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Experimental Study & Heat Transfer Analysis on Copper Spiral Heat Exchanger Using Water Based SiO_2 Nanofluid as Coolant

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Abstract

Heat exchangers have its major application in automobile, air condition, refrigerator, power plants, and many others. Heat transfer characteristics and performance of Copper spiral heat exchanger are investigated and compared with pure water. Nanofluid can enhance thermos-physical properties. Experiment is carried out for water based SiO_2 Nanofluid with 15 nm average sized nanoparticle at varying air velocity and mass flow rate of fluid to investigate its effect on heat transfer coefficient. From the experimental data, a closed form solution for Nusselt number has been calculated using $\in$-NTU method. A new correlation has been proposed as a function of Reynolds number and Prandtl number. The heat transfer rate, effectiveness, has been significantly higher compared to pure water and with increasing volume fraction of nanoparticles.

Keywords

Spiral Heat Exchanger, Nanofluid, Sonification, Effectiveness, Nusselt Number

1. Introduction

Radiators are used for transferring heat or thermal energy for cooling in case of automobile engine and heating in case of refrigerators and air conditions. In past few years, several configurations have been developed for heat exchangers or radiators to maximize the heat transfer rates and utilize the available space effectively [1]. Spiral heat exchangers are compact and have better heat transfer efficiency. They are spirally wound in a circular pattern through which the hot or cold fluid flows. Because of spiral shape, it has self-cleaning ability and even the problem of thermal expansion is in control [1]. The spiral profile helps in effective use of airflow area over it and the boundary layer formed over it is consistent. The pressure drop inside the heat exchanger is minimum which reduces the energy consumed by pump [2]. Nanofluid has a wide area of research viz. heat transfer medical, mass transfer and others [3]. Due to very small size of the particles, Nanoparticles exhibit completely different properties then its parent material as it has very large surface area to weight ratio which completely changes the properties (like magnetic, activity, conductivity). The heat transfer rate of water based Nanofluid increases, which indeed increases the efficiency and effectiveness of the cooling system [4].

Ramesh *et al.* [1] carried out numerical investigation on compact spiral radiator against air-cooled fin and tube radiator. They calculated different heat transfer characteristics by using the ∊-NTU (effectiveness—Numbers of Transfer Units) method. They made use of GARCH tool in MATLAB to correlate between different non-dimensional numbers and the results were promising. Their experiment also shows that use of ∊-NTU method can be used for heat transfer experiments. Sawant *et al.* [4] has optimized shape of the spiral by improving surface area, air flow, and coolant property. They employed a more efficient heat transfer material. They used LMTD and the ∊-NTU approach to find out effectiveness of radiators. Sivashanmugam [5] studied the changes in several physical and thermal properties of Nanofluid by the addition of nanoparticles. He developed mathematical model for different heat transfer characteristic in different kind of heat exchanger viz. tubular, double pipe, plate shell, multichannel, radial flow and electronic and double tube helical heat exchanger. And we can fairly confirm that Spiral Heat exchangers are good options to have a substitute for conventional tubular exchanger. Naphon *et al.* [6] viewed on the heat transfer characteristics and the performance of a spiral coil heat exchanger under cooling and humidifying condition, and they assumed a steel shell with spirally coiled tube unit. They used Newton-Raphson iterative method to develop and solve the Mathematical model based on mass and energy transfer to find heat transfer characteristics.

Nanoparticle, because of its smaller size, always has issues related to stability and sedimentation, use of sonification and surfactant is necessary. Yu *et al.* [3] involved the methodology for the preparation of Nanofluid, evaluate stability of nanoparticles in Nanofluid, enhance the stability of Nanofluid and stability mechanism of Nanofluid Carl *et al.* [7] used ∊-NTU method to find out theoretical effectiveness, overall heat transfer rate and outlet temperature of air and water in automotive radiator. They compared experimental heat transfer rate of air and water with the theoretical heat transfer rate. Bhogare *et al.* [2] reviewed different papers and gave a brief out view about suitability of nanoparticles with different base fluid and their thermo-physical properties like conductivity and more. They reviewed the challenges faced by Nanofluid, like half-life of the nanoparticles in fluid, thermal performance in turbulent flow and fully developed region, low specific heat of particles and high viscosity. Patel *et al.* [8] investigated and found heat transferred by the radiator as a function of air flow rate across the radiator. They analyzed, compared and verified the flow characteristic with known physical situation and existing experimental data. Bhimani *et al.* [9] conducted experiment with forced convection heat transfer in water based Nanofluid and compared to that of pure water in automobile radiator. They used water based TiO_2 Nanofluid with different concentration of nanoparticle in car radiator. They concluded that the use of 1% concentration by volume of TiO_2 could enhance the heat transfer efficiency up to 45% compared to pure water. Sundar *et al.* [10] used magnetic Ni Nanofluid in a tube and investigated its heat transfer and frictional factor for different flow rates at different concentration and temperature. Nusselt No. and friction factor were experimentally estimated as a function of particle concentration and Reynold No. per constant heat flux condition in forced convection apparatus with no peak change of Nanofluid flowing in tube.

This paper is inspired by the need of co-relation for water-based Nanofluid as coolant; therefore, an experimental setup is designed using Spiral Heat Exchanger for achieving relevant data. An appropriate data treatment and analysis are conducted to calculate Nusselt No., Effectiveness, Reynold's No. and over all heat transfer coefficients. An empirical correlation is developed between non-dimensional quantities for the setup.

2. Experimental Setup

Experimental setup **Figure 1** consists of a single 3 m long cupper spiral tube with internal diameter of 10 mm and thickness of 2 mm through which water-based SiO_2 Nanofluid passes at higher temperature with the help of pump. The spiral radiator is fixed with the help of clamps. A fan at different velocity is used to cool the Nanofluid flowing inside Spiral heat exchanger. The velocity of air is measured with the use of anemometer. Several thermocouples are used to measure the temperature of inlet and outlet Nanofluid, ambient temperature and

Figure 1. Experimental setup for spiral heat exchanger using Nanofluid as coolant.

air temperature. A constant temperature electric heater is used to heat Nanofluid at before entering into spiral heat exchanger to a constant temperature. Rotameter measures fluid flow rate and flow control valve limits the flow rate. Nanoparticles mixed with pure water by the process of sonication to achieve homogenous mixture. Since, the nanoparticle used is amorphous hydrophilic SiO_2, surfactant is not required for mixture.

3. Experimental Procedure

Constant temperature electric heater heats the Nanofluid to a constant temperature of 65˚C. Flow control valve controls the flow rate of Nanofluid entering to the inlet of the spiral tube. Once the system is in steady state, ambient temperature and fluid inlet temperature is noted, fan blows air to the spiral radiator at constant speed. Observe Outlet temperature of Nanofluid using another thermocouple and allow fluid to flow into sump again where electric heater heats fluid to 65˚C again. Repeat the experiment for various concentration of Nanofluid, different mass flow rate and air velocity. From the observed experimental data, heat transfer rate, other heat transfer coefficients is calculated and co-relation between the non-dimensional terms is developed using the ∈-NTU approach and Excel regression curve by power tool. Experimental testing is carried out on the spiral heat exchanger for different volume fraction of Nanofluid and the result is compared with the pure water flow. Average inlet temperature was kept constant and outlet fluid temperature was compared at different flow rate of fluid from 15 cc/s to 100 cc/s and for different air flow velocity viz. 5, 5.5 and 6.5 m/s (Figure 2).

4. Mathematical Modelling

After achieving experimental data, calculation has been done using below mentioned equations and Table 1 and Table 2 to achieve correlation for Nusselts Number.

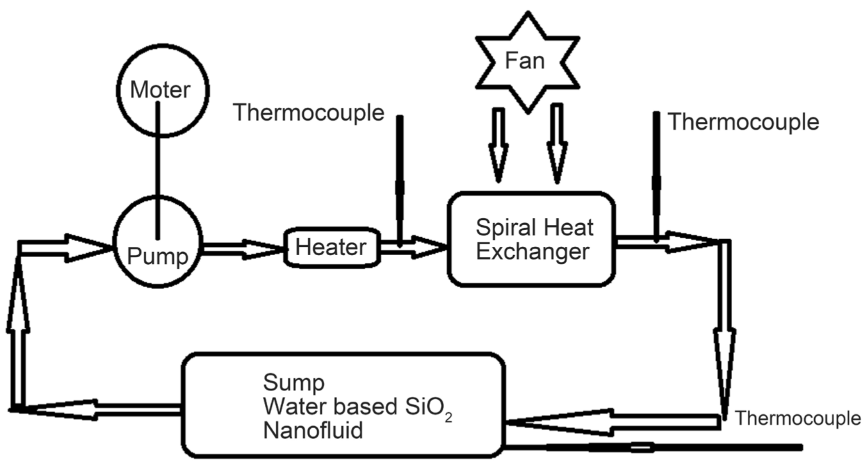

Figure 2. Schematic representation of experimental setup.

Table 1. Thermo-physical property of water and air at $T_a = 40^{\circ}\text{C}$.

	Water	Air
ρ	990	1.225
c	4183	1006.43
K	0.64	0.0242
μ	0.00048213	0.00001789

Table 2. Thermo-physical property of water based SiO_2 Nanofluid at $T_a = 40^{\circ}\text{C}$ at different volume fraction of Nano particles.

	$\varnothing = 0.05$	$\varnothing = 0.1$	$\varnothing = 0.2$	$\varnothing = 0.3$	$\varnothing = 0.4$
ρ	990.705	991.41	992.82	994.23	995.64
c	4180.90	4178.81	4174.6	4170.45	4166.27
K	0.6404	0.6408	0.6417	0.6425	0.6434
μ	0.0008504	0.00085085	0.0008517	0.0008525	0.0008534

Volume fraction of Nanofluid

$$\varnothing = \left[\frac{\frac{m_p}{\rho_p}}{\frac{m_p}{\rho_p} + \frac{m_w}{\rho_w}} \right] \times 100 \tag{1}$$

Density of Nanofluid

$$\rho_f = (1 - \varnothing)\rho_w + \varnothing \times \rho_p \tag{2}$$

Specific heat capacity of Nanofluid [5]

$$c_f = (1 - \varnothing) \times c_w + \varnothing \times c_p \tag{3}$$

Thermal Conductivity of Nanofluid [5]

$$K_f = \frac{K_p + K_w + 2\varnothing(K_p - K_w)}{K_p + 2K_w - \varnothing(K_p - K_w)} \times K_w \tag{4}$$

Viscosity of Nanofluid [5]

$$\mu_f = \mu_w (1 + 2.5) \times \varnothing \tag{5}$$

Reynolds number of Nanofluid passing through spiral heat exchanger

$$Re = \frac{\rho_f d v_f}{\mu_f} \tag{6}$$

Prandtl number of Nanofluid passing through spiral heat exchanger

$$Pr = \frac{\mu_f c_f}{K_f} \tag{7}$$

Heat capacity of both air and fluid

$$C_a = m_a c_a \tag{8}$$

$$C_f = m_f c_f \tag{9}$$

Heat lost by Nanofluid from one end of spiral tube to other end

$$Q = C_f \times \left(T_{f_i} - T_{f_o}\right) \tag{10}$$

Convective heat transfer coefficient of Nanofluid

$$h_f = \frac{Q}{A \times \left(T_m - T_a\right)} \tag{11}$$

Nusselt number of Nanofluid

$$Nu = h_f \frac{d}{K_f} \tag{12}$$

Make use of Excel regression curve by power tool to find correlation between Re and Pr, Prandtl number for given volume fraction of Nanofluid remains constant so its power can be considered constant as in Dittus-Boelter's Equation for parallel and counter flow

$$Nu = 0.023 Re^{0.8} Pr^{0.3} \tag{13}$$

Overall heat transfer coefficient of the system, since there are three steps involved for heat transfer which includes convection because of hot Nanofluid inside tube, conduction because of Copper tube wall, and convection from tube wall to air.

$$\frac{1}{U} = \frac{1}{h_a A_2} + \frac{\ln \frac{r_2}{r_1}}{2\pi L K_t} + \frac{1}{h_f A_1} \tag{14}$$

The value of $C_{\max}$ and $C_{\min}$ is the maximum and minimum value from C_a and C_f

$$C_{\max} = MAX\left[C_a : C_f\right] \tag{15}$$

$$C_{\min} = MIN\left[C_a : C_f\right] \tag{16}$$

Maximum Heat transfer rate is given by

$$Q_{\max} = C_{\min} \times \left(T_{f_i} - T_a\right) \tag{17}$$

Effectiveness of spiral radiator is

$$\in = \frac{Q}{Q_{\max}} \tag{18}$$

5. Results

In Figure 3, increasing trend of temperature has been seen because of increasing flow rate of Nanofluid as the time available for the heat transfer decreases due to which temperature drop across the spiral ends decreases. The highest temperature difference of 8˚C can be observed for 0.4% volume concentration from 100 cc/s to 15 cc/s flow rate of fluid. It can be observed that as the concentration of nanoparticles in Nanofluid increases to 0.4% the outlet temperature also decreases

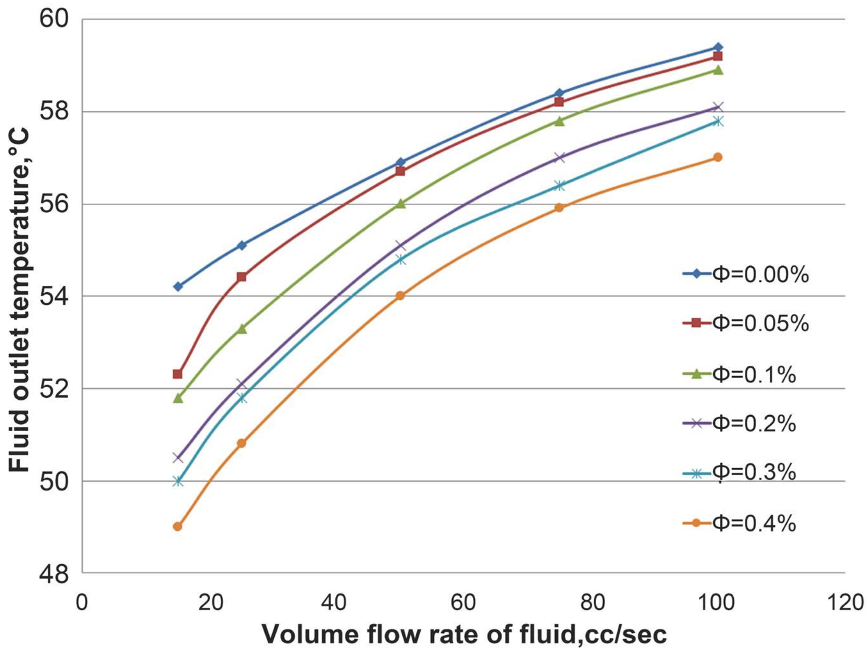

Figure 3. Fluid outlet temperature vs Volume flow rate of fluid.

for constant volume flow rate of fluid up to 6.5˚C for the reason being, as the concentration increases, thermal conductivity of fluid also increases and hence the heat transfer rate.

It can be observed in **Figure 4**, with the increase in volume flow rate the heat transfer rate increases rapidly to certain extent and slowly amount of heat transfer decreases. The increase is up to 700% compared to pure water. This is because; with the increase in mass flow rate of fluid, the amount of heat transfer decreases. With the increase in volume concentration of Nanofluid, the amount of heat transfer increases as the conductivity of fluid increases with the increasing concentration of nanoparticle in fluid. The heat transfer rate at 0% concentration of nanoparticle in water is more than that of 0.05% volume concentration of Nanofluid, because of some embedded minerals and foreign agents present in normal tap water.

There is an increase in Nusselt number with the increasing value of Reynolds number in **Figure 5**, the increase is more significant in the initial part of Reynolds number but with the increase in Reynolds number greater than 15,000 the increase is not much significant.

Since the fluid is different, the predefined equations to calculate Nusselt No. cannot be used so a correlation is found between Nusselt No., Reynolds No. and Prandtl No.

Since the Prandtl No. is the function of viscosity, specific heat and conductivity of the fluid, and these values are predetermined, there is no variation in Prandtl number, it remains constant for the given volume concentration of Nanofluid. So the major variation is found in the coefficient and the power coefficient of Reynolds number. The Nusselt Number equation is found in the form of:

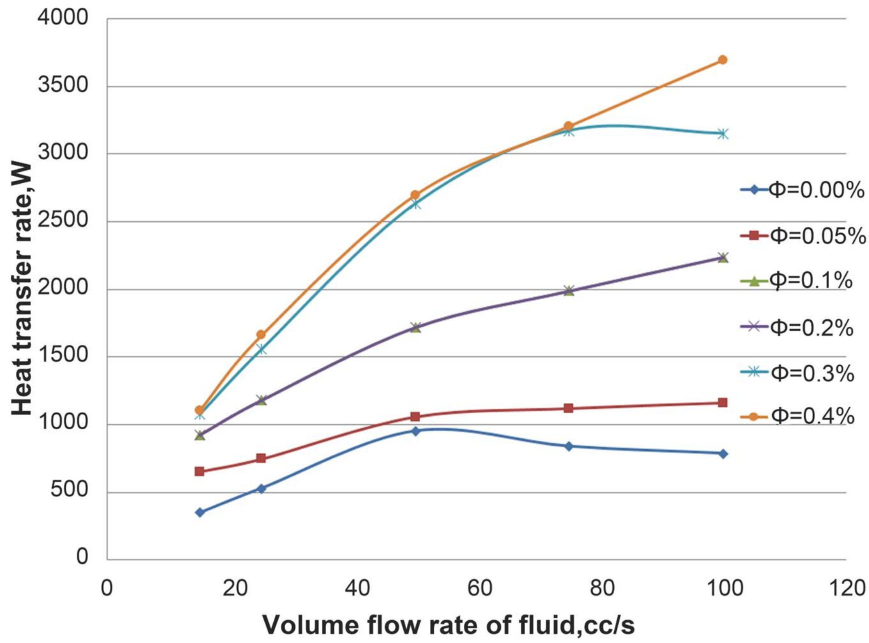

Figure 4. Heat Transfer rate vs Volume flow rate of fluid.

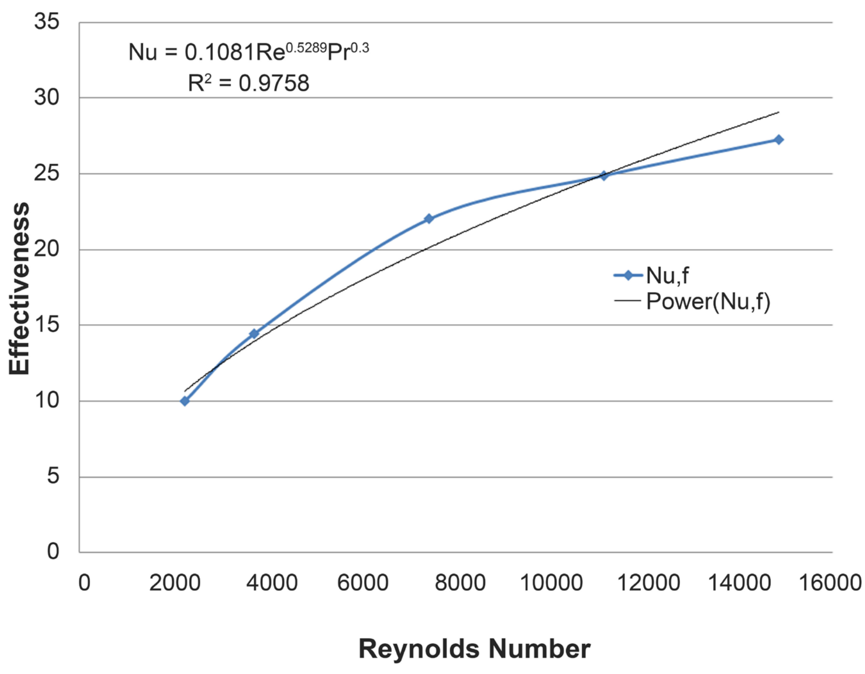

Figure 5. Nusselt Number vs Reynolds Number for 0.4% volume concentration of Nanofluid at 6.5 m/s air velocity.

$$Nu = c_1 Re^{c_2} Pr^{c_3}$$

Excel power correlation is used to find out the value of coefficients c_1, c_2 and c_3 (**Table 3**).

Effectiveness is the ratio of the actual heat transfer to the maximum heat transfer. From **Figures 6-8**, it can be observed that with increase in Reynolds

Table 3. Coefficient of correlation.

Volume concentration(Ø)	Air velocity, m/s	C1	C2	C3
	5	0.2358	0.3611	0.3
0.2%	5.5	0.4469	0.3122	0.3
	6.5	0.1945	0.4327	0.3
	5	0.2536	0.3645	0.3
0.3%	5.5	0.1667	0.4460	0.3
	6.5	0.1326	0.4982	0.3
	5	0.1915	0.4158	0.3
0.4%	5.5	0.0764	0.5452	0.3
	6.5	0.1081	0.5289	0.3

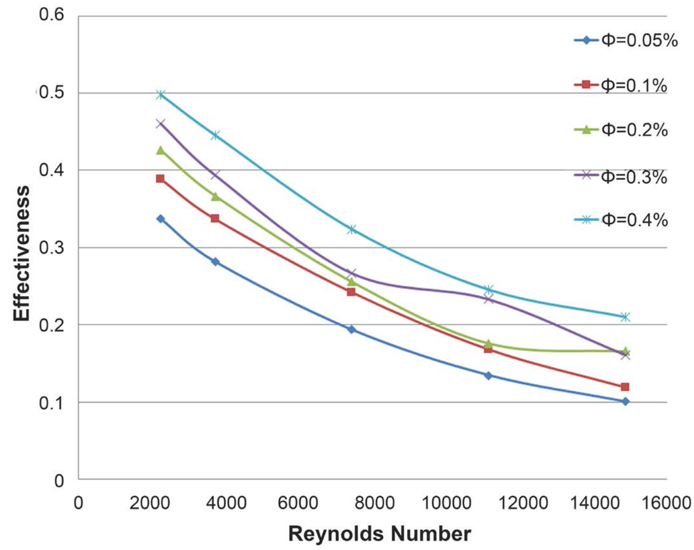

Figure 6. Effectiveness vs Reynolds Number at 5 m/s air velocity.

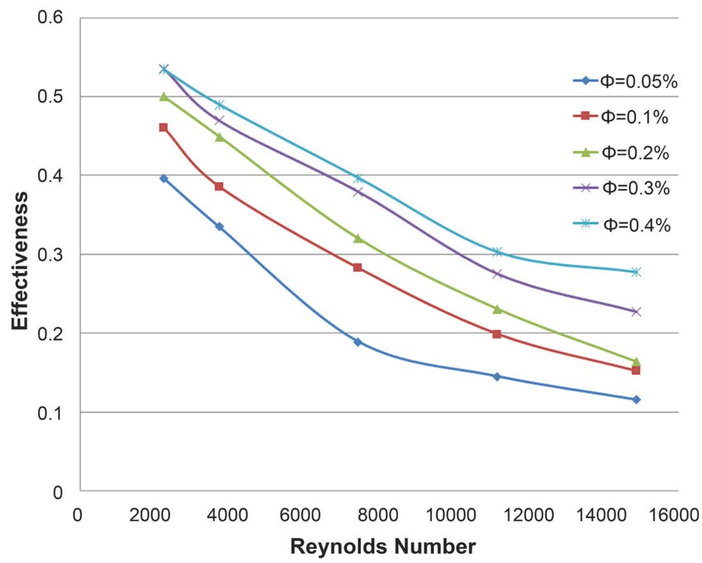

Figure 7. Effectiveness vs Reynolds Number at 5.5 m/s air velocity.

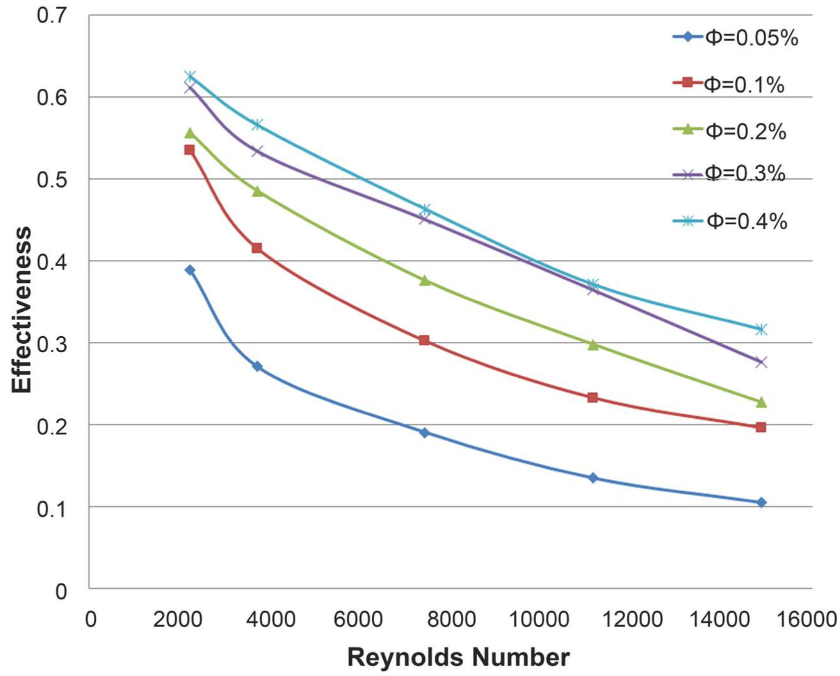

Figure 8. Effectiveness vs Reynolds Number at 6.5 m/s air velocity.

no., effectiveness decreases sharply and after certain value around 10,000, effectiveness almost remains constant. Effectiveness decreases because the flow changes from laminar flow to turbulent flow and there is transition in the flow. Further, the value of effectiveness increases with the increase in volume concentration of Nanofluid, which is because higher concentration of nanoparticle in fluid will increase its conductivity, hence heat transfer rate and finally effectiveness. For a constant Reynolds No., and volume concentration effectiveness increases with increase in flow rate of air, as more air molecules takes away heat and actual heat transfer increases. The increase in effectiveness compare to 0.05% volume concentration of Nanofluid by using 0.4% volume concentration is from 50% to 170%. Higher increase difference in effectiveness is at higher Reynolds number.

6. Conclusion

From the experimental observation conclusion that can be drawn are: maximum heat transfer occurs at 0.4% volume concentration and 100 cc/s volume flow rate of Nanofluid at 6.5 m/s air velocity. Outlet temperature of fluid is minimum for 0.4% volume fraction of Nanofluid and 15 cc/s volume flow rate of Nanofluid at 6.5 m/s air velocity. There is a substantial increase in the heat transfer coefficient by using Nanofluid compared to water. Effectiveness tends to decrease with the increase in Reynolds number, which may be attributed for change in the efficiency of spiral heat exchanger. Since, the heat transfer rate is significantly affected by both internal fluid flow rate and external air velocity, there should be some tread off between these two while choosing the operating parameters. The increment in heat transfer rate was found from 160% to 400% then by the use of normal water. Correlation among Nusselt number, Reynolds number and Prandtl number is proposed for different cases.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

NOMENCLATURE

Q = heat loss rate, W
$Ø$ = volume fraction
K = Thermal Conductivity, W/m·K
h = Convective heat transfer coefficient, W/m^2·K
T = Temperature, K
c = specific heat capacity, J/kg·K
$\in$ = effectiveness
Nu = Nusselt Number
C = heat capacity, J/K·s
Pr = Prandtl Number
m = mass flow rate, kg/s
U = overall heat transfer coefficient, W/m^2·K
r_2 = inner diameter of spiral tube, m
r_1 = outer diameter of spiral tube, m
d = average diameter of tube, m
A_1 = inner surface area of spiral tube, m^2
A_2 = outer surface area of spiral tube, m^2
L = Length of the tube, m
Re = Reynolds Number
NTU = Numbers of Transfer Units
μ = Viscosity, m^2/s
ρ = Density, kg/m^3

Subscripts

a = air
w = water
p = nanoparticle
f = fluid
i = inlet
o = outlet
m = mean
t = spiral tube
min = minimum
max = maximum