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Experimental investigation on convective heat transfer and friction factor in a helically coiled tube with Al_2O_3 / water nanofluid[†]

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Abstract

In this study, the heat transfer and friction factor of a shell and helically coiled tube heat exchanger using Al_2O_3 / water nanofluid at 0.1%, 0.4% and 0.8% particle volume concentration were tested. The test was conducted under laminar flow condition at $5100 < Re_i < 8700$. It is found that the overall heat transfer coefficient, inner heat transfer coefficient and experimental inner Nusselt number are 24%, 25% and 28%, respectively, higher than water at 0.8% particle volume concentration of nanofluid. It is observed that the presence of nanoparticles further intensify the formation of secondary flow and proper mixing of fluid when nanofluid passes through the helically coiled tube. Apart from further flow intensification, higher thermal conductivity of nanofluid and random movement of nanoparticles contribute to the enhanced heat transfer coefficient. Also found that the friction factor increases over particle volume concentration and this is due to increased nanofluid viscosity while increasing particle volume concentration.

Keywords: Al_2O_3 / water nanofluid; Effective thermal conductivity; Helically coiled tube; Nanofluid viscosity; Particle volume concentration; Secondary flow

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1. Introduction

In the past decades, heat transfer enhancement technology has been developed and widely applied in heat exchangers. Many attempts have been made to reduce the size, cost of heat exchanger and energy consumption. In general, the classification of enhancement of heat transfer techniques can be divided into three types namely; active, passive and compound techniques. Active techniques require external forces like fluid vibrations, electric field, surface vibration, injection and suction. Passive techniques require special surface geometries like varies tube inserts, coiled tubes and additives for liquids. Compound techniques are the combination of any two or more techniques simultaneously to obtain enhanced heat transfer. In view of meeting out the great thermal energy demand, Choi S.U.S, (1995) Argonne National laboratory USA dispersed Al_2O_3 nano particles in the size range of 1-100 nm in base fluid and named the suspended Al_2O_3 nanoparticles in base fluid as nanofluid. On testing Al_2O_3 nanofluid, it exhibits superior thermo-physical properties relative to those of conventional heat transfer fluids. Nanofluids are the next generation heat transfer fluids, and they offer great possibilities of enhanced heat transfer than the ordinary fluids. Nanofluids are proposed for various uses in heat energy transport fields such as cooling of electronic components, transportation, medical, and heating, ventilation and air conditioning (HVAC). Many research groups presented the higher effective thermal conductivity of nanofluid and Brownian motion of particles are the key elemental mechanisms for improving heat transfer. The major parameters that affect the effective thermal conductivity are particles volume concentration, particle size, particles shape, temperature of nanofluid, pH value , viscosity and density of nanofluids

Wang et al. [1], Choi and Eastman [2], Xuan and Roetzel [3], Das et al. [4], and Yang et al. [5] revealed the nanofluid exhibits greater enhancement in thermal conductivity (5-60%) over the particle volume concentration in the range of 0.1-5%. They reported the enhancement mainly depends on the factors such as particle volume concentration, particles shape, and particles size. They suggested the increased thermal dispersion is due to chaotic movement of nanoparticles which accelerate heat transfer and improved thermal conductivity are the mechanisms for enhanced heat transfer. Xuan and Li [6] proposed the heat transfer coefficient is decreased when adding more nanoparticle volume concentration. They reasoned the higher particle volume concentration sharply increase the viscosity which suppress the Brownian movement of nanoparti-

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cles, suppress the fluid intensification and decrease the effective thermal conductivity.

Chandrasekar et al. [7] proposed two thermal conductivity models for nanofluid based on the nanolayer thickness and Brownian motion. They reported the nanolayer thickness has no effect on nanofluid thermal conductivity at less than 1% particle volume concentration. Xie et al. [8] measured the thermal conductivity of Al_2O_3 / water nanofluid and reported the addition of nanoparticles in base fluid leads to higher thermal conductivity. Pak and Cho [9], and Patel et al. [10] presented the investigation on thermal conductivity of Al_2O_3 and CuO water based nanofluid. They revealed the reason for the same is due to the presence of nanosized particles in base fluid could move more easily and bring out a higher level of Brownian motion. Syamsunder et al. [11] applied Al_2O_3 / water nanofluid in a mini heat exchanger with tube inserts and reported the heat transfer coefficient increases over particle volume concentration. Chandrasekar et al. [12] experimentally investigated the effect of 0.1% of Al_2O_3 / water nanofluid on heat transfer and pressure drop in a pipe with coil insets. They found that the 21.53% enhancement in Nusselt number and there is no significant pressure drop. Mapa and Sana Mazhar [13] carried out an experiment on a mini double pipe heat exchanger and presented the thermo physical properties with respect to different volume concentration of nanoparticles.

Dean [14] proposed a non-dimensionless number, called Dean 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, Dravid et al. [15] proposed the correlation for inner Nusselt number at the Dean number in the range of 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. Wen and Ding [16], Janssen and Hoogendoorn [17], Prabhanjan et al. [18] proposed the helically coiled tubes are superior to straight tubes when employed in heat transfer application using conventional fluids. They reported the curvature of tube plays an important role in enhancing heat transfer rate. Salimpour [19, 20] experimentally investigated on overall heat transfer coefficient of shell and helical coil with conventional fluids. They proposed the Nusselt number correlations and reported the heat transfer rate differs while varying coiled tube pitches. Srinivasan et al. [21] analyzed the heat transfer based on friction coefficient and proposed the critical Reynolds number Re_{cr} in curved pipes. Akbarinia [22] studied the effect of laminar flow mixed convection in a horizontal curved tubes with nanofluid. He reported the presence of nanoparticle does not affect the formation of secondary flow, axial velocity and skin friction factor.

As there is no work reported in a shell and helical coiled tube with Al_2O_3 nanofluid, this study is aimed at to compare the nanofluid laminar heat transfer and friction factor with the performance of water. This investigation can be referred as compound heat transfer enhancement technique because the two passive heat transfer techniques such as helical coil and addition of nanoparticles are taken together for enhancing heat transfer.

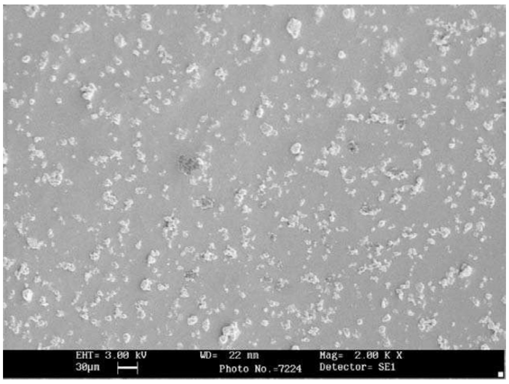

Fig. 1. SEM image of Al_2O_3 / water nanofluid.

2. Preparation of Al_2O_3 / water nanofluid

The dispersion of Al_2O_3 nanoparticles 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 of nanoparticles. Fig. 1 illustrates the Scanning Electron Microscope SEM (Jeol JSM 6360 SEM) image of agglomerated nanoparticles in base fluid. The image was obtained by sonicating nanofluid, solidifying to get a thin film which contains aggregated nanopartcles and making it conductive. It is clear from the image that the dispersed nanoparticles appear to be uniformly dispersed in base fluid. The Al_2O_3 / water nanofluid at 0.1%, 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.

3. Experimental setup

Fig. 2 illustrates the schematic of experimental setup. The set-up has shell side loop and helical coiled tube side loop. Shell side loop handles hot water. Helical coiled tube loop handles Al_2O_3 / water nanofluid. The shell side flow and coiled tube side flow are in counter flow configuration. Shell side loop consists of storage vessel with a heater of 1.75 kW capacity, magnetic pump and thermostat. Tube side loop consists of mono bloc pump, valve to control the flow on tube side, test section, cooling unit and storage vessel of five-liter capacity. The test section is horizontally placed. The coil was formed initially straight tube. Fine sand was filled the tube before bending to preserve the smoothness of the inner surface and this was washed with hot water after the test run is over.

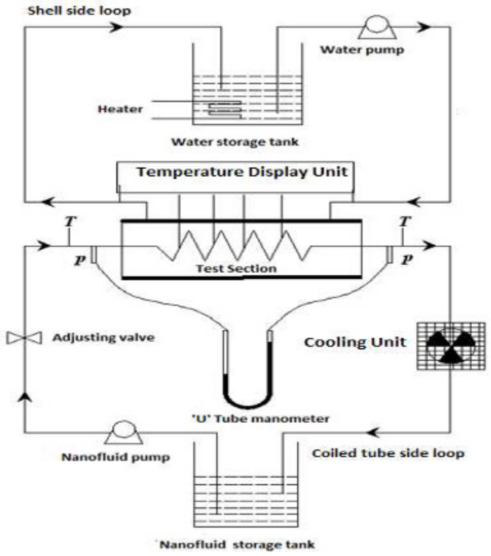

Fig. 2. Flow diagram of experimental set-up.

Helical tube is made up of copper and shell is made up of mild steel. The temperature of hot water in shell side storage vessel is maintained by thermostat. Four K-type thermocouples of 0.1°C accuracy were used to measure the inlet and outlet temperatures of shell and tube side. Four K-type thermocouples of 0.1°C were placed at equal intervals on the outer surface of coiled tube to measure the tube wall temperatures. The thermocouples were placed and glued with epoxy to avoid leakage. Flexible poly vinyl chloride (PVC) tubing was used for all connections. The calming section is provided in helical 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 cleaning the system between successive experimental runs.

The dimensions from the test section are: Helical tube internal diameter (di) - 9 mm, external diameter of helically coiled tube-10.5 mm, shell external diameter - 124 mm, the effective length (L) of the coil - 3700 mm, coil pitch - 19 mm, and coil diameter (D) - 93 mm.

3.1 Experimental procedure

Water is circulated to test the leakage, check the function of all thermocouples, 'U'tube manometer and thermostat. Hot water and cold water are allowed to shell side and tube side respectively under counter flow condition. The pump is switched on when the shell side fluid attains the required temperature. The shell side fluid temperature is controlled by thermostat. The corresponding temperatures are recorded at shell side and helical tube side. The nanofluid at 0.1% 0.4% and 0.8% volume concentration are circulated through the tube side. Hot water is circulated to the shell side. Flow rate on shell side is kept constant (0.14 kg/sec) and flow rate on tube side is varied (0.02 kg/sec-0.06 kg/sec). The temperatures are measured after attaining the steady state. 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 tests were conducted in the range of $5100 < Re_i < 8700$ under laminar flow condition. The thermal conductivity of Al_2O_3 / water nanofluid is measured with KD2 Pro thermal analyzer. The measured thermal conductivity holds decent agreement with the estimated thermal conductivity of nanofluid. 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 is carried out by using Coleman and Steele [23] and ANSI/ASME [24] reference for measurement errors. The uncertainties in this investigation measurements are 2.4%, 4% and 2.5% for Dean number, Nusselt number, and friction factor, respectively.

3.2 Estimation of nanofluid thermo-physical properties

The Al_2O_3 / water nanofluid at 0.1%, 0.4% and 0.8% volume concentration are used in this study. Choi and Eastman [2] proposed the Eqs. (1), (2) for calculating the thermo physical properties of nanofluid such as specific heat and density.

$$\left(\rho c_p\right)_{nf} = \phi\left(\rho_p c_{p,p}\right) + \rho_w\left(1-\phi\right)c_{p,w} \tag{1}$$

$$\rho_{nf} = \phi\rho_p + (1-\phi)\rho_w \tag{2}$$

Recently,Chandrasekar et al. [7] presented Eqs. (3)-(5) for estimating effective thermal conductivity and viscosity nanofluid. Where M is the molecular weight, n and b are constants. They reported the predicted thermal conductivity and viscosity hold good agreement with the measured data.

$$M_{nf} = (1-\phi)M_w + \phi M_p \tag{3}$$

$$\frac{k_{eff}}{k_f} = \left[\frac{c_{p,nf}}{c_p}\right]^{-0.023}\left[\frac{\rho_{nf}}{\rho}\right]^{1.358}\left|\frac{M}{M_{nf}}\right|^{0.126} \tag{4}$$

$$\frac{\mu_{nf}}{\mu_f} = 1 + b\left(\frac{\phi}{1-\phi}\right)^n \tag{5}$$

3.3 Data processing

The flow condition is obtained by using the critical Reynolds number Eq. (6). The average heat transfer for tube side and shell side are calculated from Eqs. (7) and (8). Fouling factor was not taken into account.

$$\mathrm{Re}_{cr} = 2100(1+12\sqrt{\delta}) \tag{6}$$

$$\mathrm{Q_w} = \dot{\mathrm{m}}_\mathrm{w}\, \mathrm{c_{p,w}}(\mathrm{T_{in}} - \mathrm{T_{out}})_\mathrm{w} \tag{7}$$

$$\mathrm{Q_{nf}} = \dot{\mathrm{m}}_\mathrm{nf}\, \mathrm{c_{p,nf}}(\mathrm{T_{in}} - \mathrm{T_{out}})_\mathrm{nf} \tag{8}$$

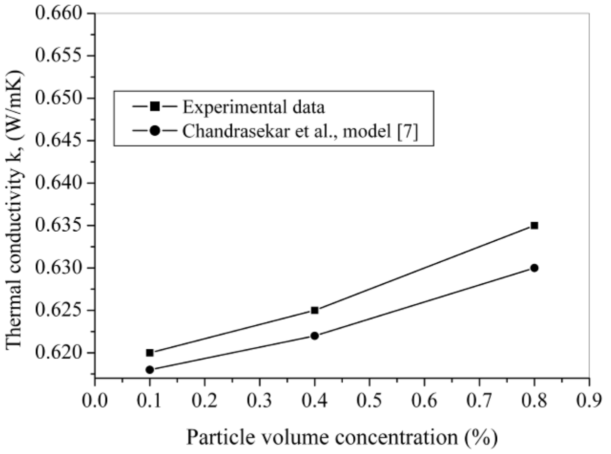

Fig. 3. Effect of particle volume concentration on thermal conductivity.

$$Q = U_0 A_0 (\Delta T) \quad (9)$$

$$Q = hiAi(T_{\text{wall}} - T_{\text{bulk}}) \quad (10)$$

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

The overall heat transfer coefficient and inner heat transfer coefficient of coiled tube are calculated from Eqs. (9) and (10). Where ΔT is the average temperature difference between the bulk fluid in coiled tube and fluid in shell side. The experimental tube side Nusselt number is calculated from Eq. (11). It measures the convective heat transfer in helically coiled tube. The experimental friction factor is obtained from Eq. (12). It involves the pressure drop ΔP across the working length of coil and velocity of flowing medium (V).

$$f_c = \left[\frac{\Delta P}{0.5\rho V^2}\right]\delta^2(4/N\pi) \quad (12)$$

4. Results and discussion

4.1 Effect of thermal conductivity of nanofluid

Fig. 3 illustrates the variation of thermal conductivity with particle volume concentration. It shows that the thermal conductivity increases with increasing particle volume concentration. Many researchers reported the thermal conductivity of nanofluid is a function of particle volume concentration. In Fig. 3, the deviation between the experimental data and predicted vale are in the range of 0.3-0.8%. Chandrasekar et al. [7] proposed the particle-to-particle interactions, random movement of particles and particle clustering are the reasons for enhanced nanofluid thermal conductivity.

4.2 Convective heat transfer for nanofluid

Fig. 4 shows the enhancement of overall heat transfer coefficient with increasing tube side Reynolds number and particles volume concentration. The enhancement of overall heat transfer coefficients were found to be 7%, 17% and 24% at 0.1%, 0.4% and 0.8% Al_2O_3 / water nanofluid respectively. The considerable enhancement of overall heat transfer coefficient is 24% at 0.8% volume concentration at the tube side Reynolds number of 8600. The reason is that the higher heat transfer rate and lower temperature drop between the bulk fluid in coil and the fluid in shell side. The enhancement by increasing nanoparticles concentration is due to higher thermal conductivity of nanofluid. However the presence of nanoparticles yields better thermal contact and better mixing so as to have lower temperature drop.

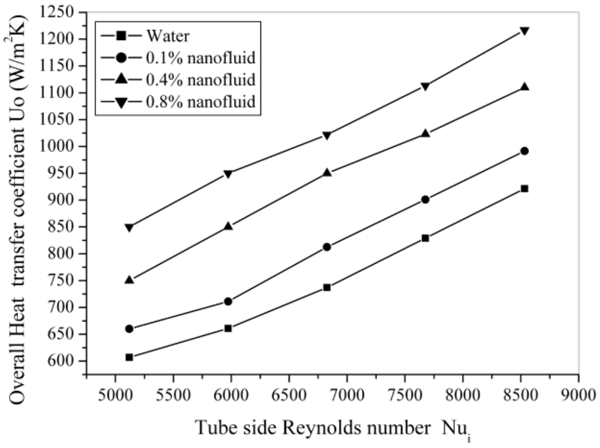

Fig. 4. Effect of tube side Reynolds number on overall heat transfer coefficient.

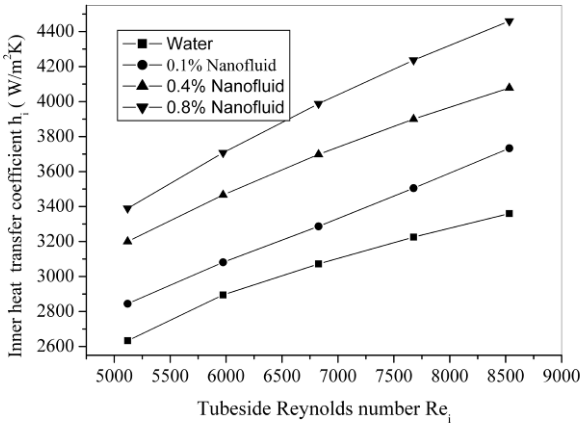

Fig. 5. Effect of tube side Reynolds number on inner heat transfer coefficient.

Fig. 5 shows the effect of increasing the particle volume concentration on inner heat transfer coefficients under laminar flow. It is clear that the tube side heat transfer coefficient increases over tube side Reynolds number. The enhancement of tube side inner heat transfer coefficients were found to be 10%, 18% and 25% at 0.1%, 0.4% and 0.8% Al_2O_3 / water nanofluid respectively. It is studied that heat transfer coefficient is improved even at 0.1% particle volume concentration. These enhancements are due to reduction of temperature difference

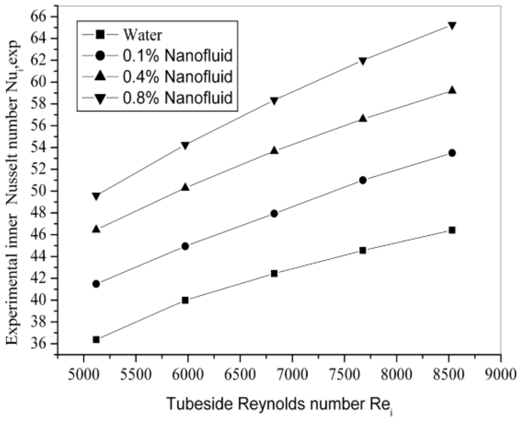

Fig. 6. Variation of experimental inner Nusselt number with tube side Reynolds number.

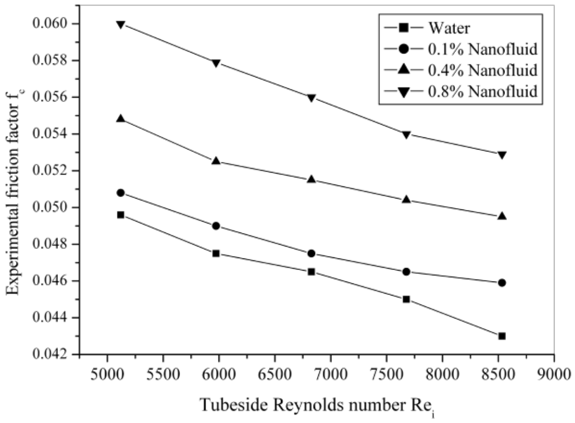

Fig. 7. Effect of tube side Reynolds number on experimental friction factor.

between the wall and the bulk nanofluid temperature. The reduction of wall temperature occurs when the dispersed and suspended nanoparticles hit the bend surfaces.

Xuan and Li [6] reported the higher particle volume concentration increases viscosity which suppress the turbulence and fluid mixing resulting lower heat transfer coefficient. Pak and Cho [9] investigated heat transfer coefficient of 3% particle volume concentration of Al_2O_3 / water nanofluid with a mean particle diameter of 13 nm. They reported heat transfer coefficient of nanofluid is 12% smaller than that of pure water. Yu et al. [25] reported in their review that the agglomeration problem becomes worse resulting lowering the thermal conductivity of nanofluid. They reasoned the increased viscosity suppresses the flow turbulence and movement of nanoparticles. They also suggested the selection of particle volume concentration is important criteria to augment heat transfer. Farajollahi et al. [26] revealed the viscosity, easy particles aggregation causing easy settling, and less Brownian motion occur when volume concentration is more than optimum value of 2%. Therefore, it is expected that the heat transfer coefficient may decrease when the particle volume concentration is more than the optimum value.

Fig. 6 shows the enhancement of experimental inner Nusselt number by varying tube side Reynolds number and particle volume concentration. The enhancement of tube side experimental Nusselt numbers were found to be 17%, 23% and 28% at 0.1%, 0.4% and 0.8% Al_2O_3 / water nanofluid respectively when compared with water. Dravid et al. [15] reveled the curvature effect leads to fasten the outer side flow than the inner side flow in a flow through coiled tube using conventional fluid. This difference in velocity of inner and outer forms the secondary flow. The secondary flow enhances fluid mixing and thus heat transfer. In this investigation, the enhancement of tube side experimental Nusselt number is due to further intensification of fluid mixing which results strong formation of secondary flow. Also, the enhanced thermal conductivity and random motion of nanoparticles play role in enhancing heat transfer. The contribution to the random motion of ultrafine particles is to accelerate energy exchange process between the fluid and wall.

4.3 Effect of friction factor

Fig. 7 illustrates the effect of nanoparticles on friction factor at different particle volume concentration. It is clear that the friction factor increases over the particle volume concentration.

The increase in friction factor are 3%, 9% and 18% at 0.1%, 0.4% and 0.8% volume concentration, respectively, when compared with water at the tube side Reynolds of 8532. Many research groups reported the viscosity of nanofluid increases while increasing the particle volume concentration. This viscosity improvement may suppress the particles motion, which leads to lower the heat transfer. This friction factor study results hold good with the conclusion conceived by Pak and Cho [9] and Xuan and Li [3]. Therefore, the presence of nanoparticles increases friction factor, which in turn increase the pressure drop. It is seen that the increase in friction factor is very small when the particle volume concentration is 0.1%. The increase of friction factor 18% is considerable at 0.8% particle volume concentration. Therefore the nanofluid can be applied at low particle volume concentration without much pressure drop.

5. Conclusions

In this paper, laminar heat transfer and friction factor of a helically coiled tube with Al_2O_3 / water nanofluid at 0.1%, 0.4 and 0.8% particle volume concentration were tested. The heat transfer enhancement of nanofluid has been compared with water. It is studied the heat transfer coefficients increase with increasing particle volume concentration. The maximum enhancement of overall heat transfer coefficient and inner Nusselt number were found to be 24% and 28%, respectively, at 0.8% volume concentration. The maximum enhancement of inner heat transfer coefficient was found to be 25% more when compared with water at 0.8% volume concentration.

From the results, it is observed that there is no negative impact of presence of nanoparticles on convective heat transfer and formation of secondary flow in coiled tube. These enhancements are due to higher thermal conductivity of nanofluid, better mixing of fluid, and random movement of nanoparticles which carry more heat energy. It is also tested that the friction factor considerably increases at 0.4 and 0.8% particle volume concentration. Therefore, the conventional heat transfer fluid can be replaced at low particle volume concentration of Al_2O_3 / water nanofluid without getting pressure drop penalty in helically coiled tube heat exchanger. Further work is needed to observe the settlement, fouling of nanoparticles in coiled tube, and heat transfer at particle loading more than optimum level.

Nomenclature

A : Surface area, m^2
c_p : Specific heat capacity, J/kg K
di : Diameter of coiled tube, m
f_c : Friction factor
h : Convective heat transfer co-efficient, W/m^2K
k : Thermal conductivity, W/m K
$\dot{m}$: Mass flow rate, kg/s
M : Molecular weight
N : Number of coil turns
Nu : Nusselt number
Q : Heat transfer rate, W
Re : Reynolds number = $\rho_{nf} V_i \, d_i / \mu_{nf}$
T : Temperature, K
V : Tube side fluid velocity, m/s.
Uo : Overall heat transfer coefficient, W/m^2K

Greek letters

ρ : Density, kg/m^3
φ : Particle volume concentration (%)
μ : Dynamic viscosity, kg/m^2s
δ : Inner tube radius r_i / mean coil radius R

Subscripts

cri : Critical
eff : Effective
i : Inside condition
f : Base fluid
nf : Nanofluids
o : Outside condition
p : Particle
w : Water

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