Experimental Performance Investigation of Helically Coiled Tube Heat Exchanger Using Al_2O_3/Water as Nanofluid

Abhishek R. Sonawane[1], N. V. Sali[2]
[1, 2] Department of Mechanical Engineering
[1, 2] GCE, Karad

Abstract- *The experimental investigation of helically coiled tube heat exchanger is carried out using Al_2O_3/Water nanofluid. The experimentation is carried out using three different helical coils with varying pitches viz. 3mm, 6mm and 9mm. The sole purpose of the study is heat transfer analysis of helically coiled tubes with water and different volume concentrations of Al_2O_3 nanofluid viz. 0.05%, 0.1% and 0.15% with water as a base fluid. The stability of nanofluid is maintained by using SDS (Sodium Dodecyl Sulphate) surfactant to avoid settlement of nanoparticles. The cold fluid flow rate is varied in the range of 1 to 5 lpm. The inlet hot water temperature is also varied between 75 to 65°C. Heat transfer enhancement and pressure drop are studied with respect to change in tube dimensions and fluid composition. From experimental result, it is found that overall heat transfer coefficient, Nusselt number and other thermal properties increases with increasing nanofluid concentration & cold fluid flow rate. It is also found that the pressure drop is more dominant than heat transfer for various combinations of heat exchanger tubes and working fluid.*

Keywords- Helical tubes, Nanofluid, Heat transfer enhancement, Pressure drop.

Nomenclature		**Greek symbols**	
De	Dean Number	μ	Dynamic viscosity
Re	Reynolds Number	Ø	Volume concentration
D	Coil diameter	ρ	Density
R	Tube radius		
P	pitch	**subscripts**	
K	Thermal conductivity	P	Particle
C_p	Specific heat	Nf	Nanofluid
		Bf	Basefluid

I. INTRODUCTION

A heat exchanger is a device that provides the transfer of thermal energy between two or more fluids, which are at different temperatures and are in thermal contact with each other. The word “Exchanger” really applied to all types of equipment in which heat is exchanged but it is often used specially to the equipment in which heat is exchanged between two process streams that are at different temperature and are separated by a solid wall. Heat exchangers are widely used as the essential units in heat extraction and recovery systems in industries. Heat exchangers play an important role in various fields such as chemical engineering, metallurgy, electric power generation, refrigeration and air-conditioning, aerospace industries, oil and petrochemical industries, sugar industries, pharmaceutical industries, chemical reactors etc. The effectiveness of heat exchanger is low i.e. actual heat transfer is low as compared to maximum heat transfer.

Energy recovery is of prime importance to optimize the energy consumption in industry. To achieve maximum utilization of thermal energy, several heat transfer enhancement techniques have been used in many thermal engineering applications such as nuclear reactor, chemical reactor, chemical process, automotive cooling, refrigeration, and heat exchanger, etc. Heat transfer enhancement techniques are powerful tools to increase heat transfer rate and thermal performance of heat exchangers. The purpose behind the augmentation is to reduce the size of the heat exchanger required for specified heat duty, to upgrade the capacity of an existing heat exchanger. All these advantages have made heat transfer enhancement technology attractive in heat exchanger applications.

There are two techniques used for heat transfer enhancement, one is active technique in which there is need of supplying external power source to the fluid or the equipment. Second one is passive technique in which heat transfer enhancement is done by turbulence promoters (such as special surface geometries, curved tubes such as spiral and helically coiled tubes, propeller, tangential inlet nozzle, snail entry, axial/radial guide vane, spiral fin) or fluid additives (such as nanofluids), without using any direct external power source. Due to easy installation, operation and cost saving, passive methods are extensively preferred for heat transfer enhancement.

One of the passive method is use of curved tube instead of straight tubes. The survey found that one of the favourable kinds of heat exchangers was the helical tube heat exchanger. Improving the coil geometry is one way to augment the heat transfer rate of the helical tube heat exchanger. The channels are curved and have a uniform cross section, which creates “spiraling” motion within the fluid. The fluid is fully turbulent at a much lower velocity than in straight tube heat exchangers, and fluid travels at constant velocity throughout the whole unit.

Another passive technique of heat transfer enhancement is use of nanofluids as working fluid in heat transfer applications. Nanofluid is a terminology for a base fluid material containing one or more than one type of nanoparticles. Usually, the nanoparticles that are used in nanofluid are made of metals, carbides, carbon nanotubes or oxides. By addition of nanoparticles, the thermo-physical properties of the working fluid are significantly improved, including thermal conductivity, viscosity, convective heat transfer coefficient. Hence nanofluid is a fluid that enhances the heat transfer rate. In order to enhance the performance of heat exchangers, recently research has been started by the use of different types of nanofluids.

Heat transfer and flow through a curved tube is comprehensively first reviewed by Naphon and Wongwises [1] and the latest review of flow and heat transfer characteristics are provided by Gabriela Huminic and Angel Huminic [2]. Experimental studies have been conducted on helical coil tubes under different operating conditions. Purandare et al. [3] carried out the parametric analysis of helical coiled tube heat exchanger with various correlations given by different researchers for specific conditions. The various correlations uses different parameters such as tube geometry for parametric analysis. S.S.Pawar [4] had experimentally investigated the steady and unsteady state convection heat transfer from helical coiled tubes mounted vertically in water for laminar flow regime. Helical coiled tubes with curvature ratios as 0.0757, 0.064, 0.055 and Prandtl number ranging from 3.81 to 4.8, Reynolds number from 3,166 to 9,658 were taken into account for this work. Rogers [5] experimentally studied the results for forced convection heat transfer and friction factors, obtained with water flowing through steam heated coils, reported and compared with the limited results available. Srinivas [6] carried out an experimental study on forced convective heat transfer study on agitated shell and helical coil heat exchanger using CuO/water nanofluid. Experiments have been carried out in shell and helical coil heat exchanger at various concentrations of CuO nanoparticles in water (0.3, 0.6, 1, 1.5, 2%wt), stirrer speed (500, 1000, and 1500rpm) and shell side (heating medium) temperatures (40, 45, 50ºc). It is observed that there is significant increase in heat transfer rate due to use of nanofluid in heat exchanger. Almohammadi [7] studied Convective heat transfer coefficient and pressure drop of Al_2O_3/water nanofluid in lamina flow regime under constant heat flux conditions inside a circular tube were experimentally investigated. Al_2O_3/water nanofluid with 0.5% and 1% volume concentrations with 15 nm diameter nanoparticles were used as working fluid. The effect of different volume concentrations on convective heat transfer coefficient and friction factor was studied. Jaafar Albadr [8] experimentally studied the forced convective heat transfer and flow characteristics of a nanofluid consisting of water and different volume concentrations of Al_2O_3 nanofluid (0.3–2%) flowing in a horizontal shell and tube heat exchanger counter flow under turbulent flow conditions are investigated.

II. HELICALLY COILED TUBE

Curved tubes are mainly consists of helical and spiral coils. They have better heat transfer characteristics as compared to straight tube heat exchanger. The fluid flowing through the helical coiled tube creates the secondary circulation of fluid flow known as double eddy or Dean effect. Due to the curvature of the tube, a centrifugal force is generated as fluid flows through the curved tubes. This introduces the generation of secondary flow along the tube wall. This rotating motion of fluids through coiled tube develops a characteristic swirling motion. The frictional resistance of tube wall and action of centrifugal force combine to produce the secondary flow.

Secondary flows induced by the centrifugal force have significant ability to enhance the heat transfer rate. The secondary flow produced is a function of curvature ratio and flow velocity. Curvature ratio is the ratio of tube diameter to the diameter of curvature of coil. Higher the velocity of fluid, for a given ratio (d/D), the greater the centrifugal force and more predominant is the secondary flow. The secondary flow is superimposed on the primary flow, known as the Dean vortex. The Dean vortex was first observed by Eustice; then numerous studies have been reported on the flow field that arrives in curved pipes. The development of secondary flow is independent of the laminar or turbulent flow. This phenomena is more predominant in case of helically coiled tube due to its geometry. Figure 3.2 shows the geometrical structure of helically coiled tube.

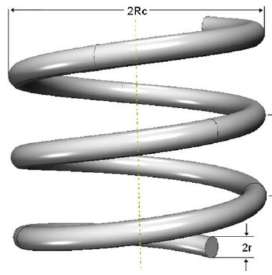

Figure 1. Geometry of Helically Coiled Tube

Dean [9] made a mathematical study to describe the flow in coiled tube. He found that the secondary flow in the curved pipes is function of Reynolds number and curvature ratio. It is given in the performance analysis of heat exchanger. Dean number which is a function of Reynolds number and curvature ratio is given by,

$$De = Re\sqrt{\frac{d_i}{D_i}} \qquad \text{(Eqn. 1)}$$

The helically coiled tube which is part of this study is shown in fig. 2.

Figure 2. Photographic Image of Helically Coiled Tube

III. EXPERIMENTATION

The experimental set-up consists of helically coiled tube heat exchangers of three types as a test section. The cold fluid enters the heat exchanger at the outer header tube i.e. from periphery of heat exchanger and comes out from the centre header tube of heat exchanger where as hot fluid enters from bottom side centre of shell and comes out from top side periphery. A schematic diagram of the experimental set-up is shown in fig.3.

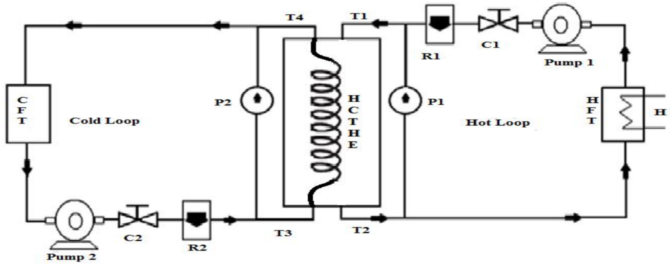

Figure 3. Block Diagram of Experimental Setup

H – Heater, HFT – Hot Fluid Tank, C1 and C2 – Control Valve, R1 and R2 – Rotameter, P1 and P2 – Pressure Transducer, HCTHE – Helically Coiled Tube Heat Exchanger, CFT – Cold Fluid Tank, T1 – Hot fluid inlet temperature, T2 – Hot fluid outlet temperature, T3 – Cold fluid inlet temperature, T4 – Cold fluid outlet temperature.

Fig. 4. shows the photographic image of experimental set-up fabricated.. The shell is having cylindrical cross section with 278 mm inside diameter and length is 270 mm. The pump is used for lifting the cold fluid from CFT to heat exchangers. As the cold fluid passes through the HTHE, its temperature increases then the heated cold fluid is circulated through another forced air cooled heat exchanger where it rejects its heat and temperature of cold fluid is maintained to the desired inlet temperature, so the cold fluid is recirculated in the system and system becomes closed loop.

Figure 4. Photographic Image of Experimental Setup

Experiments were performed by keeping the volume flow rate of hot fluid constant and varying the cold fluid volume flow rate. At the same time inlet temperature of hot fluid is also varied. Before noting any reading, system is allowed to reach steady state. The flow rates were controlled by adjusting the valve and measured by the two calibrated rotameters having range 0-5 lpm. The operating parameter and their range are given in following table:

Table 1. Operating Conditions for Experimentation

Variables	Range
Hot fluid inlet temperature, ºC	75 – 60 (In step of 5 ºC)
Cold fluid inlet temperature, ºC	30
Hot fluid flow rate, lpm	5
Cold fluid flow rate, lpm	1-5 (In step of 1 lpm)

IV. PERFORMANCE ANALYSIS

Heat transfer between cold fluid and hot fluid is calculated by using general energy balance equations. The tube side heat transfer i.e. amount of heat transferred by cold fluid from hot fluid is calculated by,

$$Q_c = m_c\, C_{pc}(T_{co} - T_{ci}) \qquad \text{(Eqn. 2)}$$

And the shell side heat transfer i.e. heat transferred from hot fluid is given by,

$$Q_h = m_h\, C_{ph}(T_{hi} - T_{ho}) \qquad \text{(Eqn. 3)}$$

The heat transfer coefficient is calculated from Newton's law of cooling as

$$Q = h\, A_s\, (T_B - T_W) \qquad \text{(Eqn. 4)}$$

The effectiveness for counter flow heat exchanger is determined by following equation:

$$\varepsilon = \frac{1-\exp[-NTU(1-C)]}{1-C\times\exp[-NTU(1-C)]} \qquad \text{(Eqn. 5)}$$

NTU for heat exchanger is given by,

$$NTU = \frac{UA_s}{C_{min}} \qquad \text{(Eqn. 6)}$$

Reynolds number for tube side fluid is given by,

$$Re_c = \frac{\rho_c V_c d_i}{\mu_c} \qquad \text{(Eqn. 7)}$$

Nusselt number gives the significance of heat transfer by convection. Larger Nusselt number indicates large convection in the fluid. Nusselt number correlation for tube side fluid i.e. cold fluid is given by Rogers [5], as

$$Nu_c = 0.023\, {Re_c}^{0.85} {Pr_c}^{0.4} \delta^{0.1} \qquad \text{(Eqn. 8)}$$

Where Pr = $\frac{\mu Cp}{K}$

Heat transfer coefficient is largely affected by the properties of fluid as well as flow conditions. Heat transfer coefficient of tube side fluid is calculated as,

$$h_c = \frac{Nu_c k_c}{d_i} \qquad \text{(Eqn. 9)}$$

The equation for overall heat transfer coefficient is given as,

$$\frac{1}{U_0} = \frac{d_o}{d_i h_i} + \frac{d_o}{2K} \ln\left(\frac{d_o}{d_i}\right) + \frac{1}{h_o} \qquad \text{(Eqn. 10)}$$

V. PREPARATION OF NANOFLUID

A nanofluid is a fluid containing nanometre-sized particles, called nanoparticles. These fluids are engineered colloidal suspensions of nanoparticles in a base fluid. The nanoparticles used in nanofluids are typically made of metals, oxides, carbides, or carbon nanotubes. Addition of nanoparticles increases the thermal conductivity of working fluid. Nanoparticles stay suspended longer than larger particles and nanofluids exhibit excellent thermal properties and cooling capacity. The thermo physical properties of nanofluids depend on operating temperature of nanofluids. The important parameters which influence the heat transfer characteristics of nanofluids are its properties which include thermal conductivity, viscosity, specific heat and density. Nanofluids are used for heat transfer applications because they increase the heat transfer coefficient value.

Alpha Al_2O_3 nanoparticles are selected for preparation of nanofluid and water as a base fluid. Table 2 shows the specification of selected Al_2O_3 nanoparticles used for current work:

Table 2. Specifications of Al_2O_3 Nanoparticles

Chemical Formula	Alpha Al_2O_3
Colour	White
Morphological	Spherical
Specific surface area, m²/g	90-160
Density, g/cc	3.89
Average particle size, nm	20 – 30

The amount of Al_2O_3 nanoparticles required for preparation of a particular volume concentration of nanofluids is calculated as

$$\text{Volume fraction of } Al_2O_3 = \frac{V_{np}}{V_{np}+V_{bf}} \qquad \text{(Eqn. 11)}$$

The powdered form of Al_2O_3 nanoparticles is shown in the figure 4.1.

Figure 5. Photographic Image of Powdered form of Al_2O_3 Nanoparticles

The amount of Al_2O_3 nanoparticles required to prepare nanofluid of different (%) volume concentration in a 1 litres of water is summarized in the table 4.2 shown below.

Table 3. (%) Volume Concentrations with the Mass of Al_2O_3 Nanoparticles

Sr. No.	% Volume Concentration (ϕ)	Mass of Al_2O_3 (in gram) in 10 litre of water
1.	0.05	19.45
2.	0.10	38.9
3.	0.15	58.35

Preparation of nanofluid is a very important stage. Nanofluid is prepared in 4 steps as follows:

1. Mixing of nanoparticles in base fluid,
2. Addition of SDS surfactant in to the mixture,
3. Magnetic stirring of nanofluid,
4. Ultrasonication of magnetically stirred mixure.

After preparing the nanofluid, thermophysical properties are very important to determine. Jaafar Albadr [9] does the experimental investigation on different volume concentrations of Al_2O_3 and water nanofluid under force convective conditions. For such an investigation, the properties of nanofluid are very important to study heat transfer and hydrodynamics of nanofluid. The properties of nanofluids are calculated by using following correlations:

A. **DENSITY**

Cho and Pak [10,11] correlations given by calculated the equation for density of nanofluid,

$$\rho_{nf} = (1 - \emptyset)\rho_{bf} + \emptyset\rho_p \qquad \text{(Eqn. 12)}$$

B. **SPECIFIC HEAT**

The correlation for specific heat was developed by Xuan and Roetzel [12] given by,

$$(C_p)_{nf} = \frac{(1-\emptyset)(\rho C_p)_{bf} + \emptyset(\rho C_p)_p}{\rho_{nf}} \qquad \text{(Eqn. 13)}$$

C. **THERMAL CONDUCTIVITY**

The equation for calculating thermal conductivity of nanofluid was given by Yu and Choi [13],

$$\frac{K_{nf}}{K_{bf}} = \frac{K_p + 2K_{bf} - 2\emptyset(K_{bf} - K_p)}{K_p + 2K_{bf} + \emptyset(K_{bf} + K_p)} \qquad \text{(Eqn. 14)}$$

D. **DYNAMIC VISCOSITY**

The correlation for finding the viscosity of nanofluid was deduced by Drew and Passman [14] and is given as

$$\mu_{nf} = (1 + 2.5\emptyset)\mu_{bf} \qquad \text{(Eqn. 15)}$$

VI. RESULTS AND DISCUSSION

The reults and discussion consists the effect of nanofluid as a working fluid in heat exchanger tubes and effect of variation in tube geometry.

1. Effect of NTU on Nussselt Number

Number of transfer units is a dimensionless parameter which is the measure of physical size (heat transfer rate) of heat exchanger. NTU is also the measure of effectiveness of heat exchanger. NTU is directly proportional to overall heat transfer coefficient and inversely proportional to heat capacity of working fluid.

Nusselt number variation with respect to NTU for heat exchanger is shown in figure 6. The maximum NTU is observed for 0.15% of nanofluid. With the increase in the concentration of Al_2O_3 nanofluid, there is improved Nusselt number variation with respect to changer in NTU. There is decrease in Nusselt number with increase in NTU because of increasing the thermal conductivity of working fluid.

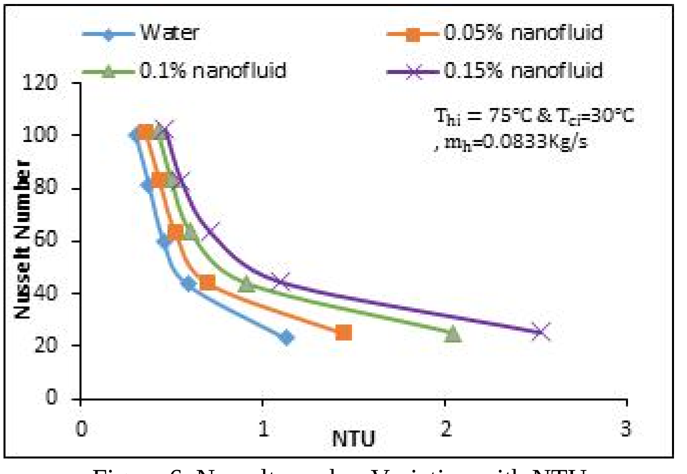

Figure 6. Nusselt number Variation with NTU

a) Nusselt Number Variation with Pitches

The variation in Nusselt number with respect to various pitches of the helical coil is shown in fig. 7. It is seen that there is gradual increase in Nusselt number with the increase in pitch of the coil. Highest value of Nusselt number is observed at pitch 9mm i.e. for tube III.

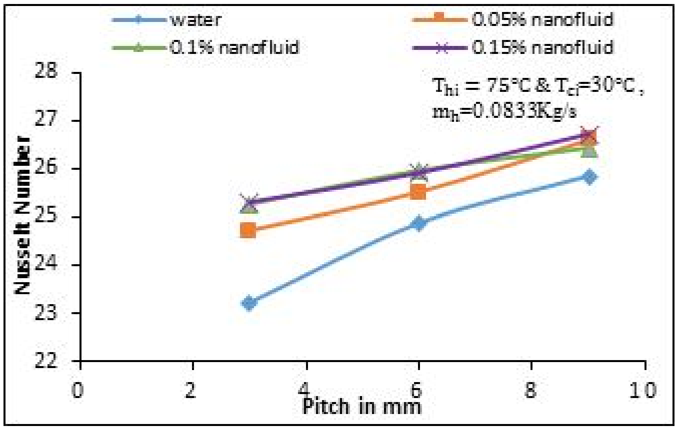

Figure 7. Nusselt Number Variation with Pitch of Coil

b) Validation of Nusselt Number

The most important parameter in case of heat exchanger is Nusselt number which is indirectly decides the heat transfer related parameters. The experimentally calculated Nusselt number is compared with correlation given by Rogers[6],

$$Nu_c = 0.023\, Re_c^{0.85} Pr_c^{0.4} \delta^{0.1}$$

The results of Nusselt number are validated with the analytical results obtained by using above correlation. The experimental Nusselt number is 10.4% lower than the theoretical due to losses and experimental errors. The variation of experimental value of Nusselt number with respect to theoretically obtained value (from correlation) is shown in fig. 8.

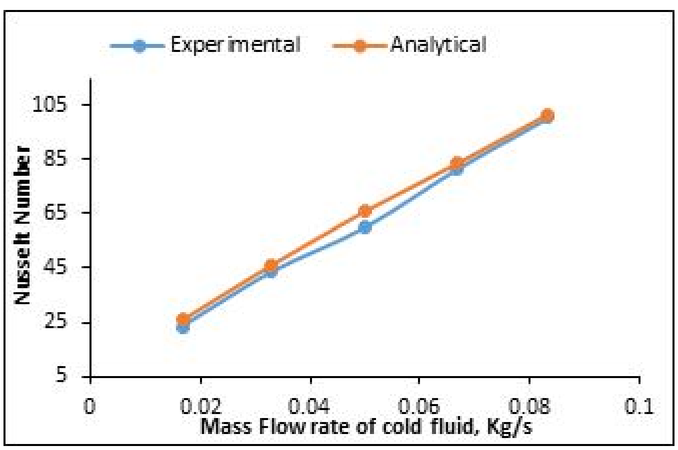

Figure 8. Validation of Nusselt number

2. LMTD Variation with Mass Flow Rate

LMTD is a logarithmic average of temperature difference between the hot and cold fluids at each end of heat exchanger.The variation in LMTD of heat exchanger for different mass flow rates for heat exchanger is shown in figure 9. It is seen that the LMTD increases with the increase in mass flow rate of cold fluid and decreases with the different concentrations of Al_2O_3 nanofluid. Highest value of LMTD obtained is for water at mc=0.0833 Kg/s is 34.6 ℃ and the lowest value for 0.15% Al_2O_3 nanofluid at mc= 0.0167 Kg/s is 16.8 ℃.

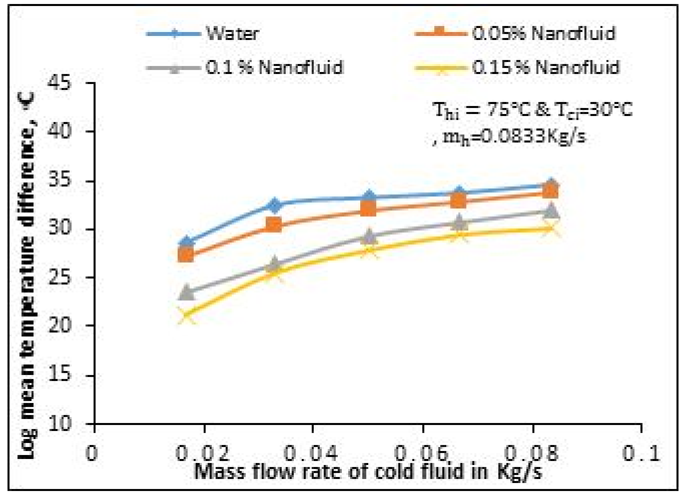

Figure 9. LMTD Variation with Mass Flow Rate

3. Pressure Drop Variation with Mass Flow Rate

The velocity of fluid increases with the increase in the mass flow rate of fluid. This leads to increase the pressure drop of heat exchanger. The variation in pressure drop of heat exchanger for different mass flow rates for tube I is shown in figure 10. It is seen that the pressure drop increases as the mass flow rate of cold fluid increases and different concentrations of Al_2O_3 nanofluid. Highest value of pressure drop obtained is for 0.15% Al2O3 nanofluid at mc=0.0833 Kg/s is 27 mm of Hg and the lowest value for water at 0.0167 Kg/s is 5mm of Hg.

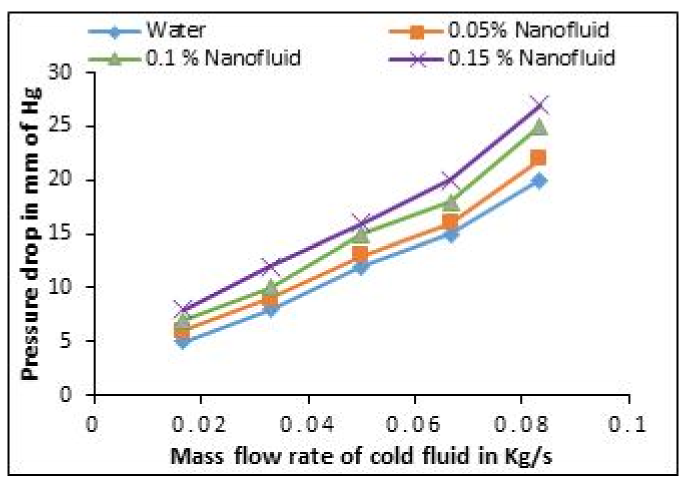

Figure 10. Pressure Drop Variation with Mass Flow Rate

4. Effect of Mass Flow Rate on Overall Heat Transfer Coefficient

The heat transfer in heat exchanger usually involves convection on each side of fluids and conduction through the wall. The variation of overall heat transfer coefficient with respect to mass flow rate of cold fluid for heat exchanger is shown in figure 11. It is observed that the overall heat transfer coefficient increases gradually with each concentration of nanofluid. The highest overall heat transfer coefficient is 840.25W/m2K for 0.15 % concentration of nanofluid at mc=0.0833 Kg/s which is 39% more than that of water The lowest overall heat transfer coefficient value obtained is 508.6W/m2K for water at mc=0.0167 Kg/s.

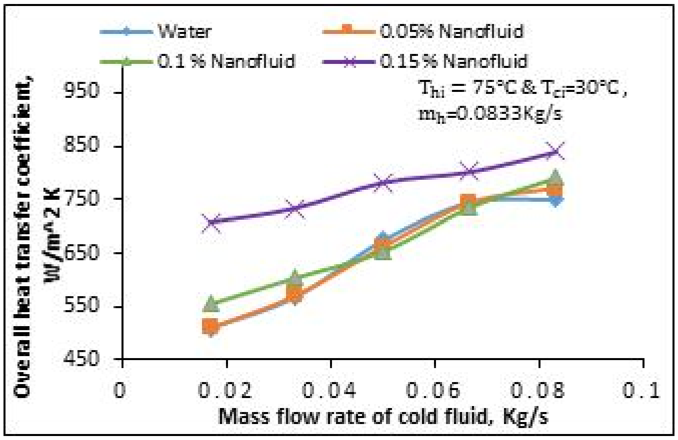

Figure 11. Overall Heat Transfer Coefficient Variation with Mass Flow Rate

a) Effect of Pitch on Overall Heat Transfer Coefficient

The variation in overall heat transfer coefficient with respect to various pitches of the helical coil is shown in fig.12. It is seen that there is gradual increase in Nusselt number with the increase in pitch of the coil. Highest value of Nusselt number is observed at pitch 9mm i.e. for tube III.

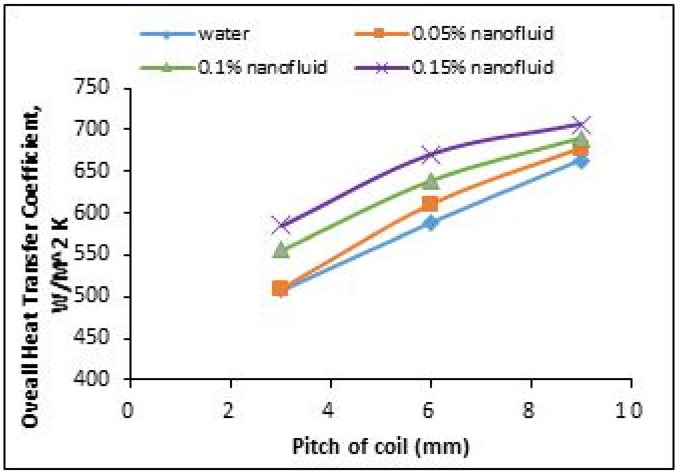

Figure 12.Effect of Pitch on Overall Heat Transfer Coefficient

5. Effect of Mass Flow Rate on Performance Index

Performance index of heat exchanger is the parameters which differentiate between the effect of heat transfer enhancement and pressure drop. Performance index more than one indicates that heat transfer enhancement is more dominant than pressure drop. If it is less than one, then pressure drop is more dominant than heat transfer for respective heat exchanger.

The variation in performance index of heat exchanger for different concentrations of nanofluids with varying mass flow rate for heat exchanger is shown in figure 13. It is seen that the performance index for 0.5% concentration of Al_2O_3 nanofluid is more than the rest of two concentrations. It decreases as the volume concentration of Al_2O_3 nanofluid increases. It increases as the mass flow rate of cold fluid increases.

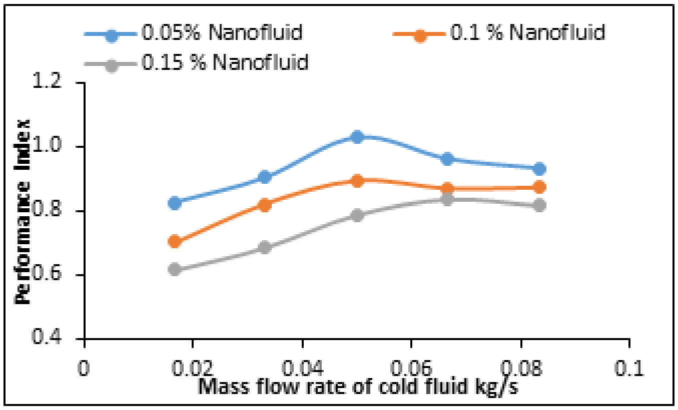

Figure 13. Effect of Mass Flow Rate on Performance Index

VII. CONCLUSION

Following are the conclusions made from the experimental investigation:

1. There is reduction in outlet temperature with the increase in mass flow rate of cold fluid for water and various concentration of Al_2O_3/water nanofluid.
2. The overall heat transfer coefficient increases gradually with increasing concentration of Al_2O_3/water nanofluid. The highest overall heat transfer coefficient observed in 0.15% volume concentration of Al_2O_3/water nanofluid and it is 39.45% more than water as a cold fluid. The overall heat transfer coefficient increases as the pitch of the helical coil increases for lower flow rates and for tube III (Pitch=9mm), it is 13.6% higher than tube II (Pitch=6mm) and 16.4% higher than tube I(Pitch=3mm).

3. There is increase in the Nusselt number with the increasing concentration of Al_2O_3 nanofluid. The highest value of Nusselt number obtained is 26.73 for 0.15% concentration of Al_2O_3 nanofluid for heat exchanger coil with pitch 9mm. Nusselt number value increases as the pitch of heat exchanger coil increases. Its value is found to be 10.4% lesser than theoretical one.
4. There is decrease in LMTD seen with the increase in concentration of Al_2O_3/water nanofluid i.e. LMTD value is maximum for water. LMTD values gradually decreases with the increase in the pitch of HCTHE coil, it is maximum for lowest pitch.
5. It has been observed that the values of PI for all the possible combinations are less than 1 which indicates that the pressure drop is more dominant than heat transfer enhancement.

VIII. ACKNOWLEDGMENT

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