



Experimental investigation on convective heat transfer and pressure drop of cone helically coiled tube heat exchanger using carbon nanotubes/water nanofluids



K. Palanisamy^a, P.C. Mukesh Kumar^{b,*}

^a M. Kumarasamy College of Engineering, Karur, 639113, Tamilnadu, India

^b University College of Engineering Dindugl, 64223, Tamilnadu, India

ARTICLE INFO

Keywords:

Energy
Mechanical engineering
Nanotechnology

ABSTRACT

This study investigates the heat transfer and the pressure drop of cone helically coiled tube heat exchanger using (Multi wall carbon nano tube) MWCNT/water nanofluids. The MWCNT/water nanofluids at 0.1%, 0.3%, and 0.5% particle volume concentrations were prepared with the addition of surfactant by using the two-step method. The tests were conducted under the turbulent flow in the Dean number range of $2200 < De < 4200$. The experiments were conducted with experimental Nusselt number is 28%, 52% and 68% higher than water for the nanofluids volume concentration of 0.1%, 0.3% and 0.5% respectively. It is found that the pressure drop of 0.1%, 0.3% and 0.5% nanofluids are found to be 16%, 30% and 42% respectively higher than water. It is studied that the prepared MWCNT/water nanofluids show good stability even after 45 days of preparation and there is no considerable deposit of nanotubes on the tube inner wall. It is also studied that there is no immediate risk of handling MWCNT and studied that there is no significant erosion of coiled tube inner wall surface even after several test runs. Therefore the MWCNT/water nanofluids are the alternate heat transfer fluids for traditional fluids in the cone helically coiled tube heat exchanger to improve the heat transfer with considerable pressure drop.

1. Introduction

The performance of the heat exchanger is enhanced by improving the heat transfer coefficient and this enhancement, in addition, reduces the heat exchangers size which is the crucial requirement in meeting out the cooling demand. In general heat transfer enhancement techniques can be grouped into active and passive techniques. The active technique needs external forces and passive group needs a special surface geometric face or fluids additives and various tube insert. Coiled tube configuration is widely used in industries such as power plants, nuclear reactors, refrigeration and air-conditioning systems, heat recovery systems, chemical processing, pharmaceutical industries and so on. The coiled tube is of two types namely helical coiled and spiral coiled tube. As reported by Dean [1], the centrifugal force induces the generation of secondary flow which makes proper mixing of fluids particles in a helically coiled tube that improves the physical contact between the tube area and the fluids. This also provides better mixing of the fluids which results in the improvement of the temperature gradient. Prabhanjan et al. [2] observed that the

heat transfer coefficient in a helical coil tube is higher than that of a similar geometry of straight tubes. Salimpour [3] conducted an experimental analysis to study the overall heat transfer coefficient of a shell and helical coil heat exchanger with water. It is reported that the Nusselt number correlation and the analysis show that there is a difference in heat transfer rate with variation in the coil tube pitch. Purandare et al. [4] investigated the effect of changing the tube angle on Nusselt number in a cone-shaped helically coiled tube. Srinivasan et al. [5] experimentally carried out the heat transfer rate, friction factor analysis and revealed the critical Reynolds number Re_{cr} in bend pipes. Sheikholeslami [6] numerically analysed the effect of magnetic force of ferrofluids on the exergy and entropy generation of porous media. Revealed that the exergy drops with reduced magnetic force and the entropy generation increase. Sheikholeslami et al. [7] investigated the application of CuO nanoparticles in energy storage efficiency in a V shaped fin. They found that the discharge rate is enhanced with increasing V shaped fin and CuO nanoparticles. Sheikholeslami [8] worked on the flow of magneto hydrodynamic Al_2O_3 – water nanofluid in a porous medium by using

* Corresponding author.

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

<https://doi.org/10.1016/j.heliyon.2019.e01705>

Received 22 November 2018; Received in revised form 9 April 2019; Accepted 8 May 2019

2405-8440/© 2019 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

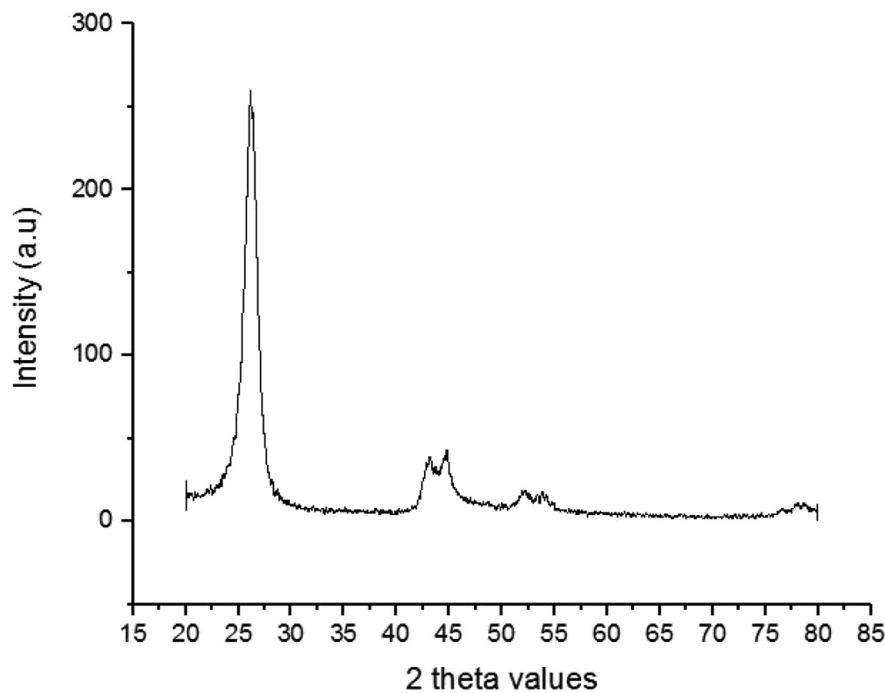


Fig. 1. XRD pattern of MWCNT nanoparticles.

innovative numerical approaches. The results showed that the convection heat transfer detracts with increasing magnetic forces. Sheikholeslami et al. [9] applied neural network for estimating heat transfer of $\text{Al}_2\text{O}_3/\text{H}_2\text{O}$ nanofluid in a duct. It is found that the heat transfer increases by increasing nanoparticles concentration. Sheikholeslami et al. [10] numerically studied the MHD generative heat transfer porous medium. The viscosity and thermal conductivity of alumina were predicted by considering Brownian motion and shape of nanoparticles numerically. Shirvan et al. [11] studied the optimization of mixed convection in ventilated square cavity filled with nanofluid. They found that the Nusselt number decreases by increasing the Richardson number and volume concentration. Ellahi et al. [12] carried out the particle shape effects on Marangoni convection boundary layer flow of a nanofluids with the blend of numerical and analytical studies. They suggested that the interface velocity reduces by increasing particle volume fraction and the spherical shape is better for heat transfer point view. Bhatti et al. [13] mathematically dealt with combined effect of heat and mass transfer on MHD peristaltic propulsion of two phase flow through a porous medium. They suggested that the heat and mass transfer in porous medium has more potential usage in two – phase flow. The heat transfer rates and flow behovirous of $\text{Al}_2\text{O}_3/\text{water}$ nanofluid is a porous medium has been investigated elaborately by Ellahi et al. [14]. They found that the kerosene- Al_2O_3 nano fluid has potential use for thrust chamber regenerative cooling in semi cryogenic rocket engine as they have enhanced the thermal properties. Ellahi et al. [15] suggested that the Bejan number decreases when λ is greater than one. Aaqib Majeed et al. [16] investigated the two dimensional boundary layer flow and heat transfer behavior of ferromagnetic fluid flow in a strecting sheet with suction. They reported the pressure profile and skin friction coefficient improves with increasing the ferromagnetic interaction parameter. Ahmed zeeshan et al. [17] carried out the analysed on the peristaltic transport of MHD Jeffrey fluid by taking Hartmann number, relaxation time and volume fraction. Farooq hussain et al. [18] mathematically modeled the Electro MHD multiphase flow of Hafnium nanoparticles. They concluded that their model may be used to design and engineer for nozzle and diffuser type of injector of automobiles. Shehzad et al. [19] worked on the electroosmotic flow of MHD power law Al_2O_3 -PVC nanofluid in a horizontal channel. They revealed that the skin friction decreases with the increase

of electroosmotic parameter with decrease Nusselt number. Hassan et al. [20] analysed the convective heat transfer of nanofluid in a porous medium over wavy surface. They proposed that the heat transfer coefficient increases by increasing nanoparticles concentration and reduces the flow velocity. The trend of working on the hybrid nanofluid is picking up momentum to analyses the hydro thermal characterization in applying the heat exchanger. Bahiraei et al. [21] applied a novel hybrid nanofluid containing graphene – platinum nanoparticles in twisted geometry in a miniature devices. They proposed that the heat transfer and pumping power in the channel increase by increasing pressure drop and Dean number. The ratio of heat transfer to the power in the chaotic channel is grater than 1.5. Bahiraei et al. [22] numerically inverted the hydro thermal and energy efficiency of a hybrid nanofluids (graphene – platinum nanofluid) in a tube connected by twisted tapes. They have taken the twisted angle, twin co – twisted tape and counter twisted tape for co-swirling flows recommended to use the counter twisted tapes with higher twisted ratio to enhance the heat transfer with reduced energy consumption. Bahiraei et al. [23] carried out the research work on applying the graphene – nanoplatelet – platinum composite powder in a triple tube heat exchanger fitted with inserted ribs. They suggested that the greater rib height and smaller rib pitch at more particle volume concentration lead to enhance heat transfer. Bahiraei et al. [24] optimized the thermo hydraulic performance of mini pin heat sink of cooling of electronic processor by eco-friendly graphene nanoplatelets and nanofluid. They observed that adding nanoparticles improves the cooling effect, however the pressure drop and pumping power do not show significant variation. They recommended to employ the nanofluid at higher concentration in the heat sink. Bahiraei et al. [25] critically reviwed the electronic cooling with nanofluids by considering liquid block, numerical approach, nanoparticle material energy consumption and second law of thermodynamics as primary aspects. They suggested that the different liquid blocks and heat pipes improve the electronic cooling technique. They presented heat transfer fluids have limited thermal energy management capacity to face higher cooling demand. More than a decade the research on applications of the nano materials and nanofluids, have picked up momentum among the researchers. In particular, the existing cooling fluids have been tried to replace with the nanofluids to solve the hurdles faced by the existing conventional heat transfer fluids. Choi [26]

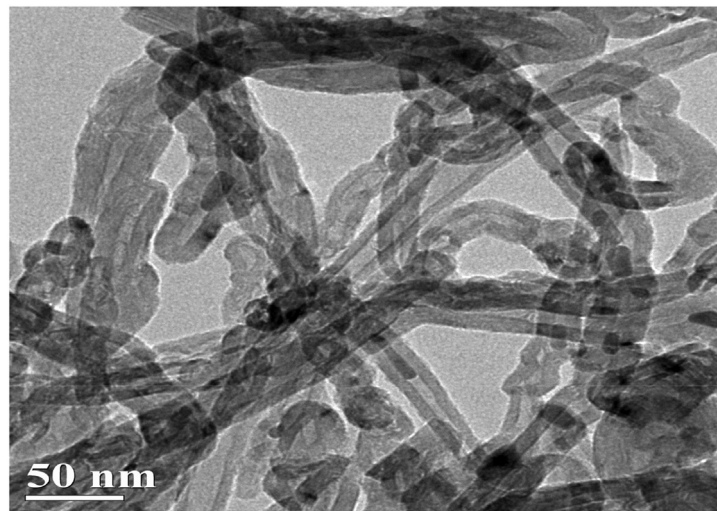


Fig. 2. TEM image of MWCNT/water nanofluid.

introduced a new traditional heat transfer fluids with 1–100 nm sized suspended nanoparticles in the base fluids and suggested that the nanofluid has a better thermal performance when compared with water. Ding et al. [27] analyzed the effective thermal conductivity of MWCNT and observed that the thermal conductivity of MWCNT increases with increase in temperature and volume concentration of MWCNT dispersed with Gum Arabic as a surfactant. Kumaresan et al. [28] investigated the thermophysical properties of MWCNT water-ethylene glycol mixture based nanofluids with SDBS as a surfactant. The maximum enhancement of thermal conductivity was 19.75% at 0.45 vol% MWCNT. Das et al. [29] calculated the thermal conductivity of nanofluids with Al_2O_3 nanoparticles and studied the result of base fluid on the thermal conductivity. Wen et al. [30] observed that the convective heat transfer characteristics of Al_2O_3 nanoparticle with water are improved in the laminar flow condition. It is suggested that the convective heat transfer characteristics are enhanced with Reynolds number as well as particle volume concentration. Suresh et al. [31] presented the convective heat transfer and friction factor characteristics of plain and helically dimpled under turbulent flow by CuO water-based nanofluids. At high volume concentration, the heat transfer rate enhances with an increase in Nusselt number. Wang et al. [32] investigated the heat transfer and pressure drop of working fluids as water-based CNT nanofluids in a circular tube as a

horizontal position. They concluded that the enhancement of average convective heat transfer increases with increase in volume concentration of nanoparticles at constant Reynolds number. Kumar et al. [33] studied the heat transfer and pressure drop in helically coiled tube heat transfer working fluid as Al_2O_3 nanofluids under a turbulent flow region. The increase in heat transfer coefficients and pressure drop are enhanced with increasing the particle concentration. Fsadni et al. [34] critically reviewed and summarized the two-phase heat transfer behaviour in a helically coiled tube heat exchanger. They reported that the work on the effect of nanofluids on the coiled tube is limited.

It is studied from the literature that the research report on the effect of nanofluids on thermal and flow performances of cone helically tube exchanger are very less, in particular the experimental work on cone helically coiled tube with MWCNT/water is very limited. Therefore this experimental work deals with the study of thermal and flow behaviour of MWCNT/Water nanofluids in helically cone coiled tube heat exchanger.

2. Materials & methods

The dry and aggregated MWCNTs have been purchased from Nano-structured & Amorphous Materials, Inc. Houston, TEXAS and USA. The purchased MWCNTs have been studied by XRD (Rigaku $\text{Cu-K}\alpha_1$ X-ray



Fig. 3. Photograph of MWCNT/water nanofluids 45 days after preparation.

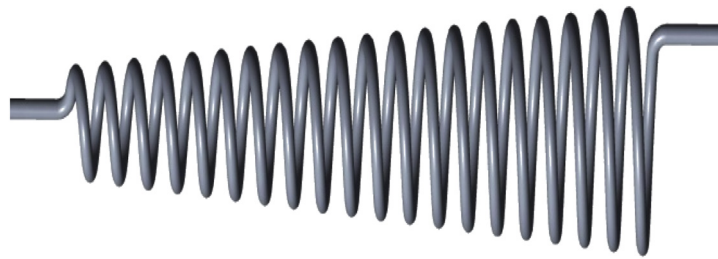


Fig. 4. Cone helically coiled tube.

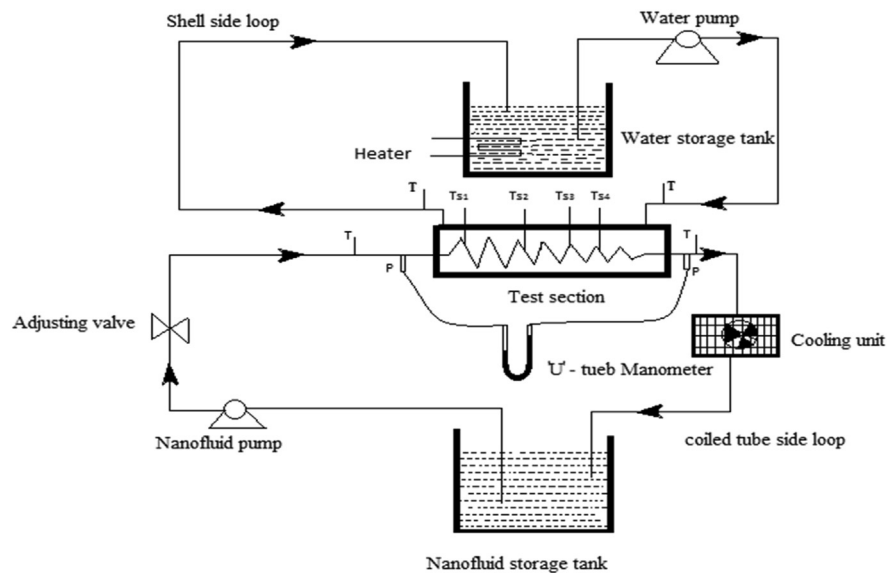


Fig. 5. Line diagram of experimental setup.

Differatometer). The average CNT dimensions are found to be between 50–80 nm (the error is within the limit of ± 5 nm) using XRD pattern of nanoparticles Fig. 1. The MWCNT water-based nanofluids have been prepared by using the two-step method. Ghadimi et al. [35] suggested that the two-step method gives higher stability and low agglomeration with a better nanostructure. The MWCNT water-based nanofluids have been synthesized at 0.1%, 0.3%, 0.5%, volume concentration. The morphological characters of MWCNT in base fluid nanofluid are obtained

by Transmission Electron Microscopy (TEM) as shown in Fig. 2. TEM Image clearly illustrates that the MWCNT core is hollow with multiple layers almost parallel to the MWCNT axis.

Garg et al. [36] investigated the effect of changing the ultrasonication trimmings on heat transfer characteristics of MWCNT/water nanofluids. They reported from their experimental work that the maximum heat transfer enhancement is obtained at 40 minutes ultrasonication. In this work, the required amount of MWCNT is taken and diffused in purified



Fig. 6. Photograph of the experimental setup.

Table 1
Dimensions of cone coil tube.

Cone coil angle (θ)	8 degree
Cone inner tube diameter (d_i)	0.8 cm
Cone outer tube diameter (d_o)	0.1 cm
Diameter of the shell	11.4 cm
Effective length of the coil	470 cm
Pitch of the coil	2 cm
Calming section length	11 cm
Cone coil diameter	6.4 cm
No of turns	16

water with the Ultrasonic bath (Citizen, India) generating Ultrasonic pulses 110 W at 40 ± 5 kHz and it set on for five hours for easy and uniform dispersion which lead to having more stability. In this work, the 0.1 vol % of Sodium dodecylbenzene sulfonates Surfactant is added to have more stability. From the Fig. 3. It is observed that the nanostructures are stable without any agglomeration and found uniformly dispersed. From the observation, it is noted that there is no significant settlement of nanoparticles even after 45 days of the static condition of nanofluid are shown in Fig. 3. Kumaresan et al. [28] presented the Sodium dodecylbenzene sulfonates (SDBS) as surfactant gives long-standing stability of nanotubes.

3. Experimental

Fig. 4 shows the image of the test section. Figs. 5 and 6 show the line diagram and photograph of the experimental setup. The experimental setup has two loops. The first one is cone helically coiled tube side which handles nanofluids. The second loop is the shell side which handles hot water. The second loop is connected with a storage vessel with size of $15\text{cm} \times 15\text{cm} \times 15\text{cm}$, with a heater 2KW capacity, magnetic pump and thermostat. Cone coiled tube loop side is connected with a monobloc pump with 0.5 hp power, valve to control the flow on tube side, test section, cooling unit and storage vessel of six-liter capacity. The straight tube with fine sand is bent to have the conical shape with the help of wooden conical shape. The use of fine sand in the tube is due to avoid the flattening of the copper tube while bending. The shell material is Stainless Steel and the cone tube is copper. The thermostat is used to cuts in and cuts off the heater. The inlet and outlet temperature are recorded by the fitted four K-type Thermocouples with the accuracy of 0.1°C . The flow entry effect is avoided by using the calming section. U-tube mercury manometer is fitted across the tube with accuracy of 1mm. The cooling unit of nanofluids handles water as cooling medium. The shell outer surface is covered with asbestoses tape to reduce heat loss. Flow control is done with the valve and the hot water from the tube is cooled by a cooling unit. Table 1 presents the geometry of cone coiled tube used for this experimental work.

3.1. Experimentation

At first, water is supplied to check the experimental setup to check the leakages through the fittings. After checking, the ordinary water is passed through the tube side and hot water is allowed through the shell side. The experimental tests have been conducted under constant wall temperature conditions of wall surfaces, turbulent flow and counter flow condition. The flow rate is varied and the corresponding readings are recorded. Similarly, the nanofluids are supplied through the tube side and hot water is allowed to shell side. The experiment is allowed to run for 30 minutes to attain the steady state condition. The corresponding reading is recorded. The nanofluids of 0.1%, 0.3% and 0.5% volume concentrations are supplied for cone helically coiled tube and hot water is supplied to the shell side. The mass flow rate of the shell side is maintained constant (0.15 kg/sec). The rate of flow is recorded manually by collecting the fluid in the jar and the stopwatch. The flow rate of the cone tube which handles nanofluid is varied from 0.05 kg/sec to 0.07 kg/sec. The

Table 2
Thermophysical properties of MWCNTs.

MWCNT nanopowder	
Properties	
Form	Solid
Outer diameter	50–80 nm
Inner diameter	5–15 nm
Length	10–20 μm
Specific Surface Area	32–40 m^2/g
True density	2.1 g/cm^3
Bulk density	0.18 g/cm^3
Purity	99.5%
Thermal conductivity	3000 W/mk
Supplier	Nanostructured & Amorphous materials, inc, a Houston, TEXAS Company USA.

corresponding Dean number range is $2200 < \text{De} < 4200$. The 'U' tube manometer is used to measure the pressure drop across the tube. The measured values for finding the Nusselt number are subjected under uncertainties because of the experimental error.

3.2. Calculation of nanofluids thermo-physical properties

Pak and Cho [37], Patel [38] and Ebrahimi - Bajestan [39] suggested the Eqs. (1), (2), (3), and (4), for determining the density, thermal conductivity, specific heat, and viscosity of nanofluids and the Eqs. (1), (2), (3), and (4), have widely been used by the researchers as the mathematical results are closer to the experimental results. Table 2 show the dry MWCNTs properties used for this experiments.

$$\rho_{nf} = \phi \rho_p + (1 - \phi) \rho_w \quad (1)$$

$$(\rho c_p)_{nf} = (1 - \phi) (\rho c_p)_w + \phi (\rho c_p)_p \quad (2)$$

$$k_{nf} = k_f \left[1 + \frac{k_p \phi r_f}{k_f (1 - \phi) r_p} \right] \quad (3)$$

$$[\mu_{nf} = \mu_f (1 + 22.7814 \phi - 9748.4 \phi^2 + 1000000 \phi^3)] \quad (4)$$

3.3. Data reduction

The flow condition is obtained by using the Dean number Eq. (5). The average rate of heat transfer of tube and shell are found by using Eqs. (6), (7), (8) and (9). and the Nu and pressure drop are calculated by Eqs. (10) and (11).

$$\text{De} = \text{Re}_i \left(\frac{d_i}{2R_c} \right)^{0.5} \quad (5)$$

$$Q_w = \dot{m}_w c_{p,w} (T_{in} - T_{out})_w \quad (6)$$

$$Q_{nf} = \dot{m}_{nf} c_{p,nf} (T_{in} - T_{out})_{nf} \quad (7)$$

$$\text{Nu}_i = \frac{h_i d_i}{k_{eff}} \quad (8)$$

$$Q = h_i A_i (T_{wall} - T_{bulk}) \quad (9)$$

$$Q = U_o A_o (\Delta T)_{LMTD} \quad (10)$$

$$\text{Pressure drop } (\Delta P)$$

$$\Delta P = \rho g \Delta h \quad (11)$$

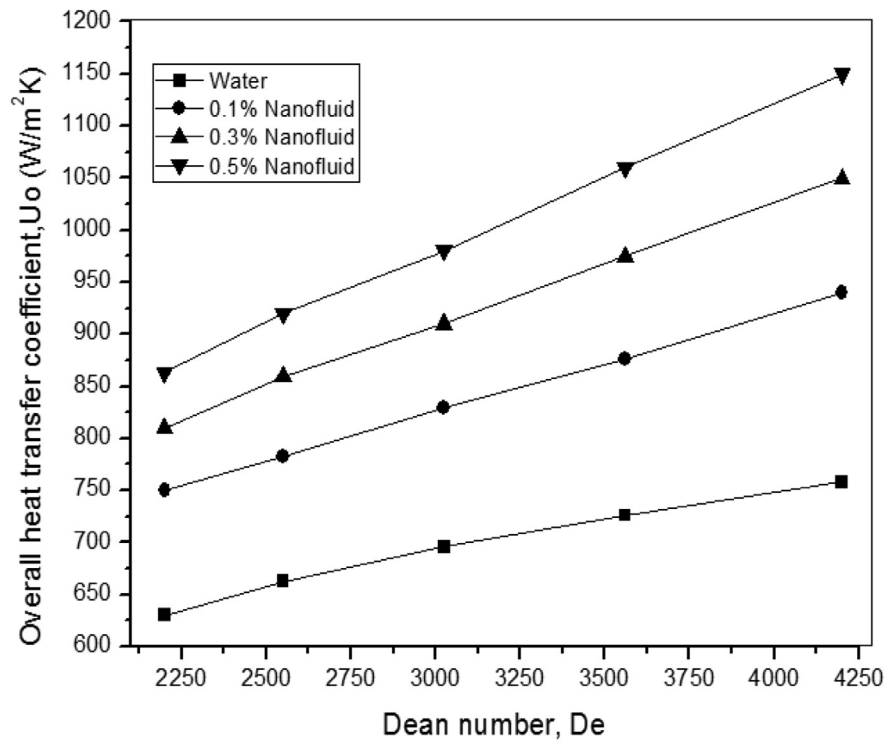


Fig. 7. Overall heat transfer coefficient Vs Dean number.

The thermal performance factor of Thermohydraulic factor deals with the thermo-hydraulic behavior of nanofluid in heat exchangers Hashemi et al. [40]. The thermal performance factor of the cone helically coiled heat exchanger is given Eq. (12). In this investigation, the thermal performance factor is found to range of 1.1–1.6. Therefore the nanofluid gives better thermal behavior than water in cone helically coiled tube

heat exchanger.

$$\varepsilon = \left[\frac{Nu_{nf}}{Nu_w} \right] \left[\frac{\Delta P_w}{\Delta P_{nf}} \right]^{0.003} \quad (12)$$

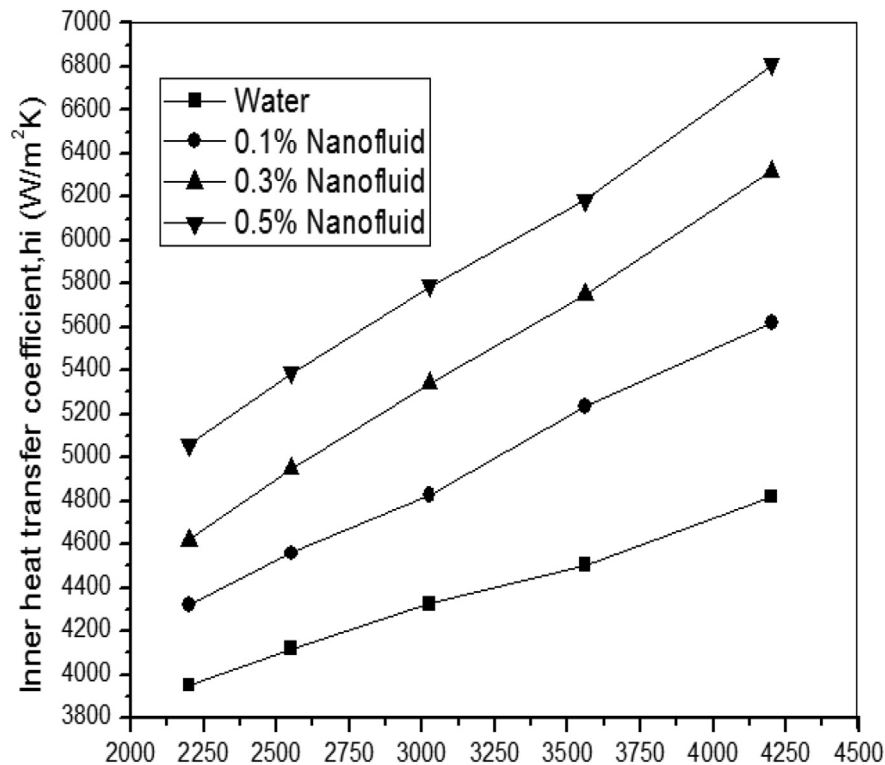


Fig. 8. Inner heat transfer coefficient Vs Dean number.

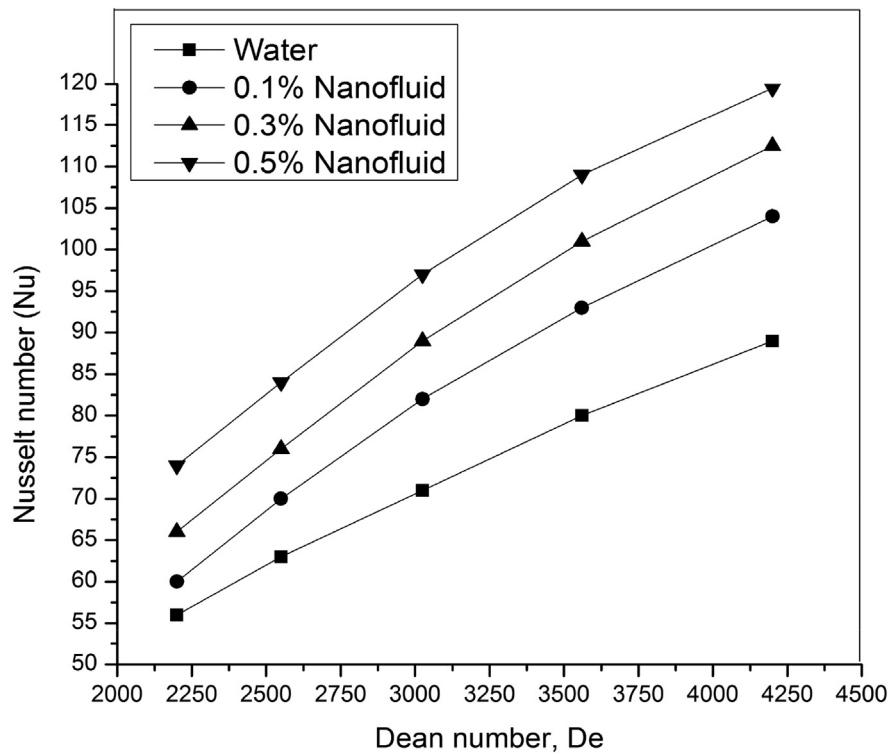


Fig. 9. Effect of nanofluids on Nusselt number.

3.4. Uncertainty analysis

The uncertainty of the measurements are calculated by using the Eqs. (13), (14), (15), (16), (17), (18) and (19).

$$\frac{\Delta h}{h} = \left[\left(\frac{\Delta m}{m} \right)^2 + \left(\frac{\Delta T_i}{T_i} \right)^2 + \left(\frac{\Delta T_0}{T_0} \right)^2 + \left[2 \times \left(\frac{\Delta A}{A} \right)^2 + \left(\frac{\Delta T}{\Delta T} \right)^2 \right]^{0.5} \right] = 3.1\% \quad (13)$$

$$\frac{\Delta Nu_i}{Nu_i} = \left[\left(\frac{\Delta h}{h} \right)^2 + \left(\frac{\Delta d}{d} \right)^2 \right] = 4\% \quad (14)$$

$$\frac{\Delta p}{\Delta p} = \frac{\Delta h_i}{\Delta h_i} = 0.4\% \quad (15)$$

$$\frac{\Delta v}{v} = \left[\left(\frac{\Delta m}{m} \right)^2 + \left(2 \times \left(\frac{\Delta A}{A} \right)^2 \right) \right]^{0.5} = 2.3\% \quad (16)$$

$$\frac{\Delta A}{A} = \left[\left(2 \times \left(\frac{\Delta d_i}{d_i} \right)^2 \right) \right]^{0.5} = 0.44\% \quad (17)$$

$$\frac{\Delta Re}{Re} = \left[\left(\frac{\Delta m}{m} \right)^2 + \left(\frac{\Delta d}{d} \right)^2 \right]^{0.5} = 2.3\% \quad (18)$$

$$\frac{\Delta De}{De} = \left[\left(\frac{\Delta \delta}{\delta} \right)^2 + \left(\frac{\Delta Re}{Re} \right)^2 \right]^{0.5} \pm 3.5\% \quad (19)$$

4. Results and discussion

4.1. Heat transfer of MWCNT nanofluids

Fig. 7 describes the Dean versus the overall heat transfer coefficient. It

Table 3

Comparison of Nusselt number of nanofluids with water.

De	water	0.1%vol	0.3%vol	0.5%vol
2200	56	60	66	74
2550	63	70	76	84
3025	71	82	89	97
3560	80	93	101	109
4200	89	104	112.5	119.5

is seen that the overall heat transfer coefficient increases with increasing the Dean number and particle volume concentration. The maximum overall heat transfer coefficient is 52% at 0.5% nanofluid in the Dean number 4200. The overall heat transfer coefficient is the effect of conduction and convection mode in the heat exchanger. While comparing the conduction heat transfer mode, the convection heat transfer is highly effective than the conduction heat transfer. In particular the inner heat transfer is highly effective due to stronger convection current between MWCNTs and water. This leaves to improve more convective heat transfer. The lower temperature difference between the tube and shell is the major cause for improved convective heat transfer.

Fig. 8 shows the effect of particle concentration on the heat transfer coefficient. It is found that the increasing trend in heat transfer coefficient with varying Dean number. The improved heat transfer coefficient is found to be 14%, 30% and 41% more than the water at 0.1%, 0.3% and 0.5% MWCNT/water nanofluid respectively. It is clearly seen that the maximum heat transfer coefficient is obtained at 0.5% nanofluid. The addition of more MWCNT increases the thermal conductivity of nanofluids. Moreover, the addition of MWCNT delays the formation of the thermal boundary layer and makes the temperature profile flatten. In addition to the delaying thermal boundary layer, the lower relative velocity of MWCNTs with water particles along the curved flow path is the reason for higher inner heat transfer coefficient at 0.5% volume concentration.

From Fig. 9 and Table 3 it is seen that the Nusselt number is enhanced by changing Dean Number and particle volume concentration. The

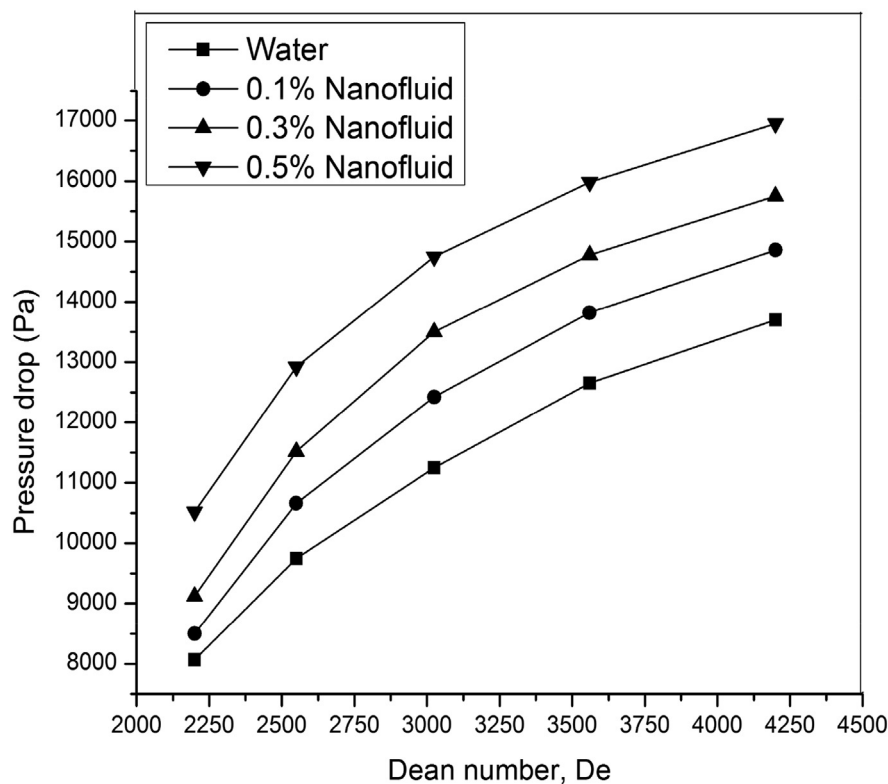


Fig. 10. Effect of nanofluids on pressure drop.

Table 4

Comparison of pressure drop of nanofluids with water.

De	water	0.1%vol	0.3%vol	0.5%vol
2200	8068	8500	9125	10520
2550	9750	10660	11520	12920
3025	11250	12420	13500	14750
3560	12650	13818	14780	15980
4200	13700	14860	15750	16950

increase in Nusselt numbers is found to be 28%, 52% and 68% at 0.1%, 0.3% and 0.5% MWCNT/water nanofluids respectively when compared with water. The improvement is because of the thorough mixing of water particles and CNTs, this also may be the contribution Brownian motion of the CNTs. Moreover, the random movement of MWCNT disturbs the boundary layer formation and the formation of secondary flows are intensified. The Nusselt number is directly proportional to the inner heat transfer coefficient and therefore Nusselt number increases with increase the heat transfer coefficient and with increasing the volume concentration. The significant Nusselt number is how effective the convective heat transfer happens. In this work the convective heat transfer is highly effective when increase particle volume concentration.

4.2. Effect of pressure drop

Fig. 10 and Table 4 reveal the increasing trend of pressure drop by varying particle volume concentration and Dean number. The pressure drop of 0.1%, 0.3% and 0.5% nanofluids are found to be 16%, 30% and 42% higher than water respectively. It is because of the higher viscosity while adding more MWCNTs. It is seen that the maximum pressure drop occurs at 0.5% nanofluid and at the Dean number 4200. It is evident that the higher pressure drop leads to the pumping power penalty. The maximum pressure drop obtained is 42% when the outlet temperature of nanofluid is at 48 °C when it leaves the tube. However, the pressure drop may vary with respect to the nanofluids outlet temperature. Higher the



Fig. 11. Assessment of deposit of MWCNTs on coiled tube before conducting tests.

nanofluid temperature means that lower the pressure drop. This is simply because of lowering the viscosity due to a higher temperature.



Fig. 12. Assessment of deposit of MWCNTs on coiled tube after conducting tests.

4.3. Assessment of health risk, deposition and erosion

Though the assessment of health risk, deposition and erosion are not the primary objectives of this work, the observation made on these is mentioned as they may lead to further work in details with appropriate techniques. The report on the risk assessment of using MWCNTs nanofluids in the laboratory is very limited in terms of heat transfer point of view. Therefore the health risk is assessed during the date of preparation of MWCNT/water nanofluids and tests conducting days (60 Days). The primary safeguarding components like standard glove, apron and air filter have been used during these days. The assessment of deposition of MWCNTs and erosive wear of tube surfaces are carried out manually and visually. Figs. 11 and 12 reveal that there is no significant deposit of MWCNTs on the inner tube surface due to impingement of MWCNTs and there is no observable erosive wear on the tube inner surface even after several test runs. George et al. [41]. suggested that the erosive wear depends on nanoparticles size, shape, impinge velocity, particles concentration and angle of attack and temperature of the fluids. It is also found that there is no considerable health risk except the irritation of MWCNTs when exposed to the bare skin.

5. Conclusions

In this paper, the turbulent flow ($2200 < De < 4200$) heat transfer characteristics and pressure drop of cone helically coiled tube with MWCNT/water nanofluid at 0.1%, 0.3% and 0.5% particle volume concentration have been experimentally studied. It is found that the maximum overall heat transfer coefficient of nanofluids is 52% higher than the water at 0.5% nanofluid in the Dean number 4200. The improved heat transfer coefficient is found to be 14%, 30% and 41% more than the water at 0.1%, 0.3% and 0.5% MWCNT/water nanofluid respectively. The increase in Nusselt numbers is found to be 28%, 52% and 68% at 0.1%, 0.3% and 0.5% MWCNT/water nanofluids respectively when compared with water. The pressure drop of 0.1%, 0.3% and 0.5% nanofluids are found to be 16%, 30% and 42% higher than water respectively. It is also studied that there is no significant deposit of the MWCNTs on the inner surface of the cone coiled tube even after several experimental test run deposit of nanotubes on the tube inner wall. Found that there are no immediate and 60 days of using MWCNT nanofluids health risk while preparing and conducting the tests with the primary safeguard kits like glove, air filter and apron. Therefore the traditional heat transfer fluids may be replaced with MWCNT/water nanofluids at considerable pressure drop in cone helically coiled tube heat exchangers. Future work is needed for investigating the thermal and flow behaviors of MWCNT/water nanofluids with higher volume concentration at different cone helically coil pitch.

Declarations

Author contribution statement

K Palanisamy: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

P C Mukesh Kumar: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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] W.R. Dean, Note on the motion of fluid in curved pipe, *Philos. Mag. A* 4 (1927) 208–223.
- [2] D.G. Prabhakaran, G.S.V. Raghavan, T.J. Rennie, Comparison of heat transfer rates between a straight tube heat exchanger and helically coiled heat exchanger, *Int. Commun. Heat Mass Transf.* 29 (2002) 185–191.
- [3] M.R. Salimpour, Heat transfer coefficient of shell and coiled tube heat exchangers, *Exp. Therm. Fluid Sci.* 33 (2009) 203–207.
- [4] Pramod S. Purandare, Mandar M. Lele, Raj Kumar Gupta, Investigation on thermal analysis of conical coil heat exchanger, *Int. J. Heat Mass Transf.* 90 (2015) 1188–1196.
- [5] P.S. Srinivasan, S. Nanda Purkar, F.A. Holland, Friction factor for coils, *Int. J. Chem. Eng. Trans.* 48 (1970) T156–T161.
- [6] M. Sheikholeslami, New computational approach for exergy and entropy analysis of nanofluid under the impact of Lorentz force through a porous media, *Comput. Methods Appl. Mech. Eng.* 344 (2019) 319–333.
- [7] M. Sheikholeslami, New computational approach for exergy and entropy analysis of nanofluid under the impact of Lorentz force through a porous media, *Comput. Methods Appl. Mech. Eng.* 344 (2019) 319–333.
- [8] M. Sheikholeslami, Numerical approach for MHD Al_2O_3 -water nanofluid transportation inside a permeable medium using innovative computer method, *Comput. Methods Appl. Mech. Eng.* 344 (2019) 306–318.
- [9] M. Sheikholeslami, M. Barzegar Gerdroodbar, R. Moradi, Ahmad Shafee, Zhixiong Li, Application of Neural Network for estimation of heat transfer treatment of Al_2O_3 - H_2O nanofluid through a channel, *Comput. Methods Appl. Mech. Eng.* 344 (2019) 1–12.
- [10] M. Sheikholeslami, S.A. Shehzad, Zhixiong Li, Shafee Ahmad, Numerical modeling for alumina nanofluid magneto hydrodynamic convective heat transfer in a permeable medium using Darcy law, *Int. J. Heat Mass Transf.* 127 (2018) 614–622.
- [11] Kamel Milani Shirvan, Mojtaba Mamourian, R. Ellahi, Numerical investigation and optimization of mixed convection in ventilated square cavity filled with nanofluid of different Inlet and outlet port, *Int. J. Numer. Methods Heat Fluid Flow* 27 (2017) 2053–2069.
- [12] R. Ellahi, A. Zeeshan Mohsan Hassan, Particle shape effects on Marangoni convection boundary layer flow of a nanofluid, *Int. J. Numer. Methods Heat Fluid Flow* 26 (2016) 2160–2174.
- [13] M.M. Bhatti, A. Zeeshan, R. Ellahi, G.C. Shit, Mathematical modeling of heat and mass transfer effects on MHD peristaltic propulsion of two-phase flow through a Darcy-Brinkman-Forchheimer porous medium, *Adv. Powder Technol.* 29 (2018) 1189–1197.
- [14] R. Ellahi, A. Zeeshan, N. Shehzad, Sultan Z. Alamri, Structural impact of kerosene- Al_2O_3 nanoliquid on MHD Poiseuille flow with variable thermal conductivity: application of cooling process, *J. Mol. Liq.* 264 (2018) 607–615.
- [15] R. Ellahi, Sultan Z. Alamri, Abdul Basit, A. Majeed, Effects of MHD and slip on heat transfer boundary layer flow over a moving plate based on specific entropy generation, *J. Taibah Univ. Sci.* 12 (2018) 476–482.
- [16] Aaqib Majeed, Ahmad Zeeshan, Sultan Z. Alamri, Rahmat Ellahi, Heat transfer analysis in ferromagnetic viscoelastic fluid flow over a stretching sheet with suction, *Neural Comput. Appl.* 30 (2018) 1947–1955.
- [17] Zeeshan Ahmed, Nouman Ijaz, Tehseen Abbas, Rahmat Ellahi, The sustainable characteristic of bio-Bi-phase flow of peristaltic transport of MHD Jeffrey fluid in the human body, *Sustain. MDPI* 10 (2018) 1–17.
- [18] Farooq Hussain, Rahmat Ellahi, Zeeshan Ahmad, Mathematical models of Electro-magneto hydrodynamic multiphase flows synthesis with nano-sized Hafnium particles, *Appl. Sci.* 8 (2018) 275.
- [19] N. Shehzad, A. Zeeshan, R. Ellahi, Electroosmotic flow of MHD power law Al_2O_3 -PVC nanofluid in a horizontal channel: Couette-Poiseuille flow model, *Commun. Theor. Phys.* 69 (2018) 655–666.
- [20] M. Hassan, M. Marin, Abdullah Alsharif, R. Ellahi, Convective heat transfer flow of nanofluid in a porous medium over wavy surface, *Phys. Lett.* 382 (2018) 2749–2753.
- [21] Mehdi Bahiraei, Nima Mazaheri, Application of a novel hybrid nanofluid containing graphene-platinum nanoparticles in a chaotic twisted geometry for utilization in miniature devices: thermal and energy efficiency considerations, *Int. J. Mech. Sci.* 138–139 (2018) 337–349.
- [22] Mehdi Bahiraei, Nima Mazaheri, Seyed Mohammadhossein Hassanzamani, Efficacy of a new graphene-platinum nanofluid in tubes fitted with single and twin twisted tapes regarding counter and co-swirling flows for efficient use of energy, *Int. J. Mech. Sci.* 150 (2019) 290–303.
- [23] Mehdi Bahiraei, Nima Mazaheri, Ali Rizehvandi, Application of a hybrid nanofluid containing graphene nanoplatelet-platinum composite powder in a triple-tube heat exchanger equipped with inserted ribs, *Appl. Therm. Eng.* 149 (2019) 588–601.
- [24] Mehdi Bahiraei, Saeed Heshmatian, Mansour Keshavarzi, Multi-criterion optimization of thermohydraulic performance of a mini pin fin heat sink operated with eco friendly graphene nanoplatelets nanofluid considering geometrical characteristics, *J. Mol. Liq.* 276 (2019) 653–666.
- [25] Mehdi Bahiraei, Saeed Heshmatian, Electronics cooling with nanofluids: a critical review, *Energy Convers. Manag.* 172 (2018) 438–456.

- [26] S.U.S. Choi, J.A. Eastman, Enhancing thermal conductivity of fluids with nanoparticles, *ASME J. Heat and Trans.* 131 (1995) 1.
- [27] Yulong Ding, Hajar Alias, Dongsheng Wen, Richard A. Williams, Heat transfer of aqueous suspensions of carbon nanotubes, *Int. J. Heat Mass Transf.* 49 (2006) 240–250.
- [28] V. Kumaresan, R. Velraj, Experimental investigation of the thermo – physical properties of water-ethylene glycol mixture based CNT nanofluids, *Thermochim. Acta* 545 (2012) 180–186.
- [29] S.K. Das, N. Putra, W. Roetzel, Temperature dependence of thermal conductivity for nanofluids, *ASME J. Heat Trans.* 125 (2003) 567–574.
- [30] D. Wen, Y. Ding, Experimental investigation in to convective heat transfer of nanofluids at the entrance region under laminar flow conditions, *Int. J. Heat Mass Transf.* 47 (2004) 5181–5188.
- [31] S. Suresh, M. Chandrasekar, S. Chandra Sekhar, Experimental studies on heat transfer and friction factor characteristics of CuO/water nanofluid under flow in a helically dimpled tube, *Exp. Therm. Fluid Sci.* 35 (2011) 542–549.
- [32] J. Wang, J. Zhang, X. Zhang, Y. Chen, Heat transfer and pressure drop of nanofluids containing carbon nanotubes in laminar flows, *Exp. Therm. Fluid Sci.* 44 (2013) 716–721.
- [33] P.C. Mukesh kumar, J. Kumar, R. Tamilarasan, S. Sendhilnathan, S. Suresh, Heat transfer enhancement and pressure drop analysis in helically coiled tube using Al_2O_3 /water nanofluid, *J. Mechanical Sci. and Tech.* 28 (5) (2014) 1841–1847.
- [34] Andrew Michael Fsadni, Justin P.M. Whitty, A review on the two-phase heat transfer characteristics in helically coiled tube heat exchangers, *Int. J. Heat Mass Transf.* 95 (2016) 551–565.
- [35] A. Ghadimi, R. Saidur, H.S.C. Metselaar, A review of nanofluid stability properties and characterization in stationary conditions, *Int. J. Heat Mass Transf.* 54 (2011) 4051–4068.
- [36] Paritosh Garg, Jorge L. Alvarado, Charles Marsh, Thomas A. Carlson, David A. Kessler, Kalyan Annamalai, An experimental study on the effect of ultrasonication on viscosity and heat transfer performance of multi-wall carbon nanotube-based aqueous nanofluids, *Int. J. Heat Mass Transf.* 52 (2009) 5090–5101.
- [37] 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.
- [38] H.E. Patel, K.B. Anoop, T. Sundararajan, Sarit K. Das, Model for thermal conductivity of CNT – nanofluids, *Bull. Mater. Sci.* 31 (3) (2008) 387–390.
- [39] E. Ebrahimnia-Bajestan, H. Niazmand, Convective heat transfer of nanofluids flows through an isothermally heated curved pipe, *Iran. J. Chem. Eng.* 8 (2) (2011) 81–97. http://www.ijche.com/article_10292_108f06076ed8ee6ef6dcb552f71f7af3.pdf.
- [40] S.M. Hashemi, M.A. Akhavan Behabadi, An empirical study on heat transfer and pressure drop characteristics of CuO – base oil nanofluid flowing in a horizontal helically coiled tube under constant heat flux, *Int. J. Heat Mass Transf.* 39 (2012) 144–151.
- [41] 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.