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Experimental study on parallel and counter flow configuration of a shell and helically coiled tube heat exchanger using Al_2O_3 / water nanofluid

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Abstract

In this work, heat transfer coefficients of shell and helically coiled tube heat exchanger using Al_2O_3 / water nanofluid were studied. This study was done by changing the parallel flow configuration into counter flow configuration under laminar flow regime. The Al_2O_3 / water nanofluid at 0.4% and 0.8% particle volume concentration were prepared by using two step method. The nanoparticles were characterized by X-Ray diffraction (XRD) and Scanning Electron Microscope (SEM). It is found that the overall heat transfer coefficient of counter flow was 4-8% higher than that of parallel flow at 0.4% nanofluid. The overall heat transfer coefficient was found to be 5-9% higher than that of parallel flow at 0.8% nanofluid. It is studied that there is no considerable effect on heat transfer coefficient on changing flow configuration. This is because of helically coiled tube flow and shell flows are perpendicular direction both in parallel and counter flow configuration. It is also studied the thermal performance of 0.8% nanofluid is higher than 0.4% nanofluid.

Key words: Al_2O_3 Nanofluid, Helically coiled tube, Overall heat transfer co-efficient, Particle volume concentration, Parallel flow and counter flow configuration, Reynolds number.

1. Introduction:

The Chemical processing industries, Power stations, Nuclear reactors, Transportation industries, Electronic industries and (Heating, Ventilation and Air Conditioning) HVAC face challenge in meeting out the cooling demand for the past decades. Therefore, an increase in efficiency of heat exchanger through augmentation techniques has been developed. There are three broad classifications of heat transfer augmentation techniques: Passive techniques which do not require any external power such as treated surfaces, rough surfaces, extended surfaces, swirl flow devices, displaced enhancement devices, coiled tube, surface tension device, additives for liquids, and additives of gases. Active techniques which require external power to facilitate the desired flow modification for augmenting heat transfer such as mechanical aids, surface vibration, fluid vibration, electrostatic fields, injection,suction,and jet impingement. Compound heat transfer technique is the combination of any two or three of the above mentioned techniques simultaneously.

The conventional heat transfer fluids have exhausted their cooling capacity. Initially the suspended micro/millimeter sized particles were used to enhance heat transfer. The use of this technique faced undesired rapid settling and erosion of tube surfaces. The new class of heat transfer fluids with 1-100nm sized nanoparticles has been suspended in base fluid by S.U.S Choi [1] and conceived the concept of nanofluid in 1995. Choi [1], Wang and Choi [2], Lee et al.[3], and Das et al.[4] measured the thermal conductivity of nanofluids containing Al_2O_3 and CuO nanoparticles and investigated the effect of base fluid on thermal conductivity of nanofluids. Li et al.[5] suggested the simultaneous control of both the pH and chemical surfactant improve the thermal conductivity of Cu / water nanofluid for practical applications. Yimin Xuan and Qiang Li [6] experimentally investigated the convective heat transfer and flow characteristics of Cu/H_2O nanofluid by flowing through a straight tube. They proposed the nanofluid enhances heat transfer under constant heat flux, laminar and turbulent flow conditions. Masuda et al.[7] reported the Nusselt number of nanofluid increases with increasing the Reynolds number and particle volume concentration. The research groups Yimin Xuan, Wilfried Roetzel [8], Dongshang wen and Yulong Ding [9], Heris et al.[10,11,12], and Hwang et al.[13] investigated the effect of nanoparticles and experimentally measured the thermal conductivity of nanofluid. They proposed the suspended nanoparticle in base fluid leads to positive impact on heat transport properties. Syam sunder and Sharma [14] experimentally investigated by inserting a twisted tap in the flow path of circular tube with Al_2O_3 water nanofluid. They formulated the correlation for heat transfer coefficient and friction factor at 0.5% volume concentration of Al_2O_3 / water nanofluid. Farajollahi et al.[15] experimentally studied the nanofluid heat transfer in a shell and tube heat exchanger. They found that the Al_2O_3/water nanofluid possesses better heat transfer behavior than TiO_2/water nanofluid.

The present investigation is a kind of compound heat transfer enhancement techniques, because the two passive techniques such as helical coil, nanofluids are taken together to enhance heat transfer. The shell and helically coiled tube exchangers are widely used in chemical reactors, agitated vessels, and food processing industries. In particular, it can be applied where space is limited and for achieving better heat transfer performance. Dean [16] proposed a non dimensionless number which relates inertia force and centrifugal force in flow through a curved pipe or channel. Dean number measures the secondary flow and effect of curvature of bend/coil on heat transfer rate. Dravid et al.[17] proposed the correlation for inner Nusselt number at the Dean number in the range 50 to 2000.They investigated the secondary flow motion induced by the curvature effects and reported the resultant centrifugal force makes heat transfer coefficient greater than that of straight tube. Prabhanjan et al.[18] suggested that the flow rate did not effect the heat transfer coefficient and did not greatly change the wall effects. Prabhanjan et al. [19] proposed the correlation for outer Nusselt number using the coil height as the characteristic length and presented the model for predicting the outlet temperature from the given coil inlet temperature. Salimpour [20, 21] experimentally investigated on overall heat transfer coefficient of shell and helically coiled heat exchanger using conventional fluids. They proposed the correlations for inner Nusselt number (Nu_i), and shell side Nusselt number. He suggested the shell side heat transfer coefficient with larger pitches is higher than that of smaller coil pitches. Srinivasan et al.[22] carried out an experiments on friction factor of coil having varies diameter and suggested the critical Reynolds number for helical pipe flow which relates to the curvature ratio. Srinivasan et al.[23] analyzed the heat transfer based on friction coefficient and proposed the critical Reynolds number (Eq.1) in curved pipes.

$$Re_{cr} = 2100(1+12\sqrt{\delta}) \qquad (1)$$

Kumar et al.[24] carried out an experiment on a shell and helically coiled tube heat exchanger using nonmetallic Sisal nanofluid at 0.1 % to 0.5% volume concentration. They reported the overall heat transfer coefficient increases while increasing particle volume fraction at various Reynolds number. Their investigation did not account the effect of coil pitch, curvature of coil, and torsion in calculating the Nusselt number. Akbarinia [25] studied the effect of laminar flow mixed convection in horizontal curved tubes using nanofluid. They reported the nanoparticle volume concentration does not affect the secondary flow, axial velocity and skin friction factor. Rogers and Mayhew [26] proposed the power –law correlation based on experimental data. The correlation proposed is the modification of Dittus- Bolter correlation of curved – duct. The heat transfer in coiled tube is the function of Dean number (De) and Prandtl number (Pr), coil pitch and curvature radius. It deals with the inertial force, centrifugal force and viscous force in the flow path of helical tube. Many researchers combined the Reynolds number and curvature ratio of helically coiled tube to analyze the heat transfer. The objective of this investigation is to study the effect of convective heat transfer of a shell and helically coiled tube heat exchanger by using Al_2O_3 /water nanofluid and by changing the flow directions.

2. Materials and Methods:

The nanoparticles were purchased from Alfa Aesar, USA. The purchased Al_2O_3 nanoparticles were characterized by XRD (Rigaku Cu- $k_{\acute{\alpha}1}$ X Ray Differatometer) and SEM (JSM 6360SEM). Figs.1 and 2 represent the XRD pattern of Al_2O_3 nanoparticles and SEM image of nanoparticles. The average particle size was found to be between 45 to 50nm (the error is with in the limit of ±5nm) using XRD pattern of nanoparticles. The typical SEM image of Al_2O_3nanofluid showed that the particles are uniformly dispersed in the range of nanometer and particles appear to be spherical in shape.

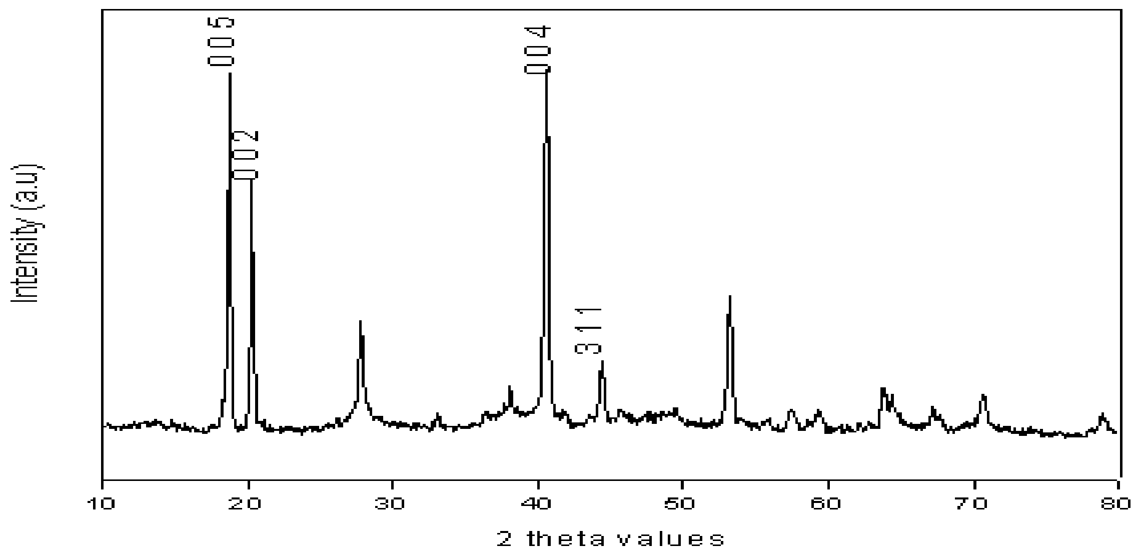

Figure.1: XRD pattern of Al_2O_3 nanoparticles

The dispersion of particles in distilled water was done by mixing the required particle volume concentration in the chemical measuring flask. Ultrasonic bath (Toshiba, India) generating Ultrasonic pulses 100 W at 36±3 kHz was switched on for 4 hours to get the uniform dispersion and stable suspension. The Al_2O_3 / water nanofluid at 0.4% and 0.8% volume concentration were prepared. No surfactant was added to maintain the stability of nanoparticles in base fluid. It is observed that there was no significant settlement of nanoparticles even after 30 days of static condition of nanofluid. It shows that the nanoparticles are stable in base fluid.

2.1 Experimental setup:

Fig.3. illustrates the schematic of experimental setup. The set-up has shell side loop and helically coiled tube side loop. Shell side loop handles hot water. Helical coiled tube loop handles Al_2O_3 / water nanofluid. Shell side loop consists of storage vessel with the heater of 1.75 kW capacity, magnetic pump and thermostat. Helically coiled tube side loop consists of mono bloc pump, valve,, test section containing shell and coil, cooling unit and storage vessel of five liter capacity. The coil is formed initially straight tube. The helically coiled shape is made by filling fine sand to preserve the smoothness of inner surface before bending. The test section is horizontally placed. Coiled tube is made up of copper and shell is made up of mild steel.

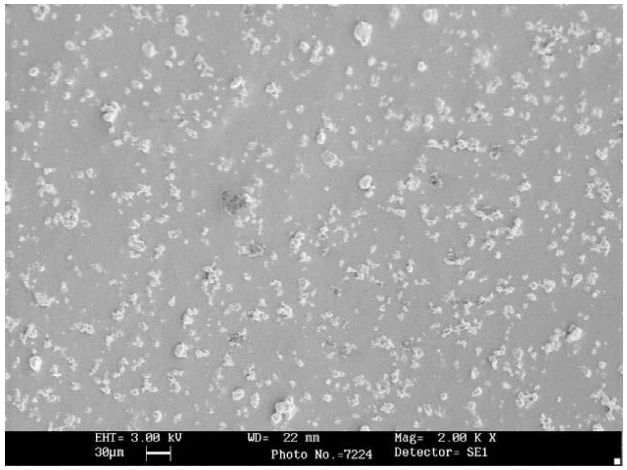

Figure. 2: SEM image of Al_2O_3 nanoparticles

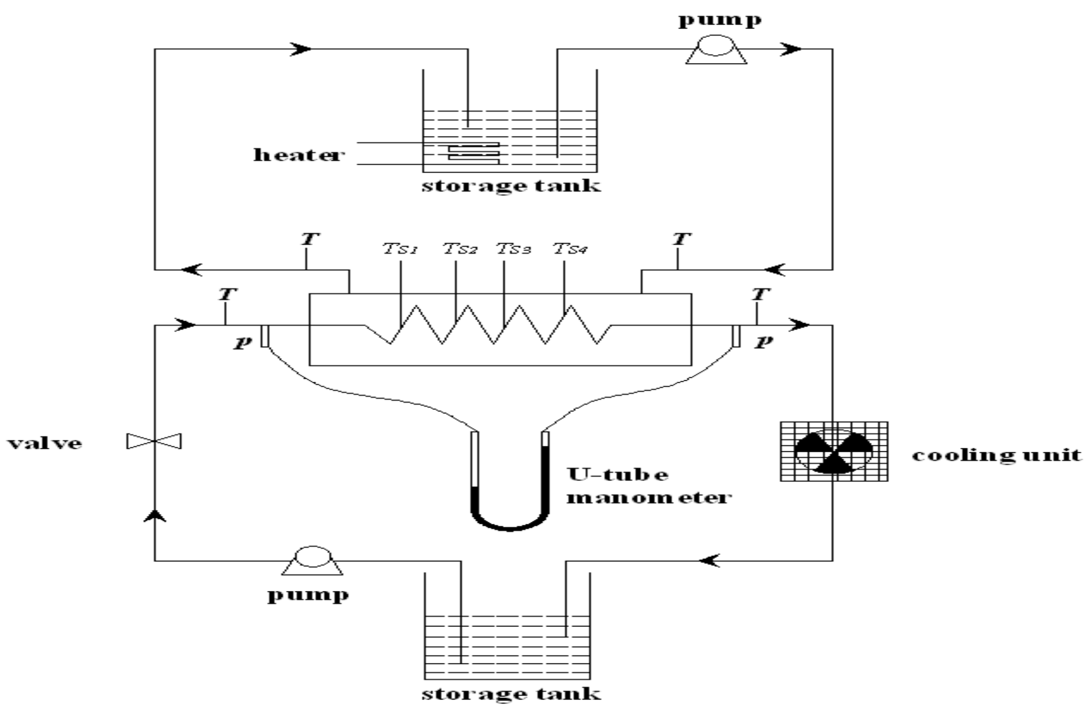

Figure 3: Flow diagram of experimental setup

The temperature of hot water in the shell side storage vessel is maintained by thermostat. Four K-type thermocouples of 0.1°C accuracy are used to measure inlet and outlet temperatures of shell and tube side. Four K-type thermocouple were placed at equal interval on the outer surface of coiled tube to measure the wall temperatures. The thermocouples are placed and glued with epoxy to avoid leakage. Flexible PVC (Polyvinyl Chloride) tubing is used for all connections. The calming section is provided in coiled tube to avoid the entrance effect. U-tube mercury manometer is placed across the helical tube to measure the pressure drop. The shell is insulated with fiber wool. A valve is provided in the flow pipe connecting the cooler section, reservoir for flow rate measurements and for cleaning the system between successive experimental runs. The flow rates are measured by collecting the fluid in the collecting station for a period of time with the precise measuring jar and stop watch.

The test section has the helically coiled tube internal diameter of (d_i) 9mm, the external diameter of helical tube (d_o) of 10.5mm and the shell external diameter (D) of 124 mm. The effective length (L) of the coil is 370 mm, the coil pitch and numbers of turns (n) are 17 mm and 13 respectively. The length of calming section is 70 mm and coil diameter (D_c) is 93 mm.

2.2 Experimental procedure:

Hot water and cold water were allowed to shell side and tube side to check the leakages in the circuit and tested the thermocouples and thermostat. Hot water was circulated to the shell side. The nanofluid at 0.4% volume concentration was circulated through the tube side. Shell side pump is switched on when water attains the prescribed temperature. The is done by thermostat attached in water storage system. The flow configuration was made parallel flow condition. The corresponding temperatures were noted after attaining the steady state. The same procedure was done for nanofluid at 0.8% volume concentration. The flow configuration is changed from parallel to counter flow. The same procedure is followed and the temperatures are noted. Flow rate on shell side (0.15 kg/sec) and coiled tube pitch are maintained constant throughout the test. The flow rate on tube side is varied .The flow in tube side is in the range of 0.03-0.05 kg/sec in laminar flow The range of Reynolds number are 5200-8600. All the quantities that are measured to estimate the tube side Nusselt number are subjected to uncertainties due to the errors in the measurement. Hence, uncertainty analysis was carried out using Coleman and Steele method [27] and ANSI/ASME standards [28] considering for measurement errors.

2.3 Estimation of nanofluid thermo-physical properties:

The Al_2O_3 / water nanofluid at 0.4% and 0.8% volume concentration are used. Pak and Cho [29], and Wang and Choi.[2] proposed the correlations for calculating the thermo physical properties of nanofluids such as density, and specific heat. The specific heat and density, thermal conductivity and viscosity of nanofluid are calculated from Eqs.(2),(3-5) and (6) respectively.

$$(\rho c_p)_{nf} = \varphi(\rho_p c_{p,p}) + \rho_w (1-\varphi) c_{p,w} \quad \text{.......... ....(2)}$$

$$\rho_{nf} = \varphi\rho_p + (1-\varphi)\rho_w \quad \text{.......... ....(3)}$$

Recently Chandrasekar et al.[30] presented a effective thermal conductivity model (Eq.5) and effective viscosity model (Eq.6). They reported that the measured thermal conductivity data of nanofluid hold good agreement with the experimental data.

$$M_{nf} = (1-\phi)M + \phi M_s \quad \text{.......... ....(4)}$$

$$\frac{k_{eff}}{k_f} = \left[\frac{c_{p,nf}}{c_{p,f}}\right]^{-0.023} \left[\frac{\rho_{nf}}{\rho_f}\right]^{1.358} \left[\frac{M_f}{M_{nf}}\right]^{0.126} \quad \text{..................(5)}$$

$$\frac{\mu_{nf}}{\mu_f} = 1 + b\left(\frac{\phi}{1-\phi}\right)^n \quad \text{.......... ....(6)}$$

2.4 Data processing:
The heat transfer for water and nanofluid are estimated from Eqs.(7) and (8). The average heat transfer is taken for this analysis. Fouling factor was not taken into account.

$$Q_w = m_w c_{p,w} (T_{in} - T_{out})_w \text{.......... ....}(7)$$

$$Q_{nf} = m_{nf} c_{p,nf} (T_{in} - T_{out})_{nf} \text{.......... ....}(8)$$

$$Q = U_O A_O (\Delta T) \text{........ ....}(9)$$

$$Q = h_i A_i (T_{wall} - T_{bulk}) \text{..........................}(10)$$

$$Nu_i = \frac{hi\, di}{k_{eff}} \text{..........................}(11)$$

The overall heat transfer coefficient and inner heat transfer coefficient of coiled tube are calculated from Eqs.(9) and (10). The experimental tube side Nusselt number is calculated from Eq.(11). It measures the convective heat transfer in the helical tube.

3. Results and Discussions

3.1 Effect of nanofluid thermal conductivity
Many theoretical thermal conductivity models were developed and available in the open literature. Still the proposed models are being faced by strong argument and critical comments on the anomalous thermal conductivity mechanism of nanofluid. Fig.4 illustrates the effect particle volume concentration on effective thermal conductivity of Al_2O_3/water nanofluid. Chandrasekar et al. model [30] reported the measured thermal conductivity holds good agreement with the predicted values. It is seen that the thermal conductivity increases over the particle volume concentration. Therefore the thermal conductivity model given by them is taken for calculation. The deviation between the classical Hamilton –Crosser [HC] [31] model and Chandrasekar et al. model [30] are significant. Because the classical HC model considered the effect of particle volume concentration, thermal conductivities of base fluid, materials and shape factor for developing model. Whereas Chandrasekar et al.[30] model incorporated the effect of molecular weight, specific heat, volume concentration and densities of base fluid and nanoparticles material. In general, the thermal conductivity increases over the particle volume concentration. This is due to higher higher surface area to volume ratio of particles. Most of the research group reported the possible mechanism for enhanced heat conduction such as Brownian motion, Molecular layering of liquid at the liquid/particle interface, nanoparticle clustering.

3.2 Heat transfer coefficient:
Fig.5 shows the deviation between the overall heat transfer coefficient of parallel and counter flow. It is clear that there is no much deviation in overall heat transfer coefficient between the parallel flow and counter flow. The deviation between them are in the range of -1% to +6%. This comparison was done at the tube side mass flow rate of 0.03 - 0.05 kg/s and Reynolds number in the range of 5200-8600 under laminar flow regime. The overall heat transfer coefficient of counter flow was 4-8% more than that of parallel flow at 0.4% nanofluid. The overall heat transfer coefficient of counter flow was 5-9% more than that of parallel flow at 0.8% nanofluid. It is observed that there is no significant effect of heat transfer on changing flow condition. The reason is that the tube side primary flow and generation of secondary flow are always perpendicular to the shell side flow. Therefore, the change of flow direction does not affect overall heat transfer. This means that the formation of secondary flow in coiled tube does not have negative impact in both flow configurations.

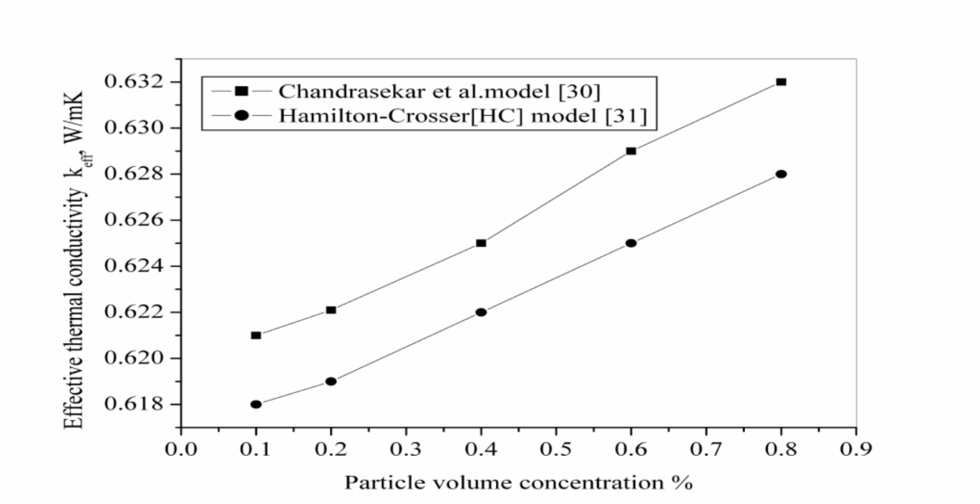

Figure 4: Thermal conductivity of Al_2O_3 / water nanofluid as a function of particle volume concentration

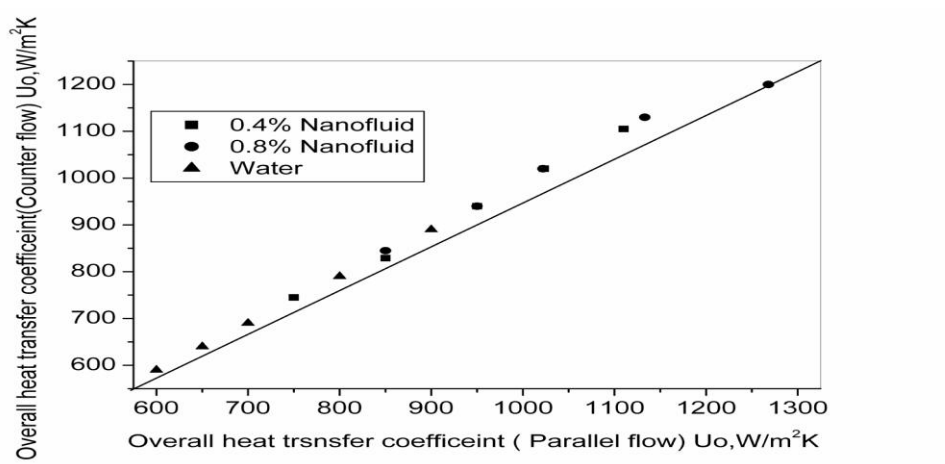

Figure 5: Comparison of overall heat transfer coefficient of counter and parallel flow configuration under laminar flow

Fig. 6 illustrates the variation of experimental inner heat transfer coefficient with different tube side Reynolds number. From the result, it is studied the heat transfer coefficient increases while increasing particle volume concentration. This is due to the reduction of temperature difference between the wall and bulk nanofluid at higher particle volume concentration. The reduction of wall temperature occurs when the dispersed suspended nanoparticles hit the bend surfaces and carry more heat energy. It is also studied the heat transfer coefficient is increasing over Reynolds number. This is due to the better fluid mixing at higher velocity. Fig.6 shows that there is no much deviation between the parallel and counter flow heat transfer coefficient. The reason is that the reduction of temperature drop between the tube wall and bulk nanofluid are the same under parallel flow and counter flow conditions.

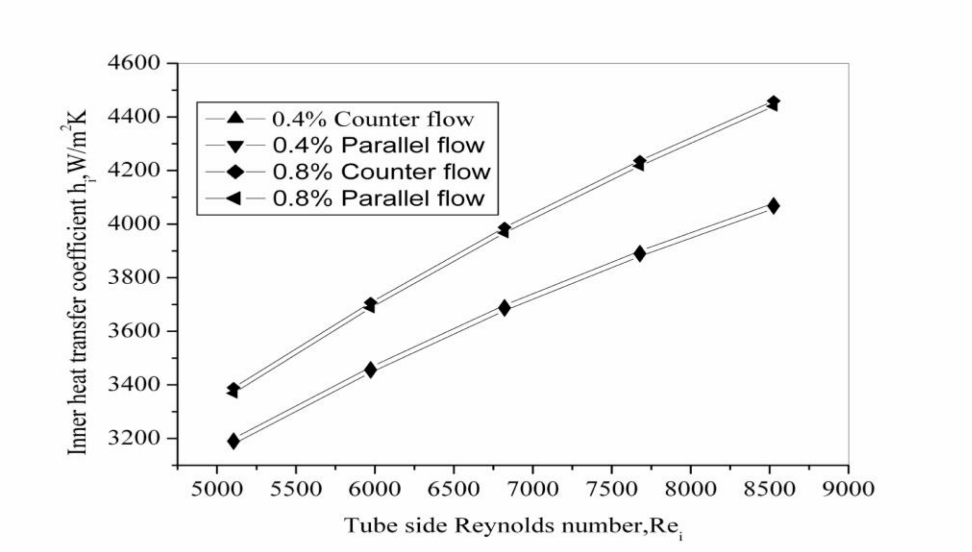

Figure 6: Variation of inner heat transfer coefficient with tube side Reynolds number

3.3 Experimental inner Nusselt number:

Fig.7 represents the variation of experimental inner Nusselt number with the inner Reynolds number. On comparing the parallel flow and counter flow configuration, it is found that there is no significant impact on inner Nusselt number when A_2O_3/water nanofluid is circulated. This is because whatever be the flow configuration between shell and coiled tube, the inner heat transfer coefficient is the same. This means that the generation of centrifugal force and secondary flow did not get negative impact. It is also observed that the inner Nusselt number increases when particle concentration is higher. This is due to higher inner heat transfer coefficient and thermal conductivity. In general, higher the thermal conductivity, higher the convective heat transfer.

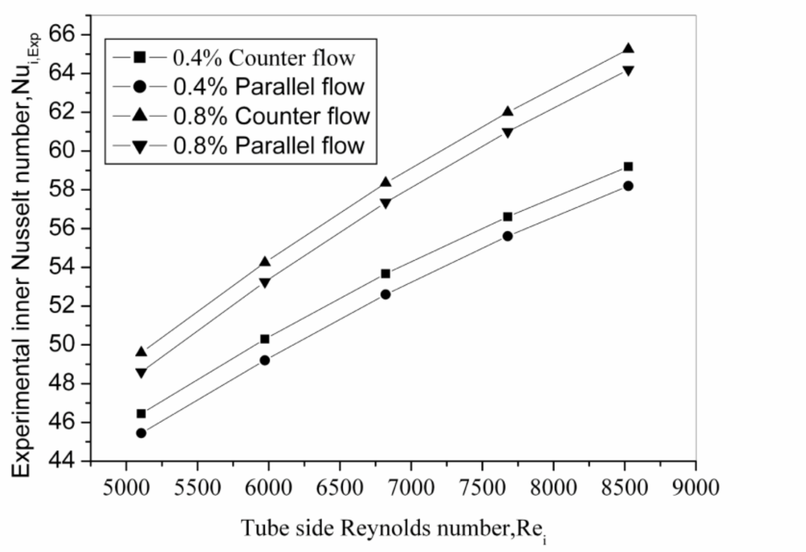

Figure 7: Variation of experimental inner Nusselt number with tube side Reynolds number

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4. Conclusion

This investigation was carried out to study the effect of Al_2O_3 /water nanofluid on heat transfer in a shell and helically coiled tube heat exchanger by changing flow direction. The nanofluid Al_2O_3 at 0.4% and 0.8% particle volume concentration were prepared and characterized by using XRD and SEM. It is studied that the overall heat transfer coefficient of counter flow is 4-8% higher than that of parallel flow at 0.4% nanofluid. The overall heat transfer coefficient is 5-9% higher than that of parallel flow at 0.8% nanofluid. It is found that there is no much impact of changing flow direction on overall heat transfer coefficient. Because both in parallel flow and counter flow conditions, the tube side flow passes perpendicular direction to the shell side flow. It is observed that the presence of Al_2O_3 nanoparticles attributes to the generation of strong nanoconvection current and better mixing. Therefore, nanofluid can be applied in helical coiled tube heat exchanger to augment heat transfer. Further work is needed to develop the coiled tube side Nusselt number correlation incorporating the effect of nanofluid and pressure drop correlations. The microscopic study on the effect of nanofluid on generation of secondary flow is also needed.

5. Nomenclature:

A Surface area, m2
b Constant
c_p Specific heat capacity J/kg K
di Diameter of coiled tube, m
De Dean number = $Re_i (d_i / 2R_c)^{0.5}$
h Convective heat transfer co-efficient ,W/m^2K
k Thermal conductivity, W/m K
L Effective length of coiled tube, m
m Mass flow rate, kg/s
n Constant
M Molecular weight
Nu Nusselt number
Q Heat transfer rate, W
Re Reynolds number = $\rho_{nf} v_i d_i / \mu_{nf}$
Rc Curvature radius, m
T Temperature, K
vi Tube side velocity, m/s.
Uo Overall heat transfer coefficient, $Wm^{-2}K^{-1}$

Greek letters

ρ Density, kg/m^3
φ particle Volume concentration
μ Dynamic viscosity, kg/m^2s
δ Inner tube radius di / mean coil radius D

Subscripts

eff Effective
i Inside condition
f Base fluid
nf Nanofluid
o Outside condition
p Particle
w Water

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