Heliyon 5 (2019) e02030

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.heliyon.com

CFD analysis on heat and flow characteristics of double helically coiled tube heat exchanger handling MWCNT/water nanofluids

P.C. Mukesh Kumar [a,*], M. Chandrasekar [b]

[a] Department of Mechanical Engineering, University College of Engineering, Dindigul, Tamilnadu, 624 622, India
[b] Department of Mechanical Engineering, Chettinad College of Engineering & Technology, Karur, Tamilnadu, 639114, India

ARTICLE INFO

Keywords:
Mechanical engineering
Nanotechnology
Computational mathematics
Volume concentration of nanoparticle
Double helically coiled tube
MWCNT /water nanofluids
Computational fluid dynamics
Pressure drop
Thermal conductivity
Nanofluid viscosity

ABSTRACT

Double helically coiled tube heat exchangers are used in different heat transfer utilization due to higher heat transfer capabilities and with their compactness. The double helically coiled tube heat exchanger increases the turbulence and enhances the maximum heat transfer rate than the straight tubes. In this investigation, the heat transfer and pressure drop of the double helically coiled heat exchanger handling MWCNT/water nanofluids have been analyzed by the computational software ANSYS 14.5 version. The computational analysis was carried out under the laminar flow condition in the Dean number range of 1300–2200. The design of new shell and double helically coiled tube heat exchanger was done by using standard designing procedure and 3D modeling was done in Cre-O 2.0 parametric. The Finite Element Analysis software ANSYS Workbench 14.5 was used to perform CFD analysis under the standard working condition. The MWCNT/water nanofluids at 0.2%, 0.4%, and 0.6% volume concentrations have been taken for this investigation. The major factors like volume concentrations of nanofluids and Dean Number are considered for predicting the heat transfer rate and pressure drop. The simulation data was compared with the experimental data. It is studied that the heat transfer rate and pressure drop increase with increasing volume concentrations of MWCNT/water nanofluids. It is found that the Nusselt number of 0.6% MWCNT/water nanofluids is 30% higher than water at the Dean number value of 1400 and Pressure drop is 11% higher than water at the Dean number value of 2200. It is found that the simulation data hold good agreement with the experimental data. The common deviation between the Nusselt number and pressure dropof CFD data and the Nusselt number and pressure drop of experimental data are found to be 7.2% and 8.5% respectively.

1. Introduction

The design of heat exchangers and heat transfer enhancement techniques are picking up momentum nowadays because of the challenging in meeting out current cooling demand. Many researchers worked on the passive heat transfer enhancement techniques rather than the active heat transfer enhancement techniques. However, the work on curved tubes and helically coiled tubes need more knowledge about the flow of primary and secondary flow formation. Helically coiled tube heat exchangers are used in power plants, nuclear plants, process plants, automobile, refrigeration, heat recovery units, processing industries and steam generation in marine due to their compact shape and effective heat transfer. The limitations of the shell and single helically coiled tube heat exchangers are the lower surface area of the flowing fluid and weaker turbulence creation than the double helically coiled tube heat exchangers.

VimalKumar et al. [1] revealed that there is a poor circulation of a fluid in the shell region of the shell and single helically coiled heat exchanger. Dean [2, 3] suggested that the helically coiled tubes are better than straight tubes in view of heat transfer rate as the coiled tube forms strong secondary flow and named the vortex as Dean vortex. Dean found that the secondary flow in coiled tubes (Dean vortex) is a function of Reynolds number and the d/D ratio. Dean [3] investigated the steady-state condition of incompressible fluid flow through the helically coiled tubes. He reported that the mass flow rate decreases with respect to the coil ratio. Mohammed et al. [4] numerically investigated the effect of geometrical parameters of helical coil tube heat exchanger handling nanofluids. They revealed that the helix radius and inner tube diameter affect the thermal and hydraulic characteristics of nanofluids under laminar flow condition. They also revealed that the counter flow configuration produces better result when compared with the flow configuration.

* Corresponding author.
E-mail address: pcmukeshkumar1975@gmail.com (P.C. Mukesh Kumar).

https://doi.org/10.1016/j.heliyon.2019.e02030
Received 1 January 2019; Received in revised form 28 February 2019; Accepted 28 June 2019

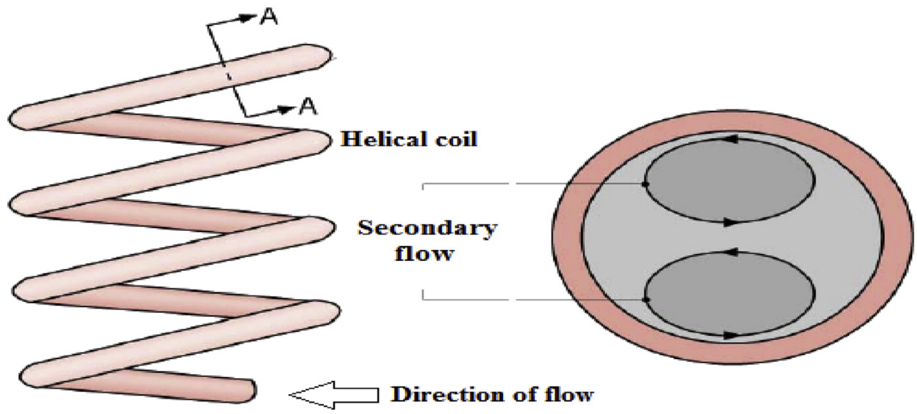

Fig. 1. Secondary flow formation.

Ferng et al. [5] worked on the effect of changing the Dean number and pitch of the helically coiled tube on heat transfer. They revealed that the creation of secondary flow becomes weaker when increasing the coiled tube pitch. Berger et al. [6] are the first for carrying out the experiments on the flow through curved tubes. They studied the heat transfer rate of coiled tube and suggested that the effect of curved tube is the cause for strong turbulence formation. Narrein and Mohammed [7] numerically studied the effect of Al_2O_3, SiO_2, CuO, ZnO concentration and size of the nanoparticles, different base fluids such as water, ethylene glycol and engine oil on the heat transfer and fluid flow characteristics. They suggested the nanofluids based on the SiO_2 has higher pressure drop than other Al_2O_3, SiO_2, CuO, ZnO nanofluids. They found that the pressure drop increases when increasing particle concentration and decreasing particle diameter as a result of improved viscosity. The nanofluid based on the engine oil has highest pressure drop when compared with the nanofluids based on the ethylene glycol and water. Bahiraei et al. [8] investigated the entropy generation due to particle migration for a biologically produced nanofluids in a mini double pipe heat exchanger. They found that the nanofluid at higher concentration and Reynolds number gives higher migration which generates more entropy. They studied that the heat transfer contribution increases when the inlet water temperature raises to 360K. They also found that the entropy generation at the wall has smaller contribution to the total entropy generation.

Naphon et al. [9] reported that the heat transfer characteristics of the coiled tube heat exchanger with respect to the Dean number produces better heat transfer coefficients with nominal pressure drop when compared with straight tubes. They suggested that the coiled tube heat exchanger is highly efficient for transferring heat. Narrein and Mohammed [10] critically reviewed the important aspects of nanofluids such as types of nanofluids at different base material and base fluid, thermophysical properties, heat and flow behavior, limitations of nanofluids and applications of nanofluids in helical coil tube heat exchanger. They observed that the use of nanofluids in helically coiled tube heat exchanger leads to the penalty of pressure drop. They proposed the use of nanofluids in industrial applications in real situation need more understanding.

Jayakumar et al. [11] analyzed the effect of changing pitch on Nusselt number with the same length of a helical coil tube. They studied that the changing coiled pitch decresers the effective heat transfer. Bahiraei et.al [12] investigated the exergy distribution and entropy generation of graphite-silver composite nanofluids in a micro heat exchanger. They reported the friction is more significant than the heat transfer in exergy distribution and the entropy distribution increases when increasing Reynolds number. They also presented the second law efficiency decreases by decreasing Reynolds number or particle volume concentration.

Naphon et al. [13] studied the flow and heat transfer characteristics of the spiral coiled tube and reported the heat transfer rate is affected by the secondary flow. The secondary formation strongly depends on the curvature of the coil ratio (d/D ratio) with the effective centrifugal force. The Secondary flow formation gives more mixing for the fluid flowing through the entire coils lengths. It is because the flow direction is perpendicular with an axial flow direction. Fig. 1 shows the formation of secondary flow from the primary flow. The secondary flow is induced by centrifugal force while the primary flow is hitting the curved surface. Bahiraei et al. [14] critically reviewed the recent research works on the use of nanofluids in heat exchangers. They summarized the recent investigation on the application of nanofluids in plate heat exchanger, double pipe heat exchanger, shell and tube heat exchanger and compact heat exchanger. they also revealed the challenges and opportunities for future research on nanofluids. Finally they summarized that the most of the researchers numerically examined the effect of nanofluids and compared the effect of conventional fluids on the heat transfer rate. Most of the research reports concluded that the heat transfer rate is augmented by increasing particle concentration and Reynolds number.

Ghorbani et al. [15] carried out the experimental work on the behavior of mixed convection heat transfer in a shell and coiled tube heat exchanger. They found that the increasing the mass flow rate in the tube leads to the better heat transfer in coiled tube heat exchangers. Bahiraei et al. [16] studied the thermal and hydraulic behavior of an ecofriendly graphene nanofluid in spiral heat exchanger with the counter current condition. They revealed the nanofluids give greater pressure drop than the base fluid when the Reynolds number is increased.. They concluded the performance index of nanofluids is almost 142% when increasing the Reynolds number from 1000 to 3000.

Yang et al. [17] worked on the characteristics of convective heat transfer of nanofluids in a helically coiled tube heat exchanger of the working fluid and revealed the nanofluids are superior heat transfer fluids. Bahiraei et al. [18] numerically examined the hydro thermal behavior and energy performance of hybrid nanofluids in a triple tube heat exchanger fitted with rib. They concluded that the overall heat transfer co efficient and heat transfer rate increase with increasing nanoparticles concentration and by decreasing rib pitch. They also studied the pressure drop is higher with smaller rib pitch and higher rib height. They suggested the heat exchanger with smaller rib and pitch and with higher nanoparticles concentration gives greater performance index than the other cases.

Srbislav et al. [19] worked on the performance of double helically coiled tube heat exchangers by taking the coiled tube windings and the pitch to study the heat transfer rate. They concluded that the heat transfer rate is higher than single tube based on the hydraulic diameter of the tube. Jamshidi et al. [20] analyzed the heat transfer in a shell and helically coiled tube heat exchanger. They found that the higher coiled tube diameter, pitch, and flow rate enhance the heat transfer rate. Jamshidi et al. [21] investigated the heat and flow behavior of helically

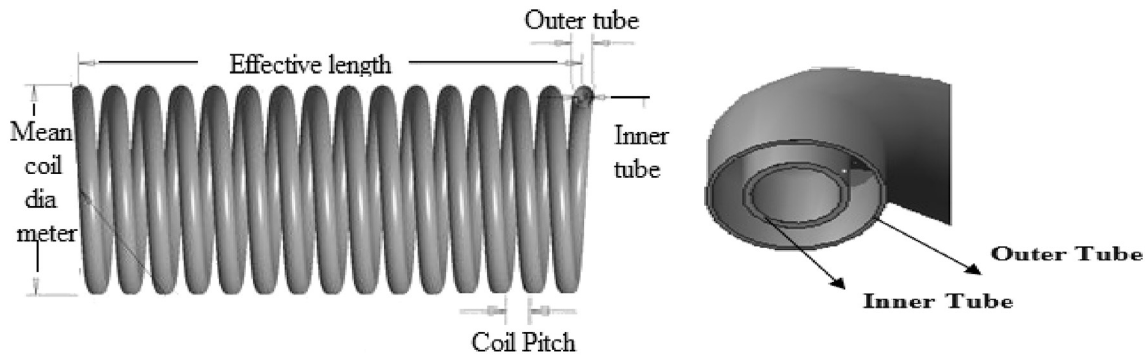

Fig. 2. Modeling.

coiled tube by using nanofluids as target fluids. They suggested that the helically coiled tube heat exchanges gives improved heat transfer coefficients with the nominal pressure drop and friction factor. Yang San et al. [22] analyzed the heat transfer coefficient, friction factor of helically coiled tube heat exchanger. They found that the friction factor increases with increasing diameter and length of the pipe and friction factor decreases with increasing Reynolds Number and also found that the Nusselt number increases with increasing Reynolds number.

Austin [23] studied that the effect of pitch in a double helically coiled tube heat exchanger on heat transfer and pressure drop. They reported the friction factor is decreased by increasing the pitch. Yang et al. [24] investigated the helically coil tube pitch affects the Nusselt number and friction factor and pressure drop in free and forced convection. Prabhanjan et al. [25] carried out the experiment on convective heat transfer in helical coil tube heat exchanger. They found that the tube side Nusselt number is better than the tube with the higher tube diameter. Akhavan-Behabadi et al. [26] conducted an experiment on helically coiled tube heat exchanger by changing the pitch and coiled tube diameter to study heat and flow behaviors. They found that the helically coiled tubes are creating more pressure drop than that of the straight tube. Pramod et al. [27] analyzed the effect of changing the diameter ratio changes the intensity of secondary flow formation to achieve maximum heat transfer rates. Jayakumar et al. [28] experimentally analyzed the heat transfer of a helically coiled tube. They found that the maximum heat transfer coefficient is obtained by maintaining a steady state condition. Prabhanjan et al. [29] and Piazza et al. [30] investigated the effect of curvature ratio on creating turbulence in a helically coiled tube. They proposed the curvature ratio is the key parameter to intensify the flow in the coil tubes.

Many works have been carried out to improve the heat transfer coefficient by different techniques. The one among them is the changing the thermal conductivity of the heat-flowing fluid. In this point of view, the solid micro particles have been dispersed into traditional heat transfer fluids and named as micro fluids. However, most of the researchers proposed that the micro fluids are not suitable for improving the heat transfer as the rapid settlement of micro-sized solid particles in the base fluids. The nanoparticles have been dispersed into the base fluid and named as nanofluids. The nanofluids are reported they have been higher thermal conductivity than the traditional fluids with more potential to applied in the heat transfer area.

Table 1
Dimensional parameters of Double helically coiled tube.

Helically coiled tube	Copper
Inner diameter of inner coil (dii)	5.85mm
Outer diameter of inner coil (dio)	6.35mm
Internal diameter of outer coil (doi)	12mm
External diameter of outer coil (doo)	12.7mm
Coil pitch(P)	20mm
No.of Coils turns(n)	15
Mean Coil inner diameter (Di)	100mm
Mean Coil outer diameter (Do)	125.35mm
Thermal conductivity of copper K	401W/m K
Density of copper	8960 kg/m^3

Alywaell [31] carried out the CFD analysis to investigate the effect of nanofluids on heat and flow behavior in a double helically coiled tube with Al_2O_3/water nanofluids. The heat transfer coefficient is improved by increasing the nanofluid volume concentrations with the pressure drop increased up to 2%. Huminic et al. [32] numerically investigated the heat transfer enhancement in a double helically coiled tube heat exchanger by using CuO and TiO_2 nanofluids, Dean number is the function of curvature ratio and it affects the heat transfer than water. Jayakumar et al. [33] Mukeshkumar et al. [34] revealed the CFD Nusselt number data holds good with experiment. Palanisamy et al. [35] experimentally investigated the effect of MWCNT/water nanofluids on heat and flow behavior of cone helical coiled tube. They reported that the MWCNT/water nanofluids offers maxumum heat transfer than water with negligible pressure drop.

Mukeshkumar et al. [36] experimentally studied the effect of the MWCNT/water nanofluids concentration on stability. The stability determines the thermal conductivity of nanofluids. They reported the MWCNT/water nanofluids with crown oil as base fluid have more stability than other two base fluids. Muruganandam et al. [37] experimentally analyzed the effect of MWCNT/water nanofluids on exhaust gas temperature in a diesel engine. They reported the diesel engine run by MWCNT/water nanofluids as a coolant gives lower exhaust gas temperature up to the level of 10–15% than water. Chaves et al. [38] numerically investigated with CFD software to study heat exchanger effect of the helically coiled tube. The outlet temperature of the fluids is found to be decreasing when increasing the number of coil turns. Increasing the number of coil turns increases higher heat transfer rate in the coiled tube heat exchanger.

Jayakumar et al. [39] computationally studied the heat transfer rate of double helically coiled tube heat exchanger with CFD software. They suggested the curved tube gives better heat transfer coefficient than straight tube and the curved tube gives more intensity of turbulence and resulting in better mixing. Kumar et al. [40] numerically investigated the heat transfer and friction factor double helically coiled tube heat exchanger with ANSYS. The meshing was generated ANSYS FLUENT. They revealed that the CFD Nusselt number and friction factor data hold reasonably good agreement with the experimental data.

It is studied from the literature review that most of the experimental works on double helically coiled tube heat exchanger have been done by using oxide nanofluids. Very little works have been done on double helically coiled tube heat exchanger by using MWCNT/water nanofluids with CFD software. Therefore this investigation deals with the thermal and flow behavior of double helically coiled tube heat exchanger handling MWCNT/water nanofluids at three different volume concentrationss.

Table 2
Testing conditions of MWCNT/water nanofluids.

S.No	Constraints	Range/standards
1	Inner tube fluid **(Inner coil)**	MWCNT/water nanofluids
2	mass flow rate of inner coil	0.050–0.08 kg/m^3
3	Dean number	1300 < De < 2000
4	Initial temperature of coil tube (inner tube)	305 K (32 °C)
5	Flow velocity of coil tube	1.2–2 m/s
6	volume concentration of nanofluid	0.2%,0.4%, and 0.6%
7	Density of nanofluid 0.2%,0.4% and 0.6%	1220, 1440, and 1660 kg/m^3
8	Thermal conductivity of nanofluid 0.2%,0.4% and 0.6%	0.62, 0.625, and 0.635 W/mK
9	Specific heat of nanofluid 0.2%,0.4% and 0.6%	3086, 1663, and 1014 J/kgK
10	Viscosity of nanofluid at 0.2%,0.4% and 0.6%	0.825, 0.83, and 0.85
11	Outer coiled tube fluid (**Outer coil)**	Hot fluid (Water)
12	Mass flow rate of Inner tube	0.139 kg/m^3
13	Dean number differences	1300 < De < 2000
14	Initial temperature of coil tube **(outer tube)**	338 K (65 °C)
15	Outer tube velocity rate	1.2–2 m/s
16	Hot water density	997 kg/m^3
17	Hot water viscosity	0.7
18	Hot water specific heat capacity	4181 J/kg K
19	Hot water thermal conductivity	0.613 W/m K

2. Methodology

2.1. Helical coil modeling

The computer system with i3-6006U core processor, 2.00 GHz, and 8 GB RAM capacity was used to model, mesh and simulate the MWCNT/water nanofluids in the test section. Governing equations are solved with the software package of ANSYS R14.5. The double helically coiled tube heat exchanger is modeled with Cre-O software. Fig. 2 demonstrates the modeling of double helically coiled tube heat exchanger used in this CFD analysis. The test section has two helically coiled tubes. One is inner tube handling nanofluids and (outer tube) tube annulus handling hot water. The test section is made with 17 coiled turns with a helical sweep. Table 1 and Table 2 show the geometrical parameters, input data and physical properties.

2.2. Meshing

The modeling of the test section is meshed with ANSYS 14.5. The coarser meshing is created throughout the effective length of the tube. Fig. 3 represents the meshing of double helically coiled tube heat exchanger used in this CFD analysis. The meshing contains the collaborated cells for triangular and quadrilateral expressions at boundary conditions. Much effort is given to the structured hexahedral cells. The smooth meshing is created, edges, as well as regions of temperature and pressure constraints, meshed. Tables 3 and 4 show the meshing information of the test section.

The following are the consideration for this CFD analysis: The MWCNT/water nanofluids are incompressible fluid and single phase fluid. The effect of radiation and net convection are neglected. The thermo physical properties are not temperature dependent. Uniform dispersion nanoparticles. The flow is hydro dynamic. And constant heat flux condition is used. Fig. 4 shows the boundary conditions of the test section.

Table 3
Details of meshing.

Domain	Nodes	Elements
Cold_fluid	389108	340938
Hot_fluid	4327200	327825
Inner-pipe	183624	100533
Outer_pipe	253576	139872
All domains	1263508	909168

Table 4
Boundary conditions.

Domain	Cold fluid	Hot fluid	Boundaries
Boundary	Nanofluid inlet	Hot inlet	Mass-flow-inlet
	Nanofluid outlet	Hot outlet	Pressure-outlet
	Wall cold fluid inner pipe shadow	Wall hot fluid inner pipe shadow	Wall
	Wall hot fluid outer pipe shadow		Wall
	Wall inner pipe		Wall
	Adiabatic wall		Wall
	Wall hot fluid outer pipe		Wall
	Wall outer pipe		Wall

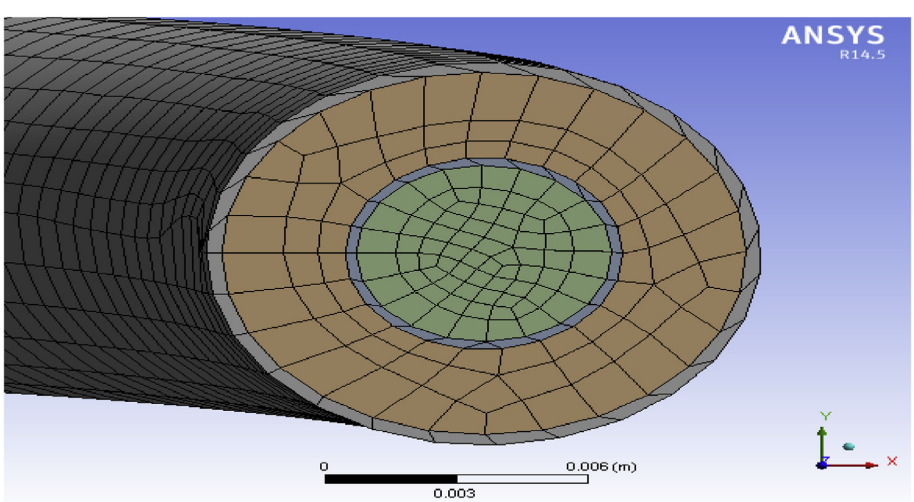

Fig. 3. Formation of meshing.

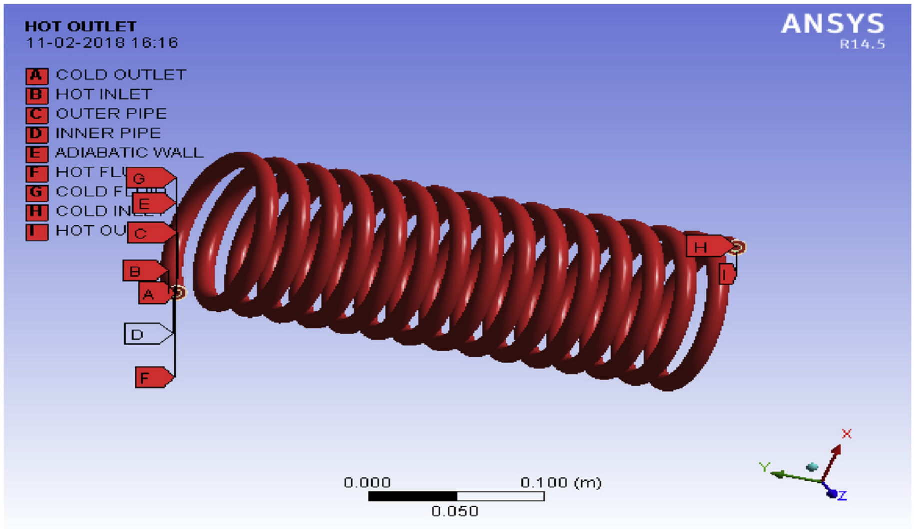

Fig. 4. Boundary conditions of the test section.

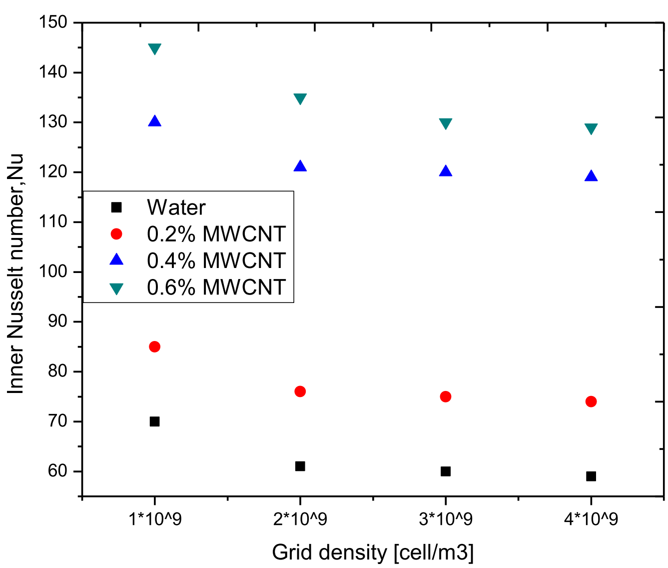

Fig. 5. Grid density (cell/m^3).

2.3. Numerical simulation

The Numerical simulation was performed by the steady state with pressure oriented methods. The partial differential equation is used to find out the mass and momentum values under steady state condition. Pressure and velocity are found by the basic algorithms and discretion equations used are in second order. All the governing equations have been used for simulation and various tests have been conducted based on the same. The k-epsilon model is chosen for this analysis as the k-epsilon model predicts well far from the boundaries (wall) and k-omega model predicts well near wall. Continuity, energy and Navier Stokes equations are used to find the conditions for flowing fluid in the helically coiled tube with Eqs. (1), (2), (3), (4), and (5).

The continuity equation gives the conservation of mass and is given by

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho U_1}{\partial x_1}+\frac{\partial \rho U_2}{\partial x_2}+\frac{\partial \rho U_3}{\partial x_3}=0 \tag{1}$$

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial x_1}=0 \tag{2}$$

$$\frac{\partial \rho}{\partial t}=0 \text{ (for incmpressible fluid)} \tag{3}$$

The momentum balance follows Newton's second law. Two forces are acting on the body and surface pressures. CFD software provides, the momentum equation is given by

$$\rho\left(\mathrm{u}\frac{\partial U}{\partial x}+\mathrm{v}\frac{\partial V}{\partial x}\right)=-\rho g-\frac{\partial \rho}{\partial x}+\mu\frac{\partial^2 y}{\partial x^2} \tag{4}$$

The governing energy equation is given by:

$$\rho Cp\left(\mathrm{u}\frac{\partial T}{\partial x}+\mathrm{v}\frac{\partial T}{\partial y}\right)=\mathrm{k}\frac{\partial^2 T}{\partial y^2} \tag{5}$$

where ρ is the density kg/m^3, t is the time in s, U, and V are velocity components, Cp is the specific heat in J/kgK, u,v are velocity along x and y directions respectively and k is the thermal conductivity in w/mK. T is the temperature in K.

2.4. Numerical analysis

The geometric modeling of the helically coiled tube was modeled by using ANSYS R14.5 software. To confirms the meshing of the coil, the grid independence test was conducted and finalized the quality of the meshing. Independency test was performed with four grid systems to check the accuracy and validity of the results. The grid densities between 1×10^9 and 4×10^9 were generated. Fig. 5 illustrates the Nusselt number and friction factor with various grid densities. It is studied that no change in Nusselt number and friction factor with the grid 2.15×10^9 density and the same density is taken for this analysis.

Initially, hot and cold water are used to check the simulation and recorded the pressure and temperature of MWCNT/water of nanofluids at 0.2%, 0.4% and 0.6% volume concentrations with the Dean number range of 1300–2000. The sample temperature and pressure profiles of 0.2% MWCNT/water nanofluids at the Dean number 2000 is taken for this CFD analysis. Total number of trails: 4 flow rate in LPH × 4 (1 Base fluid +3 different volume concentrations of MWCNT/water nanofluids) × 1 (parallel or counter flow) = 16 trails. Every trail has taken more than 7 h for simulation. Tables 3 and 4 show dimensional parameters and test conditions of MWCNT/water nanofluids in double helically coiled tube. Pak et.al [41] proposed Eqs. (6), (7), (8), and (9) for calculating the

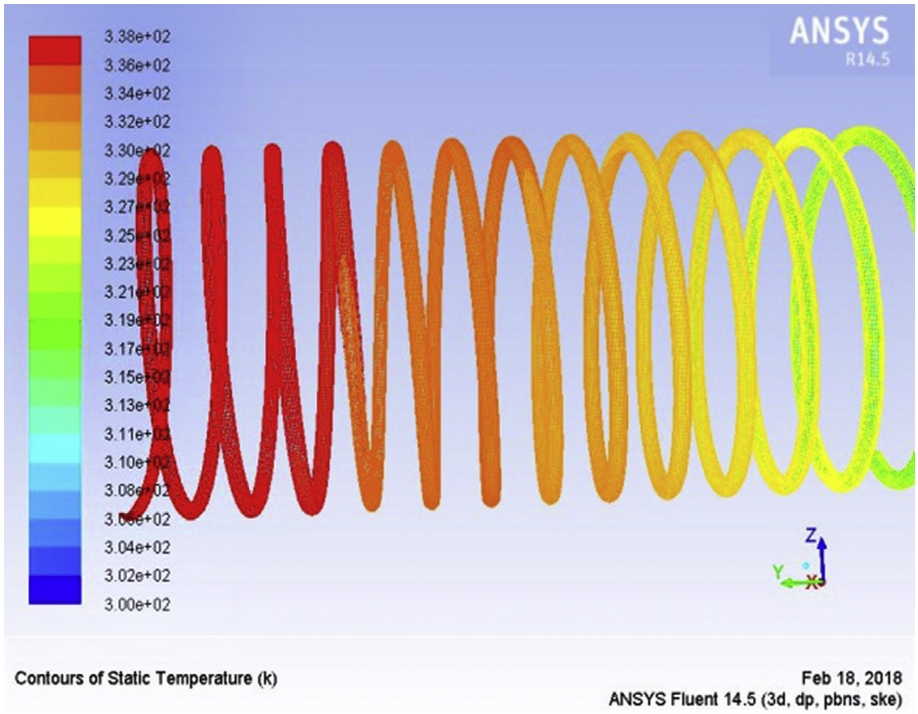

Fig. 6. Static temperature contours of 0.2 % MWCNT/water nanofluids.

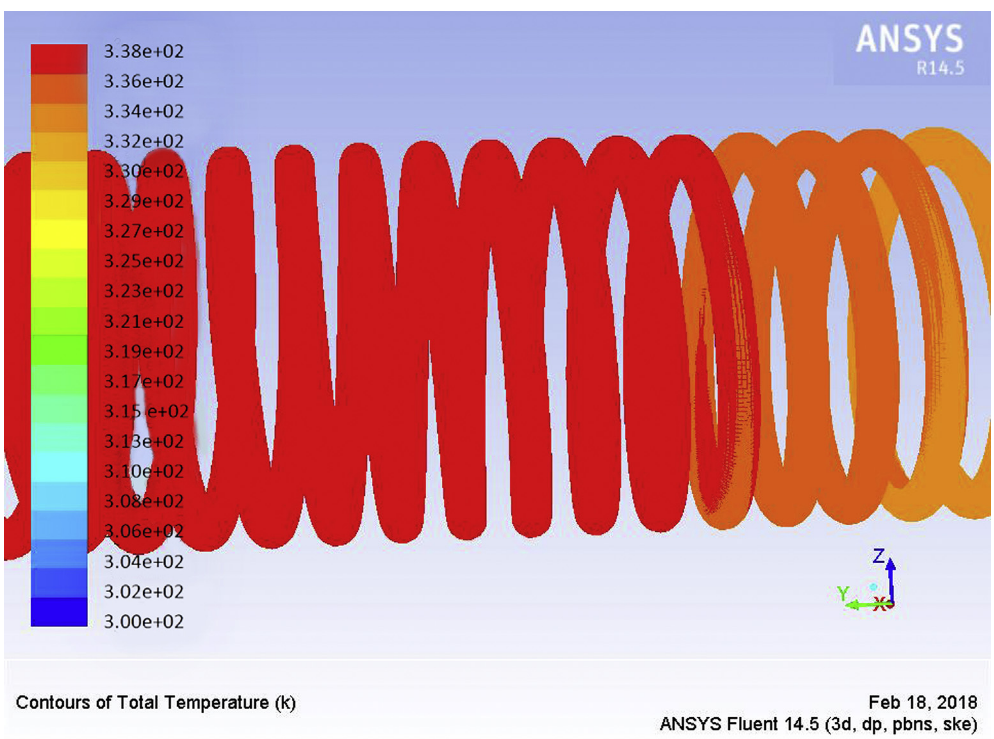

Fig. 7. Total temperature contours of 0.2% MWCNT/water nanofluids in a section YZ level.

thermo physical properties MWCNT.

Density in kg/m^3

$$\rho_{nf} = \phi\rho_S + (1-\phi)\rho_w. \tag{6}$$

Specific Heat in J/kg K

$$(\rho c_p)_{nf} = (1-\phi)(\rho c_p) + \phi(\rho c_p)_S \tag{7}$$

Effective thermal conductivity in W/mk

$$\frac{k_{eff}}{k_f} = 1 + 7.47\phi \tag{8}$$

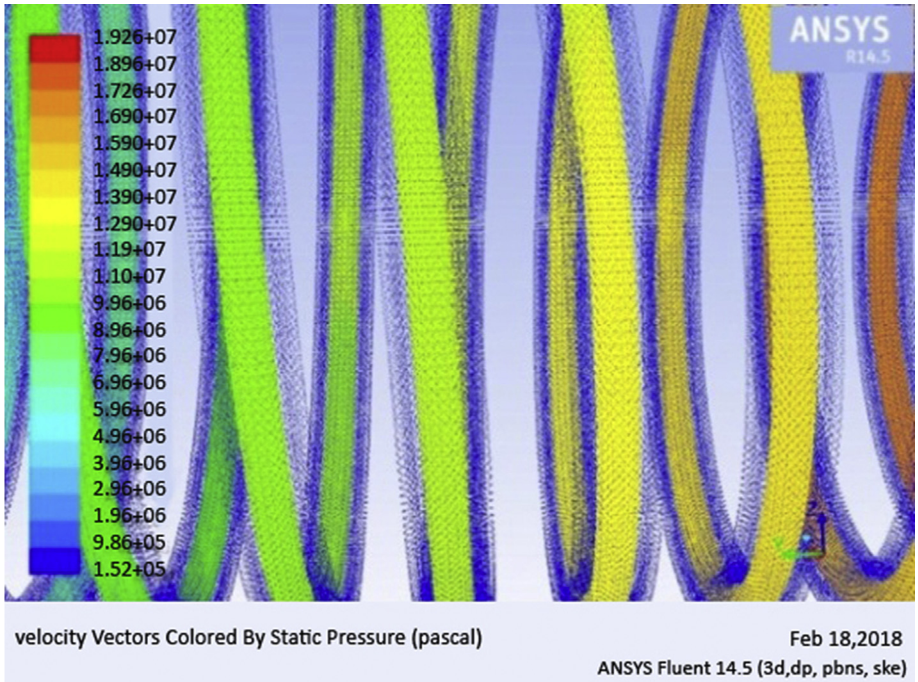

Fig. 8. Pressure drop in a section YZ level.

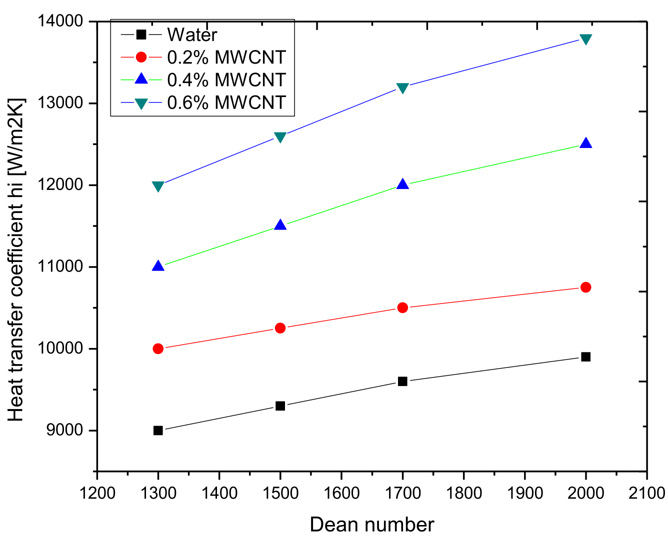

Fig. 9. Heat transfer coefficient vs Dean number.

Dynamic viscosity in kg/m2s

$$\frac{\mu_{nf}}{\mu_f} = \left(1 + 39.11\phi + 533.9\phi^2\right) \quad (9)$$

Figs. 6, 7, and 8 represent the points of static temperature, total temperature and pressure drop of particles respectively. It is shown that the two regions like minimum temperature color is marked as blue, a minimum pressure drop color is marked as blue in the inlet of the coil. Maximum temperature region color is marked as green; the maximum pressure drop color is red at the outlet of the coil. The inner coil fluid inlet temperature is 304 K, outer coil outlet fluid temperature is 338 K and the pressure drop occurred in 0.65 bar.

The laminar convective heat transfer and pressure drop of double helically coiled tube heat exchanger are described with the following dimensionless number and various parameters (Eqs. (10), (11), and (12)).

$$\mathrm{D_e} = \mathrm{R_e}(\mathrm{r/R})^{0.5} \quad (10)$$

$$\mathrm{N_u}(\mathrm{nf}) = \frac{h_i{*}d_i}{K_C} \quad (11)$$

$$\mathrm{f} = \frac{\Delta p{*}Di}{2{*}\rho{*}v^2 L} \quad (12)$$

In this analysis, the validation of CFD data is carried out with the experimental data proposed by Chandrasekar et al. [42] who conducted an experimental test on laminar convective heat transfer and flow behavior of double helically coiled tube heat exchanger in the Dean number range of 1300–2000. Experimentally found heat transfer coefficient increase with increasing the MWCNT nano particle volume concentration. The maximum heat transfer coefficient and Nusselt number were found to be 50%, 56%, and 60% respectively higher than water at 0.6% MWCNT nano particle volume concentration. Fig. 10 illustrates the experimental Nusselt number and CFD Nusselt number for water under laminar flow condition.

3. Results and discussion

3.1. Heat transfer coefficient

From Fig. 9, it is seen that the Nusselt number increases with increasing Dean number and volume concentrations of nanofluids. The Nusselt number of nanofluids is found to be higher than the water with respect to increasing Dean number in the range 1300–2000. It is studied that the rate of change of increase of Nusselt number is increased with respect to the Dean number. The maximum rate of change of Nusselt number is found to be at the highest Dean number.

The Nusselt number of MWCNT/water nanofluids is found to be 20%, 24%, and 30% at 0.2%, 0.4% and 0.6% volume concentrations respectively higher than that of water at the Dean number range of 1300–2000. This is simply because of the higher thermal conductivity of nanofluids

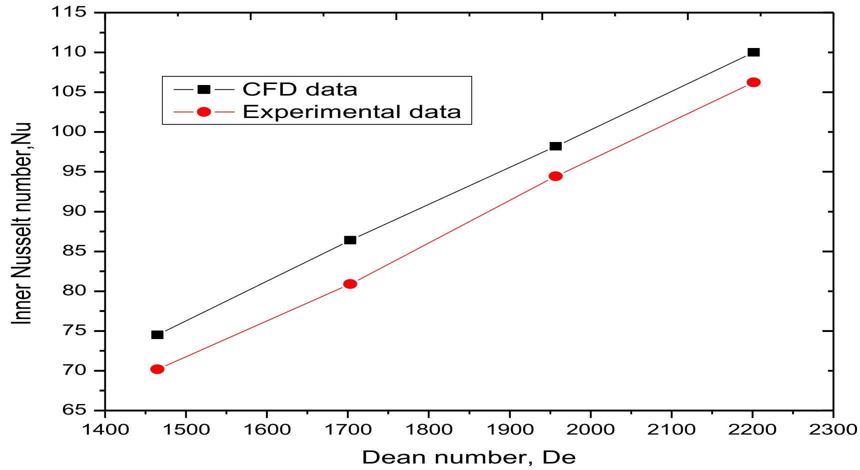

Fig. 10. Nusselt number Vs Dean number for water.

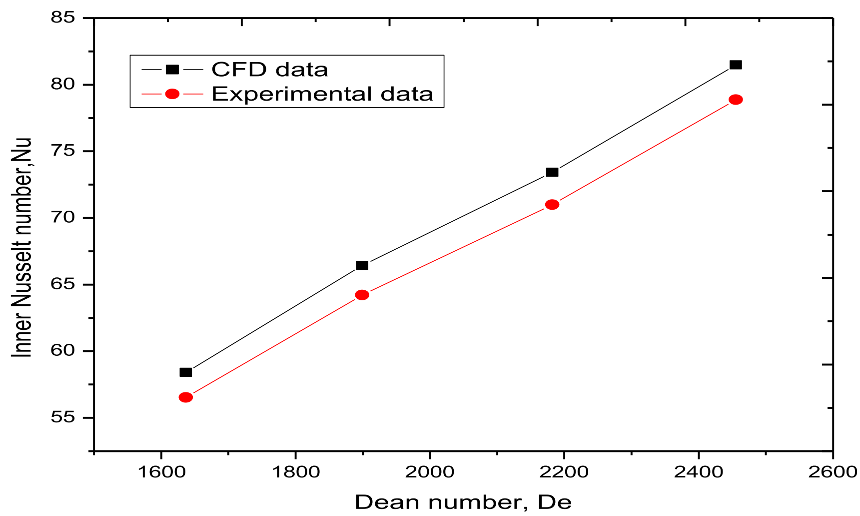

Fig. 11. Nusselt number Vs Dean number for 0.2% MWCsNT/water nanofluids.

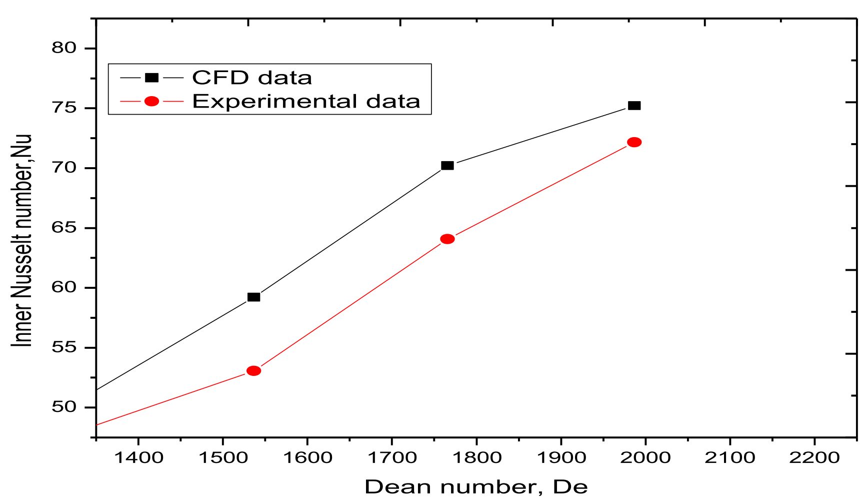

Fig. 12. Nusselt number Vs Dean number for 0.4 % MWCNT/waternanofluids.

and intensification of secondary flow formation leading to lower the residence time dispersion of nanoparticles and base fluids. This lower residence time dispersion is resulting better mixing of the fluid and nanoparticles. Apart from this the Brownian motion of MWCNT contributes a little to enhance the heat transfer.

It is seen from Fig. 10 that the Nusselt number increases with increasing Dean number. The Nusselt number is minimum at the Dean number 1300 and the maximum at the Dean number 2000. It is found

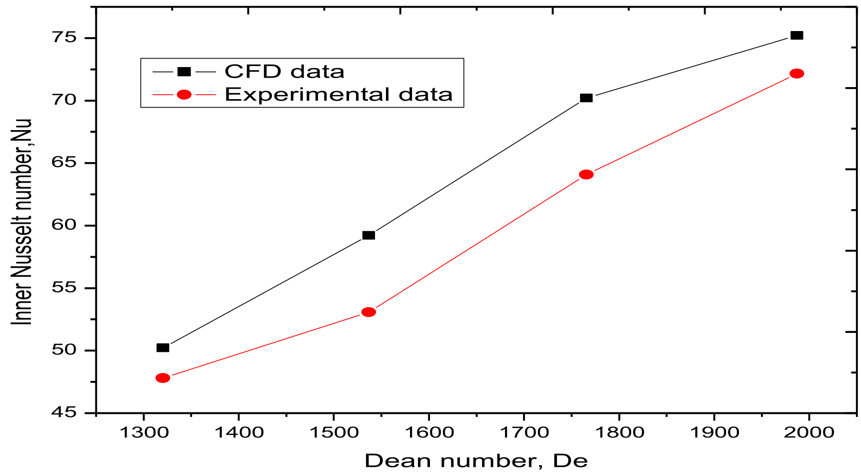

Fig. 13. Nusselt number Vs Dean number for 0.6 % MWCNT/water nanofluids.

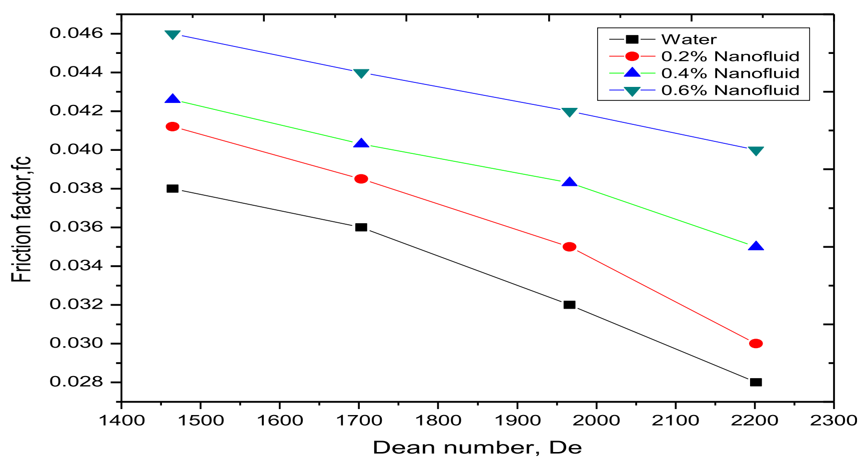

Fig. 14. Friction factor with Dean number.

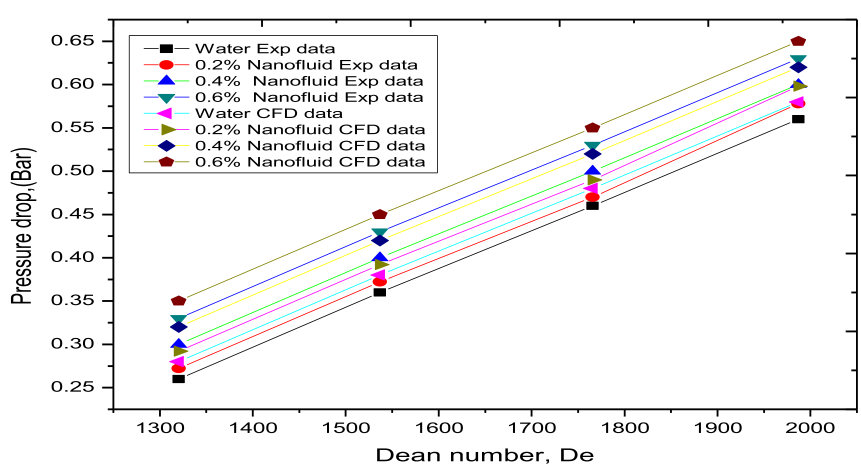

Fig. 15. CFD pressure drop Vs experimental pressure drop.

that the CFD results hold good agreement with the experimental results. The relative error between the CFD result and the experimental results is 6.5%.

Fig. 11 shows the experimental Nusselt number and CFD Nusselt number for 0.2% MWCNT/water nanofluids under laminar flow condition. Found that the Nusselt number increases with increasing Dean Number. This is due to higher mass flow rate. The Nusselt number is minimum at the Dean number of 1300 and the maximum at the Dean number of 2000. It is observed that the CFD results close to the experimental values. The relative error between the CFD result and the experimental result is 5.5%.

Fig. 12 represents the deviation between the CFD Nusselt number vs experimental Nusselt number for 0.4% MWCNT/water nanofluid under laminar flow condition. It is studied that the Nusslet number increases

Fig. 16. Before test surface of coil inner surface.

Fig. 17. After test surface of coil inner surface.

with increasing Dean number. The Nusselt number minimum at the Dean number 1300 and the maximum at the Dean number 2000. CFD results show that better performance with the experimental values. The relative error between the CFD result and the experimental result is 7%. The increase in Nusselt number with respect to Dean number is due to the higher mass flow rate of the fluids.

Fig. 13 illustrates the experimental Nusselt number and CFD Nusselt number for 0.6% MWCNT/water nanofluids under laminar flow condition. It is seen from Fig. 13 that the Nusslet number increases with increasing Dean Number. The Nusselt number is minimum at the Dean number of 1300 and the maximum at the Dean number of 2000. The CFD results show that better performance with the experimental values. The relative error between the CFD results and the experimental results is 7.5%. The increase in Nusselt number with respect to Dean number is due to the higher mass flow rate of the fluids.

3.2. *Friction factor and pressure drop analysis*

Figs. 14 and 15 show the effect of nanofluids on friction factor and pressuure drop resprctively. It is observed that the MWCNT nanoparticle volume concentrations gives remarkable changes in the flow behavior. It is found that the friction factor increases when particle volume concentrations is increased. Recorded that the friction factors are 12%, 22% and 30% greater than water for 0.2%, 0.4% and 0.6% MWCNT/water nanofluids respectively at the Dean number of 2000. The is due to loading more particles which leads to more contact area with the heat transfer surface area. Moreover the higher particle loading is resulting higher viscosity and in turn higher friction factor. This is may be due to the centrifugal force which pushes the particles towards outside and forming strong secondary flow in the coiled tube.

Fig. 15 represents the effect of MWCNT/water nanofluids on pressure drop in the coiled tube. an increasing volume concentrations of MWCNT/water nanofluids creates the maximum pressure variations. The pressure drop is found to be 4%, 6% and 10% for 0.2 %, 0.4% and 0.6% volume concentrations respectively greater than water at the Dean number of 2000. The error between the CFD and the investigational range is 2%–2.5%. The maximum pressure drop is found to be 0.38 bar for water 0.3914 bar for 0.2% nanofluids, 0.42 bar of 0.4%MWCNT/water nanofluids and 0.45 bar for 0.6% MWCNT/water nanofluids at the Dean number of 2000.

It is studied that the pressure drop increases with increasing nanofluids volume concentrations. The 0.6% nanofluid gives higher pressure drop than water and other nanofluids. This is simply because of improved viscosity when particle volume concentrations are increased. It is studied that the application 0.6% MWCNT/water nanofluids in helically coiled tube, the secondary flow generation becomes very strong and the MWCNT s are thrown out towards the coiled tube wall and resulting higher pressure drop than water. The higher pressure drop due to MWCNT/water nanofluids may be expected more than 4%, 6% and 10% for 0.2 %, 0.4% and 0.6% volume concentrations respectively when the nanofluids are passing through in the coiled tube with the same entry temperature. This is because of the effect of temperature on viscosity. In this investigation, the exit temperature of nanofluids is higher than the inlet temperature. Therefore the improved temperature of nanofluids while passing through the coiled tube reduces the viscosity and its effect. The viscosity of nanofluids is reduced by the increased temperature of nanofluids when nanofluids passes through the coiled tube. Therefore pressure drop depends on the inlet temperature of nanofluids.

3.3. *Inner tube surface modifications*

George et al. [43] reported that the wear of the tube surface depends on nanoparticles size, shape, velocity, particles concentration and turbulence of the fluids. The MWCNTs are deposited in the inner tube and they create the wear and erosion. They are shown in Figs. 16 and 17. Figs. 16 and 17 show that there is small amount of MWCNT are deposited due to higher static time of MWCNTs while passing through the coiled tube over many trails. This is because of higher volume concentration MWCNT.

4. Conclusions

In this analysis, the heat transfer and pressure drop of a double helically coiled tube heat exchanger handling MWCNT/water nanofluids have been studied with CFD software package. Initially, hot and cold water are used to check the simulation and recorded the pressure and temperature of MWCNT/water of nanofluids at 0.2%, 0.4% and 0.6% volume concentrations with the Dean number range of 1300–2000. The sample temperature and pressure profiles of 0.2% MWCNT/water nanofluids at the Dean number 2000 is taken for this CFD analysis. Total number of trails: 4 flow rate in LPH $\times$ 4 (1 Base fluid +3 different volume concentrations of MWCNT/water nanofluids) $\times$ 1 (parallel or counter flow) = 16 trails. It is studied that the Nusselt number is 20%, 24%, and 30% higher than water at 0.2%, 0.4%, and 0.6% nanofluids respectively at the Dean number of 2000. These enhancements are due to the improved higher thermal conductivity of nanofluids and generating stronger secondary flow. Also found that the pressure drops are 4%, 6% and 10% for 0.2%, 0.4%, and 0.6% nanofluids respectively are higher than water. This is due to the effect of temperature on nanofluids viscosity. Finally the CFD data were compared with experimental data and hold good agreement with the deviation of CFD Nusselt number and pressure drop are 7.2% and 8.75% with the experimental data. Therefore determining the Nusselt number and pressure drop of double helically coiled tube heat exchanger handling MWCNT/water nanofluids with CFD software analysis is the good choice.

Declarations

Author contribution statement

P. C. Mukesh Kumar: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

M. Chandrasekar: Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] Vimal kumar, Supreet saini, Manish sharma, K.D.P. Nigam, Pressure drop and heat transfer study in tube helical coil heat exchanger, Chem. Eng. 61 (2006) 4403–4416.
[2] W.R. Dean, Note on the motion of fluid in A curved pipe, Phil. Mag. Ser. 7 (4) (1927) 208–223.
[3] W.R. Dean, The streamline motion of fluid in A curved pipe, Phil. Mag. Ser. 7 (5) (1928) 673–695.
[4] H.A. Mohammed, K. Narrein, Thermal and hydraulic characteristics of nanofluid flow in a helically coiled tube heat exchanger, Int. Commun. Heat Mass Transf. 39 (2012) 1375–1383.
[5] Y.M. Ferng, W.C. Lin, C.C. Chieng, Numerically investigated effects of different dean number and pitch size on flow and heat transfer characteristics in a helically coil-tube heat exchanger, Appl. Therm. Eng. 36 (2012) 378–385.
[6] S.A. Berger, L. Talbot, L.S. Yao, Flow in curved pipes, Annu. Rev. Fluid Mech. 15 (1983) 461–512.
[7] K. Narrein, H.A. Mohammed, Influence of nanofluids and rotation on helically coiled tube heat exchanger performance, J. Comput. Theor. Nanosci. 11 (2014) 911–927.
[8] Mehdi Bahiraei, Mohammad Jamshidmofid, Saeed Heshmatian, Entropy generation in a heat exchanger working with a biological nanofluid considering heterogeneous particle distribution, Adv. Powder Technol. (2017) 2380–2392.
[9] Paisarn Naphon, Somchai Wongwises, A study of the heat transfer characteristics of a compact spiral coil heat exchanger under wet-surface conditions, Exp. Therm. Fluid Sci. 29 (2005) 511–521.
[10] K. Narrein, H.A. Mohammed, Heat transfer and fluid flow characteristics in helically coiled tube heat exchanger (HCTHE) using nanofluids, A Review"- Journal of Computational and Theoretical Nanoscience 11 (2014) 911–927.
[11] J.S. Jayakumar, S.M. Mahajani, J.C. Mandal, N. Iyer Kannan, P.K. Vijayan, CFD analysis of single-phase flows inside helically coiled tubes, Comput. Chem. Eng. 34 (2010) 430–446.
[12] Mehdi Bahiraei, Mohammad Jamshidmofid, Mohammad Amani, Ramtin Barzegarian, Investigating exergy destruction and entropy generation for flow of a new nanofluid containing graphene–silver nanocomposite in a micro heat exchanger considering viscous dissipation", Powder Technol. (2018), 06-007.
[13] Paisarn Naphon, Study on the heat transfer and flow characteristics in a spiral-coil tube, Int. Commun. Heat Mass Transf. 38 (2011) 69–74.
[14] Mehdi Bahiraei, Reza Rahmani, Yaghoobi Ali, Erfan Khodabandeh, Ramin Mashayekhi, Mohammad Amani, "Recent research contributions concerning use of nanofluids in heat exchangers: A critical review", Appl. Therm. Eng. 133 (2018) 137–159.
[15] Nasser. Ghorbani, Taherian Hessam, Gorji Mofid, Mirgolbabaei Hessam, An experimental study of the thermal performance of shell-and-coil heat exchangers, Int. Commun. Heat Mass Transf. 37 (2010) 775–781.
[16] Mehdi Bahiraei, Hamid Kiani Salmia, Mohammad Reza Safaeib, Effect of employing a new biological nanofluid containing functionalized graphene nanoplatelets on thermal and hydraulic characteristics of a spiral heat exchanger, Energy Convers. Manag. 180 (2019) 72–82.
[17] Zhen Yang, Zhenxing Zhao, Yinhe Liu, Yongqiang Chang, Zidong Cao, Convective heat transfer characteristics of high-pressure gas in the heat exchanger with membrane helical coils and membrane serpentine tubes, Exp. Therm. Fluid Sci. 35 (2011) 1427–1434.
[18] Mehdi Bahiraei, Nima Mazaheri, Rizehvandi Ali, "Application of a hybrid nanofluid containing graphene nanoplatelet– platinum composite powder in a triple-tube heat exchanger equipped with inserted ribs", Appl. Therm. Eng. (2018), 12-072.
[19] B. Genic Srbislav, M. Jacimovic Branislav, S. Jaric Marko, J. Budimir Nikola, M. Dobrnjac Mirko, Research on the shell-side thermal performances of heat exchangers with helical tube coils, Int. J. Heat Mass Transf. 55 (2012) 4295–4300.
[20] N. Jamshidi, M. Farhadi, D.D. Ganji, K. Sedighi, Experimental analysis of heat transfer enhancement in the shell and helical tube heat exchangers, Appl. Therm. Eng. 51 (2013) 644–652.
[21] Naghmeh Jamshidi, Mousa Farhadi, Kurosh Sedighi, Davood Domeiry Ganji, Optimization of design parameters for nanofluids flowing inside helical coils, Int. Commun. Heat Mass Transf. 39 (2012) 311–317.
[22] San Jung-Yang, Chih-Hsiang. Hsu, Chen Shih-Hao, Heat transfer characteristics of A helical heat exchanger, Appl. Therm. Eng. 39 (2012) 114–120.
[23] D.S. Austen, H.M. Soliman, Laminar flow and heat transfer in helically coiled tubes with substantial pitch, Exp. Therm. Fluid Sci. 1 (1988) 183–194.
[24] G. Yang, F. Dong, M.A. Ebadian, Laminar forced convection in A helicoidal pipe with finite pitch, Int. J. Heat Mass Transf. 38 (1995) 853–862.
[25] Devanahalli G. Prabhanjan, Timothy J. Rennie, G.S.Vijaya Raghavan, Natural convection heat transfer from helically coiled tubes, Int. J. Therm. Sci. 43 (2004) 359–365.
[26] M. Fakoor-Pakdaman, M.A. Akhavan- Behabadi, P. Razi, An empirical study on the pressure drop characteristics of nanofluid flow inside helically coiled tubes, Int. J. Therm. Sci. 65 (2013) 206–213.
[27] S. Pramod, Purandare, M. Mandar, Lele Rajkumar Gupta, Parametric analysis of helical coil heat exchanger, Int. J. Eng. Res. Technol. 1 Issue 8 (2012) 1–5.
[28] J.S. Jayakumar, S.M. Mahajani, J.C. Mandal, P.K. Vijayan, Rohidas Bhoi, Experimental and CFD estimation of heat transfer in helically coiled heat exchangers, Chem. Eng. Res. Des. 86 (Issue 3) (2008) 221–232.
[29] D.G. Prabhanjan, T.J. Rennie, G.S.V. Raghavan, Natural convection heat transfer from helically coiled tubes, Int. J. Therm. Sci. 43 (4) (2004) 359–365.
[30] Ivan Di Piazza, Michele Ciofalo, Numerical prediction of turbulent flow and heat transfer in helically coiled pipes, Int. J. Therm. Sci. 49 (2010) 653–663.
[31] A. AlyWaelI, Numerical study on turbulent heat transfer and pressure drop of nanofluid in coiled tube-in-tube heat exchangers, Energy Convers. Manag. 79 (2014) 304–316.
[32] Gabriela. Huminic, Huminic angel, "heat transfer characteristics in double tube helical heat exchangers using nanofluids, Int. J. Heat Mass Transf. 54 (2011) 4280–4287.
[33] J.S. Jayakumar, S.M. Mahajani, J.C. Mandal, K.N. Iyer, P.K. Vijayan, CFD analysis of single-phase flows inside helically coiled tubes, Comput. Chem. Eng. 34 (4) (2010) 430–446.
[34] P.C. Mukesh Kumar, K. Palanisamy, J. Kumar, R. Tamilarasan, S. Sendhilnathan, CFD analysis of heat transfer and pressure drop in helically coiled heat exchangers using Al_2O_3/water nanofluid, J. Mech. Sci. Technol. 29 (2) (2015).
[35] K. Palanisamy, P.C. Mukesh kumar, Heat transfer enhancement and pressure drop analysis of a cone helical coiled tube heat exchanger using MWCNT/water nanofluid, J. Appl. Fluid Mech. 10 (2017) 7–13.
[36] P.C. Mukesh Kumar, M. Muruganandam, Stability analysis of heat transfer MWCNT with different base fluids, J. Appl. Fluid Mech. 10 (2017) 51–59.
[37] M. Muruganandam, P.C. Mukesh Kumar, Experimental analysis of four stroke diesel engine by using carbon nano tubes based nano fluids as a coolant, J. Appl. Fluid Mech. 10 (2017) 1–5.
[38] C. Achaves, D.R.F. Decastro, W.Q. Lamas, J.R. Camargo, F.J. Grandinetti, CFD simulation to analyze the performance of tube in tube helical coiled of heat exchanger, Acad. J. 9 (7) (2014) 181–188.
[39] R. Manna, J.S. Jayakumar, R.B. Grover, Thermal hydraulic design of a condenser for a natural circulation system, J. Energy Heat Mass Transf. 18 (1996) 39–46.
[40] V. Kumar, S. Saini, M. Sharma, K.D.P. Nigam, Pressure drop and heat transfer in tube-in-tube helical heat exchanger, Chem. Eng. Sci. 61 (2006) 4403–4416.
[41] B.C. Pak, Y.L. Cho, Hydrodynamic and heat transfer study of Dispersed fluids with submicron metallic oxide particles, Exp. Heat Transf. 11 (1998) 151–170.
[42] M. Chandrasekar, P.C. Mukesh kumar, Experimental investigation on heat transfer and pressure drop in double helically coiled tube heat exchanger with MWCNT/water nanofluid, J. Appl. Fluid Mech. 11 (2018) 23–29.
[43] Gibin George, R. Krishna sabareesh, Shijo Thomas, V. Sajith, T. Hanas, Sumitesh Das, C.B. Sobhan, Experimental investigation of material surface erosion caused by Tio_2 nanofluids impingement, J. Nanofluids 3 (2014) 97–107.