Analysis of heat transfer characteristics in helically coiled heat exchanger using Al$_2$O$_3$ and CuO nanofluids

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Abstract. Heat exchangers play a vital role in engineering implementations across various domains of engineering. The advent of nanofluids have enabled and facilitated better modes of heat transfer in heat exchangers. An experimental run is conducted to note the heat transfer characteristics of a helical coil heat exchanger with Aluminium oxide-water, copper oxide-water based nanofluids at three different concentrations (0.1 %, 0.2 %, 0.3 %). It was observed that there was an increase in heat transfer during the usage of nanofluids when compared to the conventional water being used as a working fluid. The increased heat transfer resulted in an increased effectiveness of heat transfer of the heat exchanger when run with the Aluminium oxide nanofluid and copper oxide nanofluid than water. The heat transfer characteristics of copper oxide nanofluid were more effective and efficient when compared to Aluminium oxide nanofluid. The experimental results were simulated in ANSYS Fluent and the simulated results correlate with the experimental results with minimal deviation (<4%).

Keywords: Nanofluids; Heat transfer; Heat exchangers; Helical coil.

1. Introduction

Heat transfer phenomenon has diverse applications in various fields. Heat exchangers facilitate heat transfer to the fullest extent in order to perform the desired energy transfer operation to produce useful work. Helical coil heat exchangers have coiled tubes which act as an effective heat transfer set up for various applications including modern energy conversion systems, air conditioning systems, chemical industries, etc [1-2]. It is also established that helical coils offer more net effective heat transfer compared to linear tube heat exchangers. Evidences of higher heat transfer coefficient compared to straight tube heat exchanger can be attributed to the constantly varying flow direction [3-5]. The presences of centrifugal forces contribute effectively to the total heat transfer per unit length of the coiled section in comparison with a linear arrangement. Increased heat transfer area per unit volume is obtained with helical coil heat exchangers and heat exchangers that has coiled tube geometry. It results in improved coefficient of heat transfer of the internal surface of the tube [6].
1.1. Study on thermal conductivity of nanofluids

The first experimental evidence of thermal conductivity enhancement was reported by using Aluminium oxide nanoparticles in water. This experimental evidence proved as a trigger for curiosity as a greater number of researchers began publishing their experimental investigations with nanofluids and associated thermophysical properties. [7]. However, studies also show the evidence of the existence of differences in results as a consequence of the usage of different techniques of measurement [8]. Masuda’s team from Japan experimentally verified that 4.3% nanoparticle volume fraction of the metallic oxides (silica, alumina, etc..,) dispersed in water increased the thermal conductivity of nanofluids by 30%, although the friction factor almost doubled four times. Wang and team also reported thermal conductivity enhancements. They showed that thermal conductivity enhancement is inversely proportional to the nanoparticle size but nearly proportional to the volume fraction of the particles [9]. The usage of transient line method to calculate and find out the thermal conductivity of helical coil heat exchangers run by Aluminium oxide nanofluid proves the dependency of the transient line methods to effectively estimate and verify thermal conductivity of nanofluids [10].

1.2. Study on base fluids

There are several studies where researchers have proposed the usage of different nanofluids on helically coiled heat exchangers to study the heat transfer characteristics. The usage of non-newtonian fluids such as carboxymethyl cellulose [11-12] ,ethylene glycol, cotton oil ,canola oil [13] have been studied and experimented in helical coil heat exchangers to observe the heat transfer characteristics ,friction factor and the other parameters that influence the overall efficiency of the heat exchanger setup. Studies have also been conducted on frictional pressure drop and were studied on pseudo plastic polymer solutions in helical coils of varying curvatures [14]. Multi walled carbon nano tubes [15], graphene based [16] rGO–TiO$_2$ nanocomposite based nanofluids [17] were studied extensively to observe their heat transfer properties in helically coiled heat exchangers.

Studies on the usage of Aluminium, copper oxide and water based nanofluids for helical coil heat exchangers are reported over the duration of the past decade alongside with other metal oxides in the similar heat exchanger setup. However, there are no significant studies over an extreme high-end value for the mean effective diameters for coil. The authors are hence motivated to fabricate a setup with high mean effective diameter for the coil and to analyze the heat transfer characteristics of Aluminium oxide- water based and copper oxide-water based nanofluid in the experimental setup.

2. Experimental setup

![Figure 1. Block diagram of experimental setup](image)
The experimental section (figure 1) of helical coil is connected to a closed circuit which gives flow access for experimental setup and the required input devices and actuators. The shell and the coil are made up of copper. The circular pipe used to construct the shell part has 0.052m inner diameter (ID) and 0.054m outer diameter (OD) and coil section has a 0.0158m OD and 0.0148m ID (table 1). The helical coil is wound over the shell which forms the shell and tube heat exchanger. A temperature controller with a release valve is provided to constantly maintain the temperature setup of the hot fluid section. The hot fluid is allowed to flow through gravity. On the other side the cold water is pumped using a SS-1000F with the power of 15W. The digital display sensors are employed at critical and required places to show the inlet and the outlet temperatures of the hot and the cold fluids respectively.

Table 1. Dimensions of heat exchanger

| Body  | Material | Inner Diameter (m) | Outer Diameter (m) | Length (m) | Pitch (m) | Number of Turns |
|-------|----------|--------------------|--------------------|------------|-----------|----------------|
| Shell | Copper   | 0.052              | 0.054              | 0.5        | -         | -              |
| Coil  | Copper   | 0.0148             | 0.0158             | 2          | 0.028     | 11             |

2.1. Preparation of nanofluid for experimentation
Aluminium oxide and copper oxide nanoparticles with an average size of 50nm were procured from Sigma-Aldrich Chemicals Private Limited and is used for experimental analysis in the experimental work. X-ray diffraction (XRD) (X Ray- 30 kV 20mA Speed- 8.0000 deg./min Step Width - 0.0200 deg.Scan Axis - 2 Theta/ ThetaScan Range- 10.0000 - 80.0000 deg) and Transmission electron microscope (TEM) results confirm the presence of copper and Aluminium oxide respectively and the nanosize (figure 2 and figure 3).

Figure 2. TEM and XRD results of Copper Oxide nanoparticle

A stable nanofluid having uniform particle distribution is required for the experimental analysis. The following formula was used to calculate and find out the volume fraction needed for the experimental analysis. The nanoparticles were weighed in electronic balance.

\[
\Phi = \left( \frac{m_n}{V_n} \right) \left/ \left( \frac{m_n}{V_n} + \frac{m_f}{V_f} \right) \right.
\]

The same nanofluid(s) (before sedimentation started to occur (>=3 hours)) are used for measuring the properties of the nanofluid. The experimental analysis uses pure water as the base/to be dispersed.
upon fluid for preparation of Aluminium oxide and copper oxide nanofluid. The nanoparticles are weighed and mixed in the base fluid and stirred manually and mechanically using an ANALAB sonicator (30KHz, 1000Watt, 60°Celsius) apparatus for the required volumetric concentrations (0.1%, 0.2%, 0.3%)

Figure 3. TEM and XRD results of Aluminium Oxide nanoparticle

In the present study, no surfactants or dispersions were added and were subjected into the sonication bath for 2 hours under suitable temperature range. It was observed that no steady particle settlement was happening even after 2 hours after the sonication process (figure 4). The time taken to measure the thermal conductivity and run the experiments in the heat exchanger setup is less than the time required for the first sedimentation to take place.

Figure 4. Visible signs of the start of sedimentation process of the nanofluids
2.2. Estimation of thermophysical properties of nanofluids

2.2.1. Estimation of thermal conductivity of nanofluid(s). Estimation of thermal conductivity ($k_{nf}$) of the experimental nanofluid is measured using the digital machine called the KD2-PRO. It uses the transient line heat source method to measure and estimate thermal conductivity. It is calibrated according to the factory specifications with tolerance limits of 5-10% of thermal conductivity measurements. It complies to the ASTM D5334-08 and IEE 442-1981 standards respectively and corrects for linear temperature drifts automatically.

The measurements that are taken are verified by using the relations for thermal conductivity for nanofluids and which is proposed in literature [18] (figure 5 and figure 6).

$$k_{nf} = \left( k_p + 2k_f + 2\Phi(k_p - k_f)\left(k_p + 2k_f - \Phi(k_p - k_f)\right)^{-1}\right)$$

Figure 5. Thermal conductivity of copper oxide - water based nanofluid

The measurements that are taken are verified by using the relations for thermal conductivity for nanofluids and which is proposed in literature [18] (figure 5 and figure 6).

$$k_{nf} = \left( k_p + 2k_f + 2\Phi(k_p - k_f)\left(k_p + 2k_f - \Phi(k_p - k_f)\right)^{-1}\right)$$

Figure 6. Thermal conductivity of Aluminium oxide- water based nanofluid
2.2.2. Estimation of density and specific heat of nanofluid(s). Estimation of density ($\rho_{nf}$) and specific heat ($C_{p_{nf}}$) of the nanofluid(s) are calculated by using the models proposed by Pak and Cho’s [19] and Xuan Roetzel's equations [20] respectively.

\[
\rho_{nf} = (1 - \Phi)\rho_f + \Phi\rho_p \tag{3}
\]

\[
C_{p_{nf}} = \left( (1 - \Phi)\rho_f C_{pf} + \Phi\rho_p C_{pp} \right) (\rho_{nf})^{-1} \tag{4}
\]

2.3. Input configuration and data processing

The experimental conditions for a counterflow nanofluid driven heat exchanger are specified below (table 2). The same values are taken for the simulation environment where the details of the simulation are specified in the next section. The fouling factor was not taken into account and the proposed mass flow rates are calculated for a laminar flow in transition. The overall heat transfer coefficient ($U_o$) is calculated by from the equations proposed by P.C Mukesh Kumar and team [21]

\[
Q = U_o A_0 \Delta T \tag{5}
\]

Where $Q$ = total rate of heat transfer, $U_o$ = overall heat transfer coefficient, $A_0$ = total contact surface area and $\Delta T$ = average temperature difference between the bulk fluid in coiled tube and the fluid in shell side. The Nusselt number ($Nu$) is calculated with the help of calculation of inner heat transfer coefficient ($h$) as follows

\[
h = q(AT_{LMTD})^{-1} \tag{6}
\]

Where, $q$ = inner rate of heat transfer, $A$ = cross sectional area of shell, $T_{LMTD}$ = Logarithmic mean temperature. The Nusselt number ($Nu$) can then be calculated as follows

\[
Nu = hdk^{-1} \tag{7}
\]

Where $d$ = diameter of circular cross section of the shell and $k$ = thermal conductivity of the fluid.

**Table 2. Input/inlet configurations**

| Parameters                        | Value-1                                      | Value-2                                      |
|-----------------------------------|----------------------------------------------|----------------------------------------------|
| **1) Coil tube section fluid**    | Al$_2$O$_3$ - Water based nanofluid          | Copper Oxide - Water based nanofluid          |
| Inlet temperature                 | 312K                                         | 312K                                         |
| % Fraction                        | 0.1, 0.2, 0.3                               | 0.1, 0.2, 0.3                               |
| Nanofluid density at 0.1,0.2,0.3% | 1263,1550.3,1837.7 kg/m$^3$                 | 1528.7, 2060.2,2590.9 kg/m$^3$               |
| Thermal conductivity of NanoFluid at 0.1,0.2,0.3% | 0.619,0.621,0.624 W/mK                  | 0.628 ,0.645 ,0.675 W/mK                       |
| Specific heat of NanoFluid at 0.1,0.2,0.3% | 3086, 2611, 2137 J/KgK                       | 4160 ,4137 ,4078 J/KgK                       |
| Mass flow rate                    | 0.050-0.17 kg/s                             | 0.050-0.17 kg/s                             |
2) Shell section Fluid | Water | Water
---|---|---
Inlet temperature | 333 K | 333 K
Density of water | 997 kg/m³ | 997 kg/m³
Thermal conductivity of water | 0.615 W/mK | 0.615 W/mK
Specific heat of water | 4181 J/kgK | 4181 J/kgK
Mass flow rate | 0.050-0.17 kg/s | 0.050-0.17 kg/s

2.4. Simulation conditions

The 3D Model was modelled in SOLIDWORKS 2018 and was converted into a STEP File to be imported into the simulation software ANSYS FLUENT 15.0. The governing equations that are needed for the analysis are solved using ANSYS FLUENT. The convergence criterion was kept at 1e-4 for all the residuals involved at default settings. The SIMPLE algorithm was used to solve via the pressure correction approach and the relaxation factor was set to default. Sufficient velocity, mass flow rate conditions were given at inlet with pressure alongside outflow conditions were tried in the outlet boundary condition.

An experimental investigation procedure proposed by Kumar and team [21] was followed and the important factors that included are summarized as follows 1) treatment of nanofluid as a single phase incompressible medium throughout the computational continuum, 2) spherical morphology for nanoparticles and are uniformly dispersed 3) the flow is hydro dynamically developed, 4) coiled tube (with smooth inner surface) handles nanofluids and shell handles the hot water, 5) thermophysical properties of the nanofluids are assumed constant through the computational domain, 6) temperature of the wall tube is constant throughout the entire process, 7) negligible heat conduction through the tube material. 8) the nanoparticles and the fluid phase have zero relative velocities between them and are in thermal equilibrium with each other. The continuity, momentum, and energy equations are taken as partial differential equations and are solved by using thermo physical parameters of nanofluids along with boundary conditions. No-slip boundary condition was employed at the walls.

Figure 7. Meshing schematics of the heat exchanger before sizing

The numerical solution is carried out with steady state implicit pressure based FLUENT code. The partial differential equations are solved for steady state flow and the pressure velocity coupling is carried out using the SIMPLE algorithm. MESH SIZING is used for meshing the geometry. The
independence test and mesh optimization were carried out to effectively carry out the simulation with minimum variation in the various computational trials (<5%). The standard k-epsilon model was used to model the turbulence and the main associated differential equations as written by Kumar and his team in tensor form is stated below [21] and the details of the meshing are mentioned in (table 3) and the diagram can be visualized from (figure 7).

\[
\frac{\partial}{\partial x_i}(\rho U_i) = 0
\]  

(8)

\[
\frac{\partial}{\partial x_i}(\rho U_i \tau) = \frac{\partial}{\partial x_i} \left( \frac{\mu \partial \tau}{\rho r_{\partial x_j}} - \rho \bar{u}_i \right)
\]  

(9)

\[
\frac{\partial}{\partial x_i}(\rho U_i U_j) = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} \left( \frac{\partial U_i}{\partial x_i} + \frac{\partial U_j}{\partial x_j} \right) - \rho \bar{u}_i \bar{u}_j
\]  

(10)

The standard model along with default wall functions were chosen while deploying the model. The values for turbulence were unchanged and the nanofluid flow was modelled using a single-phase model as multi-phase models gave over fitting estimations.

**Table 3.** Meshing details

| S. No | Detail/ Parameter               | Value    |
|-------|---------------------------------|----------|
| 1     | Total Nodes                     | 115636   |
| 2     | Total Elements                  | 101089   |
| 3     | Minimum Orthogonal quality      | 0.871797 |
| 4     | Maximum Aspect Ratio            | 3.739    |
| 5     | Element Type                    | Quad     |

**3. Results and Discussion**

![Figure 8. Heat exchanger setup for water-water based simulation](image)

It can be observed from the simulation (figure 8) that heat transfer takes place as the contour colour changes slightly from one end to the other. Water was employed as fluid in both the shell and the coil respectively. The thermophysical properties for the nanofluids were edited in the default database and were stored separately. The deployment of nanofluids in the coil section of the heat exchanger is
shown in (figure 9). It shows significant heat transfer enhancement compared to (figure 8). The theory is validated along with the computational fluid dynamics (CFD) simulation results that nanofluids enhance and facilitate heat transfer.

Figure 9. Nanofluid driven coil showing appreciable temperature gradient

3.1. Overall heat transfer coefficient
The overall heat transfer coefficient was found out for water, Aluminium oxide and copper oxide nanofluids for different concentrations using the earlier mentioned formula from equation (5).

Figure 10. Overall heat transfer coefficient

It can be seen from (figure 9) that the net overall heat transfer coefficient increases as volumetric concentration increases. There is an average 6% increase in the overall heat transfer coefficient with the nanofluids compared with the heat exchanger setup that has water in the coil section for 0.1%
concentration. The CFD results shows variations within 5% deviation in both the type of nanofluids. The deviation between the two types of results can be attributed to the environmental conditions in physical experimental setup, meshing and convergence condition in the simulation setup.

3.2. Nusselt number
Nusselt number can be defined as the ratio of net convective heat transfer to that of conductive heat transfer. It can be calculated by the formula defined in the earlier section from equation (6).

It physically signifies how high convective heat transfer is when two distinct modes of heat transfer namely conduction and convection occur. The fluids are not in contact with each other and hence convective heat transfer occurs and as shown in the previous segment, the overall heat transfer coefficient for the nanofluids is higher than that of the water under given temperature and Reynolds number. The same trend of phenomenon is carried over to the Nusselt number as the Nusselt number for water is 5.9 which is 15% lower than that of the nanofluids with 0.1% concentration (figure 11). The deviation between the two type of results can be attributed to the environmental conditions in physical experimental setup, meshing and convergence condition in the simulation setup. The increase in Nusselt number with the increase in concentration is reported in literature that included study of nanofluids in coiled tube [21]. It can also be seen that since, copper oxide nanofluid has a significantly higher overall heat transfer convective heat transfer coefficient, the value of the Nusselt number for copper oxide nanofluid is higher than that of the Aluminium oxide nanofluid with respect to the due concentrations.

3.3. Temperature variation across the length of the heat exchanger
The net temperature difference is calculated by taking the end readings in the experimental setup (that is the inlet and the outlet configurations). The average values of both the experimental and simulation were taken into consideration while plotting the temperature distribution across the length of the heat exchanger.

The net temperature difference across the length of the heat exchanger for a water-based coil setup lies in the closed region of (1-2.5 Kelvin). There is no significant deviation observed in the CFD simulation and the experimental observation. It may be attributed to the fact that only an average and a discrete value is taken as the parameter to be measured. The temperature variation for 0.1% nanofluid is slightly higher than that of the water by 3-4% (figure 12). It thus effectively adds to the overall heat transfer with the same given inlet configurations. Furthermore, the temperature variation for 0.2% and
0.3% Aluminium nanofluid concentration significantly show a raise of 2% increase in temperature variation from the previous volumetric concentration.

**Figure 12.** Temperature variation for 0.1% concentration

This result correlates with the previous results that heat transfer enhancement increases with increase in volumetric concentration. The temperature variation for the copper-oxide based nanofluid almost shows a linear relationship to its Aluminium counterpart with respect to the increasing volumetric concentrations. The intuitive and natural guess would be to postulate an increased temperature variation in the copper oxide based nanofluid for 0.1% concentration compared with the water-water based setup. The intuition is firmly backed by the result as a significant 3.5-4.5% increase in temperature variation is observed for the 0.1% copper oxide based nanofluid.

**Figure 13.** Temperature variation for 0.2% concentration
Furthermore, the temperature variation for 0.2% (figure 13) and 0.3% (figure 14) Aluminium nanofluid concentration significantly show a raise of 2% increase in temperature variation from the previous volumetric concentration. This result correlates with the previous results that heat transfer enhancement increases with increase in volumetric concentration. It is also noted that there is no significant deviation amongst the experimental and the CFD results.

![Figure 14](image)

**Figure 14.** Temperature variation for 0.3% concentration

### 3.4. Effectiveness of the heat exchanger

The effectiveness of heat exchanger quantifies how efficient a heat exchanger in exchanging maximum heat with minimum loss to the surroundings. The effectiveness of the heat exchanger (\( \varepsilon \)) is calculated as follows

\[
\varepsilon = \left( \frac{m_h c_{ph}}{c_{min}} \right)^{-1} (T_1 - T_2)
\]  

(11)

where \( m_h \) is the mass of hot fluid, \( c_{ph} \) is the specific heat of the hot fluid, \( T_1 \) corresponds to inlet temperature of hot fluid, \( T_2 \) corresponds to the outlet temperature of the hot fluid and \( t_1 \) corresponds to inlet temperature of the cold fluid. \( c_{min} \) is defined mathematically as the minimum value of the specific heats of the hot and the cold fluids respectively. The experimental values are taken into consideration in order to plot the results of the effectiveness of the heat exchanger for varying concentrations of the nanofluids at constant mass flow rate.

![Figure 15](image)

**Figure 15.** Effectiveness of heat exchanger using different nanofluids at different concentrations
It can be observed from (figure 15) that nanofluids having higher concentration render the heat exchangers more effective than the nanofluids with lower concentration. One key contributing reason for the same might be the increased thermal conductivities of the nanoparticles with increase in volumetric concentration. The effectiveness of the water - water based system is around 0.07 and there is a significant increase in the effectiveness of the heat exchanger for Aluminium oxide based nanofluids and copper oxide based nanofluids. Copper oxide based nanofluids are more effective than Aluminium oxide based nanofluids as the respective volumetric concentration increases discretely. It can be attributed to increased thermal conductivity of copper oxide based nanofluid and higher specific heat values of copper oxide based nanofluids at the respective concentrations of the nanofluids.

4. Conclusion
In this research paper, an experimental setup was proposed to study and visualize the heat transfer phenomenon in a helically coiled heat exchanger. The Al$_2$O$_3$ and CuO nanofluids (0.1, 0.2, 0.3 % concentration) were used as working fluids in the coil and water was taken as the default working fluid in the shell. The heat transfer enhancement was compared with water- water based experimental setup. The experimental results were compared with the results simulated and it was studied that a significant increase in the overall heat transfer rate was observed in the nanofluid-water based setup than the water-water based setup. From the results, conventional heat transfer fluid can be replaced by Al$_2$O$_3$ and CuO nanofluids at low concentrations. It is also seen that Copper oxide based nanofluid offers better heat transfer characteristics than Aluminium oxide based nanofluid at the same given conditions. The experimental results were simulated and correlated with existing literature to validate the values and the heat transfer characteristic relationship shown by the nanofluids. Further scope lies in the research which focuses on the effect of sedimentation and settlement of nanofluids in order to overcome the same to use nanofluids effectively as an effective heat transfer medium for long durations of time.

Nomenclature:

\( \Phi \) : Volumetric concentration (%)
\( k_{nf} \) : Nanofluid thermal conductivity (W/mK)
\( k_p \) : Nanoparticle thermal conductivity (W/mk)
\( k_f \) : Fluid thermal conductivity (water) (W/mK)
\( \rho_{nf} \) : Nanofluid density (kg/m$^3$)
\( \rho_p \) : Density – nanoparticle (kg/m$^3$)
\( \rho_f \) : Density – fluid (kg/m$^3$)
\( C_{pnf} \) : Specific heat – nanofluid (J/kgK)
\( C_{pp} \) : Specific heat – nanoparticle (J/kgK)
\( m_n \) : Mass of Nanoparticle (kg)
\( m_f \) : Mass of Fluid (kg)
\( U \) : Fluid velocity vector
\( \mu \) : Dynamic viscosity (kg/m$^3$s)
\( \tau \) : Viscous stress tension

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