tube diameter on fluid flow thermal performance experimentally in another research. Palanisamy and Kumar [7] studied the helical tube using a high-stable nanofluid. They proposed MWCNT/water nanofluid as a coolant flow in the heat exchanger's tube. Logesh et al. [8] studied the thermal behavior of three different nanofluid s. Their results show that adding nanoparticles increase the thermal performance of heat exchanger. Ying et al. [9] developed a numerical model for assessing salt-based thermal molding flow performance of Al_2O_3 nanoparticles. Their findings demonstrate the thermal conductivity of less than 0.125% of the mass fraction. Wang et al. [10] compared the thermal performance of a helical and straight tube. The results reveal that the helical tube's thermal performance is around 1.16 to 1.36 times higher than that of a straight tube. Fares et al. [11] investigated graphene nanofluid. The results showed that the thermal conductivity is slightly improved by 29% using 0.2% graphene nanofluid. Naghdbishi et al. [12] compared the active cooling and passive cooling (paraffin) experimentally. They applied carbon nanotubes as the nanoparticles. The literature review shows that nanofluids' thermal performance in curved tubes has been studied widely. To the best of our knowledge, investigating the CNT/water nanofluid thermal performance for the helical triple tubes heat exchanger has not been studied before. This research discussed how the heat exchanger of CNT nanoparticles, the tube shape, the nanoparticle volume part, and the Reynolds number affect the thermal performance.

2 Experimental apparatus

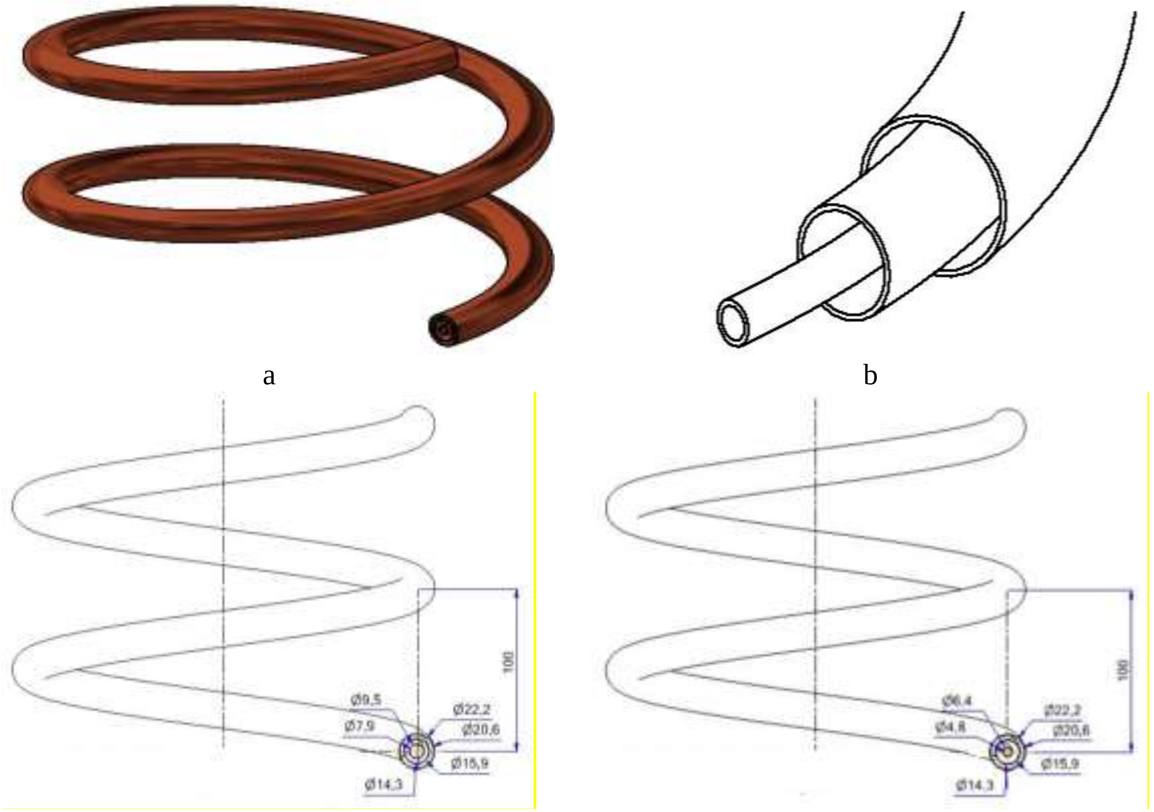
Several materials include distilled water, GA, CNT nanoparticles are required to synthesize CNT/nanofluid. Two helical triple tubes are used in the experiments. The dimensions of the tubes are tabulated in Table (1) As seen from this table, only the inner tube's dimension varied in the two cases, with different curvature ratios. The overview of the helical triple tube may be seen in Figure (1) In SEM and TEM photos, respectively, Figure (2a and 2b) reveal CNT nanoparticles. The synthesized nanofluid is made by Garg et al. [13] method.

2.1. Experimental setup

As shown in Figure (3), the heat exchanger's test stand is designed and constructed to evaluate the new coolant flow's thermal performance. The test stand consisted of the following components; heat exchanger, heater, condenser, pump, reservoir, and control and measure devices. In this laboratory setup, the water vapor produced in the heater section enters the heat exchanger, and after exchanging heat with the coolant flow, its volumetric flow is measured by the flow meter and finally enters the reservoir. The heating circuit supplies the heat required for the steam generator. Control valves are used to adjust the flow rate, and glass wool has been used to insulate the steam generator's outer body and condenser. Six RTDs (accuracy 0.1 ° C) have been used at various steam generator locations to measure temperature. These sensors are connected directly to the data logger and computer. Measurements were reported after the 30-minute stability of the test stand.

Table 1 Detail of dimensions for the helical triple-tube heat exchangers

Case	d_{1I}(mm)	d_{1O} (mm)	d_{2I} (mm)	d_{2O} (mm)	d_{3I} (mm)	d_{3O} (mm)	D(mm)	b (mm)	$\delta = d/D$
1	7.9	9.5	14.3	15.9	20.6	22.2	471.8	100	0.010
2	4.8	6.4	14.3	15.9	20.6	22.2	471.8	100	0.0167



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c d

Figure 1 Schematic view of a) helical triple tube, b) tube's cross-section c) case1 d) case 2

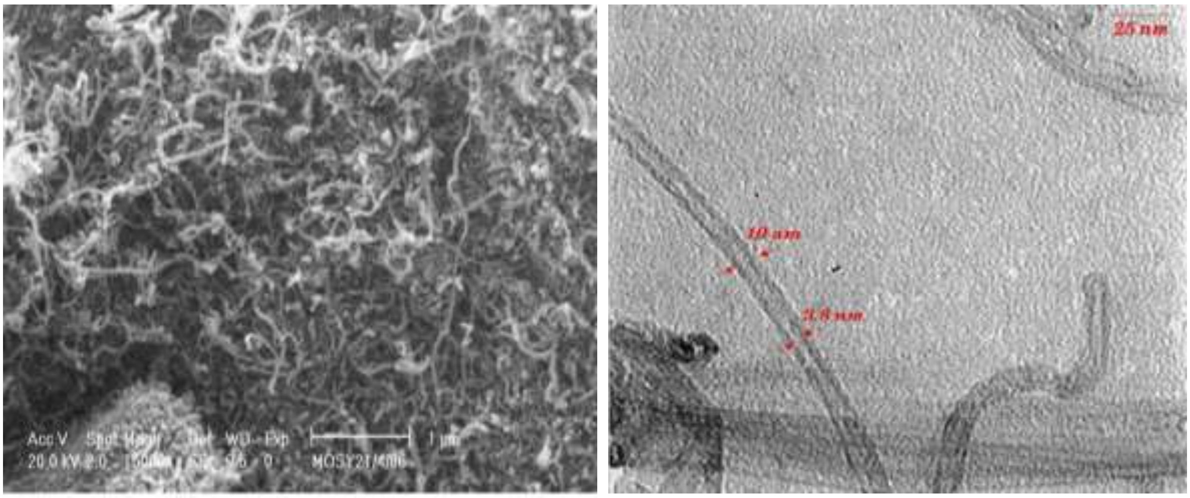

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Figure 2 Photograph of CNT, a) SEM and b) TEM

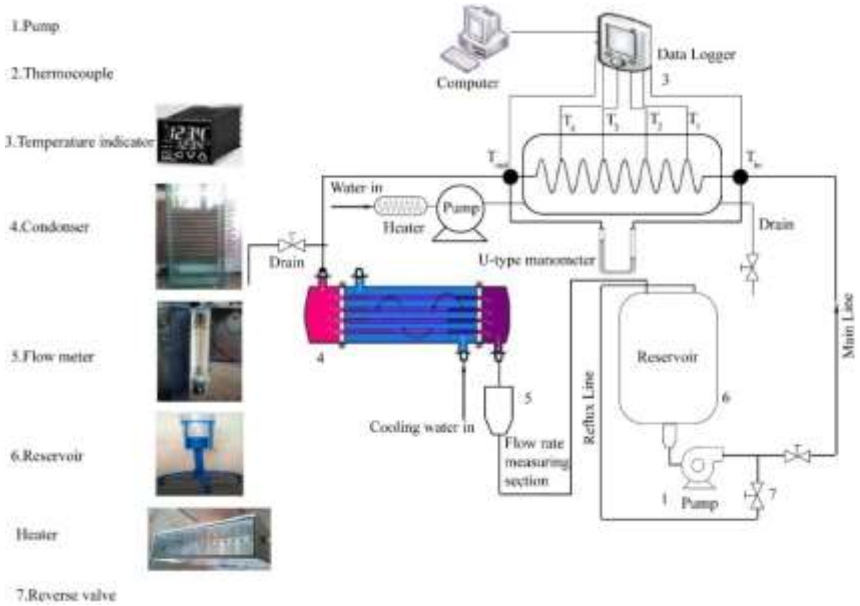

Figure 3 Diagram of the experimental test stand

3 Data reduction

Different devices have been used to measure the coolant's different properties, which are listed in Table (2) of the device and the measured values.

3.1. Heat transfer

On the inner and outer sides of the tube, heat transfer occurs. Therefore, two heat transfer coefficients are defined to consider heat transfer at both walls. The outer path is first blocked to measure the heat transfer coefficients while hot water passes through the helical tube's core. The convective coefficient is expressed as follows:

$$h = \frac{\dot{m}C_p(T_{h_i} - T_{h_o})}{A.LMTD} \tag{1}$$

where logarithmic average temperature difference (LMTD) is obtained as follows:

$$LMTD = \frac{(T_{h_i} - T_{f_o}) - (T_{h_o} - T_{f_i})}{\ln\left(\frac{T_{h_i} - T_{f_o}}{T_{h_o} - T_{f_i}}\right)} \tag{2}$$

Table 2 Thermophysical parameters of nanofluid

Thermophysical properties	Nano particle	water	nanofluid			Device
			0.01 %	0.1 %	0.5 %	
Density [kg m^{-3}]	2100	1024	1034.76	1131.6	1562	Density meter (DA-130N; Precision: ±1 x 10^{-3}g/cm^3)
specific heat [J kg^{-1} K^{-1}]	530	4001.1	3966.4	3653.9	2265.6	scanning calorimeter (DSC, Q20; Precision: ± 0.05°C)
Thermal conductivity [w m^{-1}K^{-1}]	2000	0.596	0.62	0.87	4.14	KD2-pro instrument (Decagon Devices; Precision: ± 5 to ± 10%)
Viscosity [Ns m^{-2}]	-	0.00108	0.001108	0.001405	0.006109	parallel disk rheometer (PaarPhysica MCR 300, accuracy of < 1µm)

T_{hi}, T_{ho}, T_{fi}, and T_{fo} are the inlet temperature of hot water, the outlet temperature of hot water, inlet, and outlet temperature of the nano fluid. Nusselt number is defined as follows:

$$\mathrm{Nu} = \frac{hD_h}{k} \tag{3}$$

Dh is the hydraulic diameter of the tube (Dh=4(flow cross sectional/wetted perimeter)), and k is the fluid's thermal conductivity.

The performance evaluation criterion, called PEC, is used to evaluate the heat transfer at the same mass flow rate. It is defined as below [14]:

$$\mathrm{PEC} = \frac{\mathrm{Nu}/\mathrm{Nu}_b}{(f/f_b)^{\frac{1}{3}}} \tag{4}$$

where Nu_b and f_b are the base nusselt number of fluid without nano particle and viscosity of fluid, respectively. A dimensionless number known as Dean number (De) is introduced by Dean and Hurst [15], to examine the secondary stream of a helical tube. The following are defined:

$$\mathrm{De} = \mathrm{Re}\sqrt{\frac{r}{R}} \tag{5}$$

where, Re, R, and r are Reynolds number, tube radius, and tube twist radius.

3.2. Validation

predicted results of [16] compared with the present study results under two different boundary conditions: constant flux and constant temperature. As Figure (4) shows, the tube's internal Nusselt numbers have a fair agreement with the predicted results.

3.3. Uncertainty study

Table (3 shows the uncertainty of the measured results for the measuring instruments. After calculations related to uncertainty based on the Moffat's method [17], the maximum uncertainty for calculating the Nusselt number is 6%. Therefore, laboratory results can be assured on this basis.

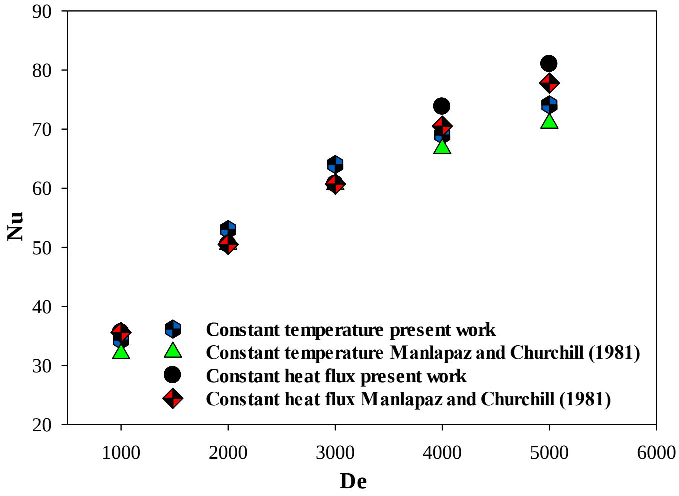

Figure 4 Comparison of present work with Manlapaz and Churchill [16]

Table 3 Uncertainty of measurement devices

Instrument and parameter	Uncertainty
Flowmeter [kg/s]	4%
Length [m]	0.001
RTD [℃]	0.1
Data logger [℃]	0.1

4 Results and discussion

In this study, the effect of changing the pitch in the helical tube (fixed-length 100 mm) to the ratio of curvature on thermal performance has been investigated. The effect of centrifugal force due to centrifugal force on Nusselt number and subsequently on the tube's thermal performance can be investigated. Figure (5a and 5b) show the Nusselt number curve in terms of Reynolds number for two different cases at different percentages of nanoparticles' mass fractions. Obviously, the Nusselt number is raised due to the rise of the Reynolds number. In addition, it can also be inferred that by evaluating the percentage of mass fraction of nanoparticles in the base fluid. This increase can be explained by the Brownian motion of the suspended nanoparticles, the decrease of the boundary layer by the carbon nanotubes' irregular motion, and the thermal conductivity increase. Because case 2 has a higher value of curvature coefficient than case 1, it has a higher Nusselt number and improved heat transfer. It can be seen that the highest Nusselt number in the second case is obtained in the curvature coefficient of 0.067 and for the nanofluid flow with 0.5% of the volumetric concentration of CNT.

Figure (6a and 6b) show the variations of the tube's inner and outer Nusselt number for two different items according to the number of religions, respectively. The data clearly show that increasing the curvature coefficient within the tube enhanced the internal Nusselt number. On the other hand, changing the curvature coefficient seemed to have no significant effect on the pipe's external Nusselt number. Therefore, the coefficient of heat transfer near the exterior wall could be significantly affected by the coefficient of curvature.

Figure (7a and 7b) show the tube's internal pressure drop vs. Reynolds number for the two pipe cases. The findings show that as the Reynolds number rises, so does the pressure drop decrease. In addition to the proportion of nanoparticles in the base fluid, the viscosity rises, leading the pressure drop to rise. The maximum pressure drop inside the tube is almost three times higher than the pressure drop inside the tube.

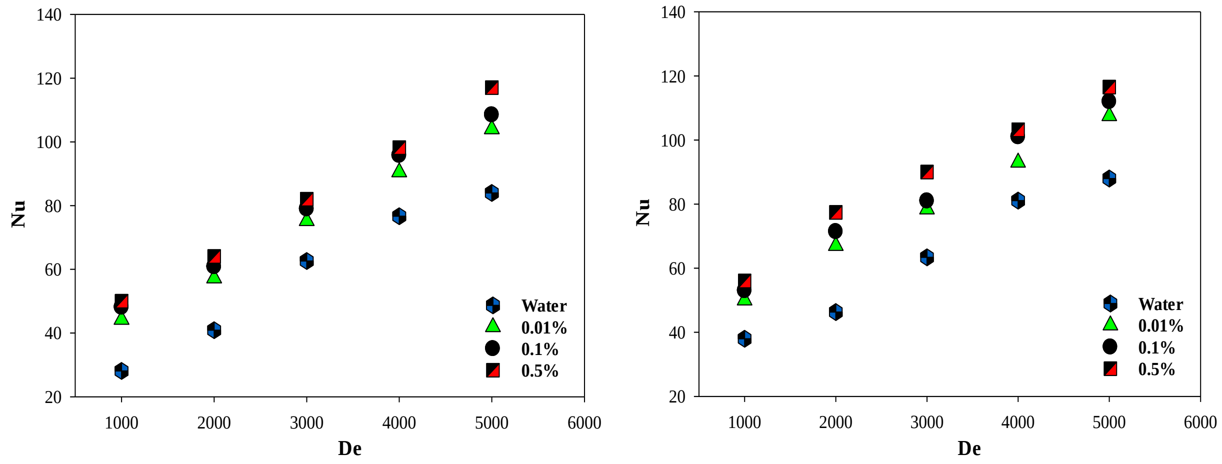

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Figure 5 Variations of inner Nu vs. De at the different percent of nanoparticle mass fraction for a) case 1 and b) case 2, respectively.

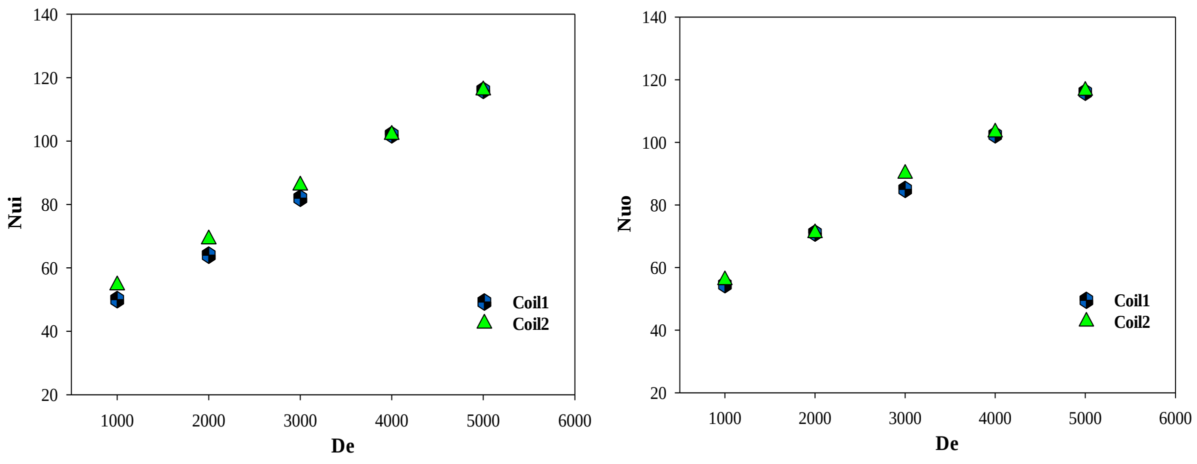

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Figure 6 Effect of the geometry of helical triple tube heat exchanger on a) inner and b) outer Nusselt number

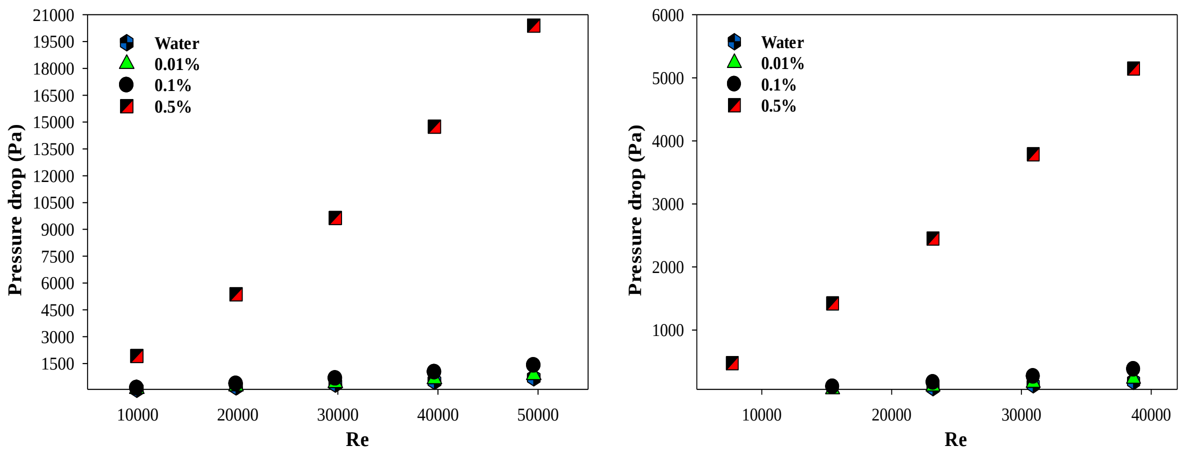

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Figure 7 Effect of Reynolds number and nanoparticle mass fraction on the pressure drop in the a) case 1 b)case 2

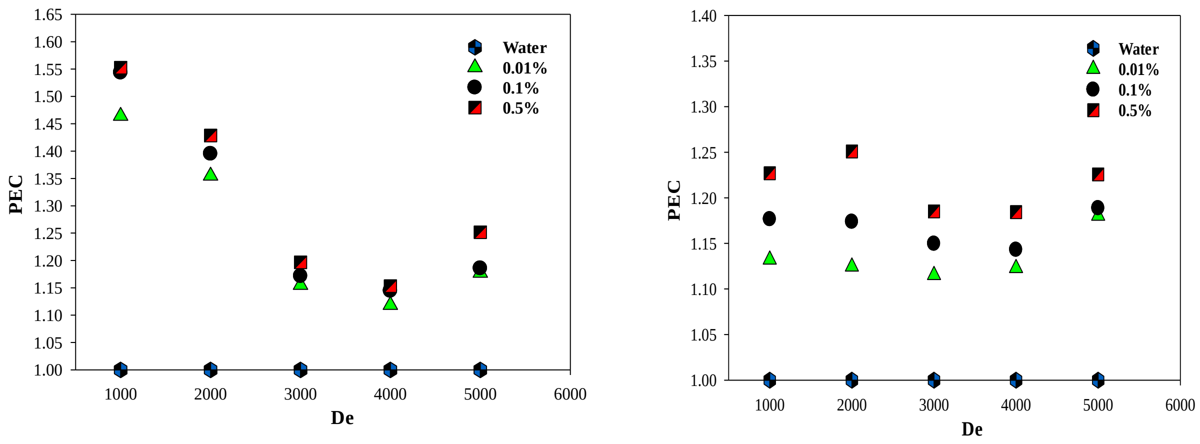

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Figure 8 The effect of helical tube geometry on a) inner and b) outer Nusselt numbers

5 Conclusion

The thermal performance of a heat exchanger with helical triple tubes is studied in this study using various nanofluid/CNT percentages. Before starting the experimental research on the cases, the experimental study is validated. The obtained results are listed as below:
1- Applying nanofluid, the Nusselt number has been increased due to the increase in surface to volume.
2- the maximum and minimum value of the Nusselt number is obtained in the Reynolds number of 1000 and 5000, respectively.
3- For the flow of pure water, with increasing the Dean number, the pressure drop increases slightly.
4- By adding carbon nanotubes to pure water, the pressure drop increases. At volumetric percentages of less than 0.1%, it increases with a shallow slope and with higher volumetric percentages, with a greater slope.
5- The pressure drop of nanofluids with low volume percentages, compared to water, increases with a slight slope and is almost equal.

References

[1] Maghrabie, H.M., Attalla, M., and Mohsen, A.A.A., "Performance Assessment of a Shell and Helically Coiled Tube Heat Exchanger with Variable Orientations Utilizing Different Nanofluids", Applied Thermal Engineering, Vol. 182, 116013, doi:10.1016/j.applthermaleng.2020.116013, (2020).

[2] Amrollahi, A., Hamidi, A.A., and Rashidi, A.M., "The Effects of Temperature, Volume Fraction and Vibration Time on the Thermo-physical Properties of a Carbon Nanotube Suspension (Carbon Nanofluid)", Nanotechnology, Vol. 19(31), doi:10.1088/0957-4484/19/31/315701, (2008).

[3] Mukeshkumara, P.C., Kumarb, J., Sureshc, S., and Praveen babuc, K., "Experimental Study on Parallel and Counter Flow Configuration of a Shell and Helically Coiled Tube Heat Exchanger Using Al2O3 / Water Nanofluid", Journal of Materials and Environmental Science, Vol. 3(4), pp. 766-775, (2012).

[4] Kannadasan, N., Ramanathan, K., and Suresh, S., "Comparison of Heat Transfer and Pressure Drop in Horizontal and Vertical Helically Coiled Heat Exchanger with CuO/Water Based Nano Fluids", Experimental Thermal and Fluid Science, Vol. 42, pp. 64-70, doi:10.1016/j.expthermflusci.2012.03.031, (2012).

[5] Akbaridoust, F., Rakhsha, M., Abbassi, A., and Saffar-Avval, M., "Experimental and Numerical Investigation of Nanofluid Heat Transfer in Helically Coiled Tubes at Constant Wall Temperature Using Dispersion Model", International Journal of Heat and Mass Transfer, Vol. 58, pp. 480-491, doi:10.1016/j.ijheatmasstransfer.2012.11.064, (2013).

[6] Kim, S., Tserengombo, B., Choi, S.H., Noh, J., Huh, S., Choi, B., Chung, H., Kim, J., and Jeong, H., "Experimental Investigation of Heat Transfer Coefficient with Al2O3 Nanofluid in Small Diameter Tubes", Applied Thermal Engineering, Vol. 146, pp. 346–355. doi:10.1016/j.applthermaleng.2018.10.001, (2019).

[7] Palanisamy, K., and Mukesh Kumar, P.C., "Experimental Investigation on Convective Heat Transfer and Pressure Drop of Cone Helically Coiled Tube Heat Exchanger Using Carbon Nanotubes/Water Nanofluids", Heliyon. Vol. 5(5), e01705. doi:10.1016/j.heliyon.2019.e01705, (2019).

[8] Logesh, K., Tiwari, R., Harish, R., Ajay, S., and Sunilrao, N.A., "Experimental Studies on Convective Heat Transfer Coefficient of Al2O3/Ethylene Glycol-carbon Nano Tube Nanofluids", Material Today Proceeding, Vol. 18, pp. 4738–4744. doi:10.1016/j.matpr.2019.07.461, (2019).

[9] Ying, Z., He, B., Su, L., Kuang, Y., He, D., and Lin, C., "Convective Heat Transfer of Molten Salt-based Nanofluid in a Receiver Tube with Non-uniform Heat Flux", Applied Thermal Engineering, Vol. 181, doi:10.1016/j.applthermaleng.2020.115922, (2020).

[10] Wang, G., Wang, D., Peng, X., Han, L., Xiang, S., and Ma, F., "Experimental and Numerical Study on Heat Transfer and Flow Characteristics in the Shell Side of Helically Coiled Trilobal Tube Heat Exchanger", Applied Thermal Engineering, Vol. 149, doi:10.1016/j.applthermaleng.2018.11.055, (2019).

[11] Fares, M., AL-Mayyahi, M., and AL-Saad, M., "Heat Transfer Analysis of a Shell and Tube Heat Exchanger Operated with Graphene Nanofluids", Case Studies in Thermal Engineering, Vol. 18, 100584. doi:10.1016/j.csite.2020.100584, (2020).

[12] Naghdbishi, A., Yazdi, M.E., and Akbari, G., "Experimental Investigation of the Effect of Multi-wall Carbon Nanotube – water/Glycol Based Nanofluids on a PVT System Integrated with PCM-covered Collector", Applied Thermal Engineering, Vol. 178, 115556. doi:10.1016/j.applthermaleng.2020.115556, (2020).

[13] Garg, P., Alvarado, J.L., Marsh, C., Carlson, T.A., Kessler, D.A., and Annamalai, K., "An Experimental Study on the Effect of Ultrasonication on Viscosity and Heat Transfer Performance of Multi-wall Carbon Nanotube-based Aqueous Nanofluids", International Journal of Heat and Mass Transfer, Vol. 52, pp. 5090-5101, doi:10.1016/j.ijheatmasstransfer.2009.04.029, (2009).

[14] Abdul Hamid, K., Azmi, W.H., Mamat, R., and Sharma, K.V., "Heat Transfer Performance of TiO2–SiO2 Nanofluids in a Tube with Wire Coil Inserts", Applied Thermal Engineering, Vol. 152, doi:10.1016/j.applthermaleng.2019.02.083, (2019).

[15] Ding, Y., Alias, H., Wen, D., and Williams, R.A., "Heat Transfer of Aqueous Suspensions of Carbon Nanotubes (CNT Nanofluids)", International Journal of Heat and Mass Transfer, Vol. 49, pp. 240-250, doi:10.1016/j.ijheatmasstransfer.2005.07.009, (2006).

[16] Manlapaz, R.L., and Churchill, S.W., "Fully Developed Laminar Convection from a Helical Coil", Chemical Engineering Communications, Vol. 9, pp. 185-200, doi:10.1080/00986448108911023, (1981).

[17] Moffat, R.G., "Describing the Uncertainties in Experimental Results", Experimental Thermal and Fluid Science, Vol. 1, pp. 3–17, doi:10.1016/0894-1777(88)90043-X, (1988).

Nomenclature

A	surface area (m^2)
Ac	cross-sectional surface area of coil (m^2)
b	Pitch of coil (m)
Cp	specific heat (j $kg^{-1}K^{-1}$)
d	Tube's diameter (m)
D	Coil's diameter (m)
h	Convection coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L	Tube's length (m)
$\dot{m}$	mass flow rate (kg s^{-1})
N	number of turns
Nu	Nusselt number
P	Pressure (Pa)
Re	Reynolds number
T	temperature (K)
U	average velocity (m s^{-1})

Greek Symbols

ΔT	temperature difference (K)
ρ	density (kg m^{-3})
μ	dynamic viscosity (Pa s)
δ	curvature ratio (=d/D)
ϕ	Nanoparticle volume fraction (%)

Subscripts

f	fluid
in	inner
LMTD	logarithmic mean temperature difference