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Structural and CFD Analysis of Concentric Tube Heat Exchanger Using CuO Nanofluid

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Abstract

Heat dissipation is the prerequisite in most of the industries like steel manufacturing industry, food processing industry,etc which involves the use of heat exchangers to thermally process materials, maintain ideal temperatures and can be used to heat or cool a variety of goods. The heat dissipation rate can be increased either by changing the design of the heat exchangers or by changing the medium / composition of the heat transfer fluid (coolant).The present work focusses on performing structural analysis on inner tube of heat exchanger by using different materials(structural steel,copper and aluminium).Results from structural analysis will be used to perform comparative analysis between different materials which concludes copper as best suited material for inner tube of heat exchanger having thermal conductivity of 385W/m-K and deformation of 8.2e-07.The performance of concentric tube heat exchanger in parallel and counter flow arrangement is experimentally investigated and optimized by utilizing heat transfer fluids like CuO/Water Nanofluids in place of conventional heat transfer fluids prepared in 0.2% ,0.4%,0.5%,0.8% and 1% volumetric concentrations. CFD simulations were used to verify the experimental results and heat exchanger's temperature distributions. Also the overall heat transfer coefficient increases with increase in particle volume concentration of nanofluid up to 0.8% and then decreases. The counter flow arrangement of heat exchanger provides optimum performance of heat exchanger with better heat transfer and effectiveness of 49.03% for 0.8% concentration of CuO-water nanofluid than parallel flow arrangement.

Keywords
Concentric tube Heat exchanger, CuO Nanofluid, Heat Transfer Coefficient, Counter flow.

1.Introduction
Heat transmission from one fluid to another is the main purpose of a heat exchanger. The liquids may be in direct contact or separated from one another by a solid wall to prevent mixing. Concentric tube heat exchangers are viable option for the present work as they are inexpensive to develop and maintain with straight forward construction having two tubes, one of which conveys hot fluid and the other, cold fluid. Between them, heat exchanges. The cold fluid often acts as a coolant or heat transfer fluid to lower the temperature of the hot fluid. The most common heat transfer fluid used are water. The heat exchanger can be arranged to operate in Parallel flow and counter flow direction depending whether hot and cold fluid flows in same direction or in opposite directions.

With advancement in Nanotechnology, nanoparticles(1-100nm) are developed which are used in preparation of nanofluids. Nanofluids are prepared by combining nanoparticles with base fluids in a certain ratio. These fluids have excellent thermal conductivity and outstanding heat transfer properties when compared to conventional heat transfer fluids. Copper Oxide-Water nanofluid were chosen for our study due better heat transfer properties.

In order to improve heat exchanger performance, a number of techniques are examined, including new structure configurations, designs or their modification, modifying operational parameters or opting for better working fluid types. From all the options available, the most viable option is substituting traditional fluids/coolants used in heat exchangers with Nanofluids that helps improve the efficiency and heat transfer performance of heat exchanger. The aim of the project is to select suitable material for heat exchanger using structural analysis and then optimizing the performance of heat exchanger by performing CFD analysis under parallel and counter flow conditions using CuO Nanofluids.

1.1. Objectives

The following are research objectives:

- To carry out structural analysis of heat exchanger using different materials with good conductivity and perform comparative analysis for the same to determine best material for inner tube of heat exchanger.
- To carry out experimentation for parallel flow and counter flow heat exchanger using conventional fluid-water and copper oxide nanofluids of different concentrations.
- To carry out simulations for the heat exchanger performance using conventional fluid as water and CuO nanofluids of different concentrations.
- To validate the experimental and simulation results obtained for both parallel as well as counter flow arrangement.

2.Literature Review

Stephen Pierre Louis et al. (2022) conducted a detail investigational study on the influence of various thermophysical properties (size, shape, density, viscosity, etc) of nanofluids which is prepared by mixing nanoparticle of size 1-100 nm in a base fluid on the heat exchanger performance. The research study concluded that utilizing smallest size of nanoparticle improves the thermal conductivity as well as dynamic viscosity of nanofluid .However, spherical shaped nanoparticles are preferred for decreasing pressure drop in heat exchanger over cylindrical and platelet shaped ones.Syed Sameer et al. (2020) experimented with shell and tube heat exchanger having 25% baffle cut to determine it's overall heat transfer coefficient and effectiveness. They used CuO-DW nanofluid for experimentation prepared in 05%,0.1% and 2.0% volumetric concentrations with varying range of flowrates They conducted the experiment at different flowrates ranging from 0.2 lpm to 1 lpm for different concentrations of CuO-DW nanofluid ranging from 0.5% to 2% volumetric concentrations. it was found that maximum overall heat transfer coefficient and effectiveness of STHE occurs in counter flow set up of heat exchanger at 0.6 lpm mass flow rate with CuO-DW and the value is higher than that of water for the same flowrate.

Kunal Koushal Dew et al. (2018) conducted a simulation study on double pipe heat exchanger by using different nanofluids(CuO-Water,Al_2O_3 -Water and Fe_2O_3 -Water) of different volume concentrations(0.25% and 0.5 %). They concluded that Copper oxide nanofluid has better heat transfer characteristics than other nanofluids and has shown to have 8% and 39.90% better heat transfer in comparison to Al_2O_3 and Fe_2O_3 nanofluids. Bayram Sahin et al. (2015) experimented numerically the heat transfer and pressure drop characteristics of CuO-water nanofluid prepared in 0.5%,1%,2% and 4%volume concentration of CuO nanoparticles in water under steady state and turbulent flow conditions.They discovered that with the presence of CuO nanoparticles in base fluid more than 0.5% concentration resulted in decrease in heat transfer performance. Highest and lowest heat transfer was achieved at Re = 16 with volume concentration 0.005 and at Re=20 with volume concentration of 0.02.Pankaj D. Lad et al. (2015) conducted structural analysis of concentric pipe heat exchanger using material SA 516 Grade 70 with major focus on optimizing the tube sheets ,inner pipe and nozzles as per the ASME Code. The simulation results of heat exchanger using hot and cold fluid were verified experimentally by them as per ASME Code. They concluded that the induced von-mises stress in simulation is 281.71 MPa which is less than 414 MPa (ASME Code) and deformation is 32.011mm in simulation against 29.3 mm (experimental result).

Some conclusions drawn from literature are that copper and steel are most preferred materials for heat exchanger inner tube fabrication owing to their thermal conductivities. Most of the research work has been focused on improvising efficiency and heat transfer coefficient of heat exchanger system under variable flow rate and temperatures in parallel as well as counter flow arrangements , restricted to very small concentrations of nanofluids (i.e. less than 0.2% volume conc.) .CuO-water and SiC-Water is most convenient coolant choice due to better heat transfer performance followed by Al_2O_3-Water and Fe_2O_3-Water.

3. Methods

Initially structural analysis was performed on innertube by choosing different materials which concludes copper as an effective material suitable to enhance heat transfer. Concentric tube heat exchanger with inner tube made with copper material and outer shell made with galvanized iron is chosen for experimentation. The test apparatus consists of a set of concentric tube type pipes in which the hot fluid is hot water , which is obtained from an electric geyser and it flows through the inner copper tube while the cold fluid is plain water as well as various concentrations of nanofluids, which flows through the annulus when the equipment is used for both parallel as well as counter flow arrangement. The inner tube is made of copper material where as the annulus (outer tube) is fabricated by using Galvanized iron.
The schematic diagram depicting flow direction and experimental setup of heat exchanger is shown in Figure 1 and 2.

Figure 1. Experimental setup of Concentric tube Heat Exchanger

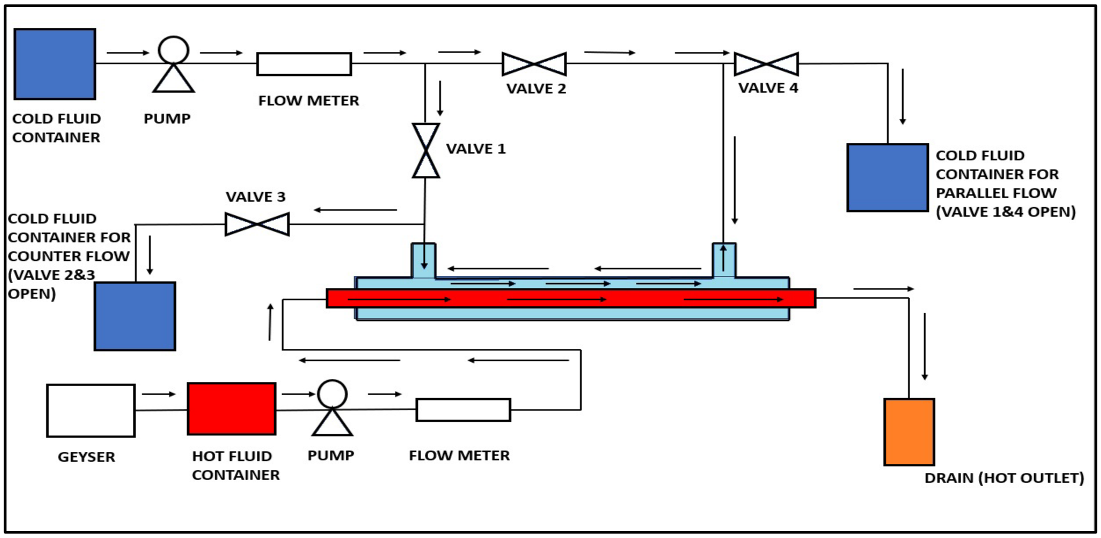

Figure 2. Schematic of Concentric Tube Heat Exchanger Setup

The setup has provision of four valves attached to the heat exchanger that helps in controlling the flow direction of cold fluid in the annulus.When valve 1 & valve 4 is open and valve 2 and valve 3 is closed as depicted in fig 2 , the set up operates as **Parallel flow Heat exchanger**. When valve 2 and valve 3 is open and valve 1 and valve 4 is closed,the set up operates as **Counter flow Heat exchanger.**The specifications of experimental setup are mentioned in Table 1.

Table 1. Specifications Of The Experimental Setup

Model	Concentric heat exchanger
Volume of coolant in container	5 Litres
Geyser Heat capacity	3000 watts
Self priming Pump	Operating pressure less than 0.2 kg/cm^2
Hot fluid mass flow rate	1/60 (kg/s)
Cold fluid mass flow rate	1.5/60 (kg/s)
Hot fluid volume flow rate	1 lpm
Cold fluid volume flow rate	1.5 lpm
Thermocouple sensors	2 nos at hot water line 2 nos at cold water line

4.Data Collection

The materials chosen for structural analysis are structural steel, copper and aluminium whose properties are given as input parameters during structural analysis .In Table 2 properties of different material is mentioned.

Table 2. Specifications of inner tube materials used in Structural Analysis of H.E.

Materials used	***Poisson's ratio, υ***	***Youngs Modulus, E in GPa***	***Thermal Conductivity,K in W/m K***	***Internal pressure,p_i in N/m^2***	***Thickness of inner tube,t in m***
Steel	0.30	200	50	19613.3	0.0032
Copper	0.34	120	385		
Aluminium	0.33	70	205		

According to Lame's equation , stress ,strain and deformation induced in inner cylindrical tube is determined by using the given equations:-

Von-mises stress , $\sigma_{vm} = \sqrt{\sigma_t^2 + \sigma_r^2 - \sigma_t\sigma_r}$

Tangential stress , $\sigma_t = \frac{p.d}{2t}$

Radial stress , $\sigma_r = \frac{p.d}{4t}$

Strain , $\varepsilon = \frac{\sigma_{vm}}{E}$

Deformation ,**Δd = ε.d**

where, σ is stress in Mpa, t is thickness(mm) , E is Youngs modulus , Δd is diametrical deformation of tube(mm) ,d is inner diameter of concentric tube(mm) and ε is strain induced in tube (Table 3 and Table 4).

Table 3. Properties of Inner and Annular Tube of Concentric Heat Exchanger

Properties	**Inner Tube**	**Annular Tube**
Material	Copper	Galvanized Iron
Inner diameter	12.7 mm	34.3 mm
Outer diameter	15.9 mm	42.4 mm
Length of tube	1640 mm	1760 mm
Density(ρ)	8960 Kg/m^3	7870 kg/m^3
Thermal Conductivity(K)	385 W/m-K	204.2 W/m-K
Specific Heat Capacity(Cp)	400 J/Kg-K	896 J/kg-K

Table 4. Properties Of CuO Nanoparticles

Average particle size	50nm
Purity	99%
Colour	Brownish black
Morphology	Spherical
Density	6320 kg/m^3
Melting point	1336 ^{0}C

The hot water input temperature is kept constant at 60°C and the cold fluid inlet temperature is maintained at 29°C through out experimentation and simulation.In Table 3 ,properties of inner and annular tube are mentioned. In Table 4 properties of copper oxide nanoparticles used in nanofluid preparation are mentioned.

The various formulae that were used to determine the density, specific heat ,thermal conductivity, dynamic viscosity and volume concentration of nanofluid are given by the following correlations

Density of Nanofluid: $\rho_{nf} = [\phi \ \rho_{np}] + [(1-\phi)\ \rho_{bf}]$

Specific heat of Nanofluid: $(C_P)_{nf} = \frac{[\phi\,(\rho_{np}\,(C_P)_{np}) + (1-\phi)\,(\rho_{bf}\,(C_P)_{bf})]}{\rho_{nf}}$

Dynamic viscosity of Nanofluid: $\mu_{nf} = [1+(2.5\ \phi)]\ \mu_{bf}$

Thermal conductivity of Nanofluid: $K_{nf} = \frac{[K_{np} + (2\ K_{bf}) + \{2\ (K_{np} - K_{bf})\ \phi\}]}{[K_{np} + \{2\ K_{bf}\} - \{(K_{np} - K_{bf})\ \phi\}]}$

Prandtl number of Nanofluid: $P_{r,nf} = \frac{\mu_{nf}\ (C_P)_{nf}}{K_{nf}}$

Amount of nanoparticles required for preparation of Nano fluids is calculated by using Volume Concentration

$$\textbf{\% vol.conc. } (\Phi) = \frac{W_{np}/\rho_{np}}{\frac{W_{np}}{\rho_{np}}+\frac{W_{bf}}{\rho_{bf}}} = \frac{W_{CuO}/6320}{\frac{W_{CuO}}{6320}+\frac{100}{1000}}$$

Where ρ is density (kg/m^3),W is weight (grams), ϕ is volume concentration of nanofluid (%), C_P is specific heat (J/kg-K) ,µ is dynamic viscosity(kg/m-s), K stands for thermal conductivity(W/m-K) and P_r stands for Prandtl number. The subscripts nf stands for nanofluids, np stands for nanoparticle, CuO is Copper oxide and bf stands for base fluid. Further data related to concentric tube heat exchanger is acquired using the following mathematical formulae:

Heat transfer rate through Hot fluid: $Q_H = m_h C_{ph}[T_{hi}-T_{ho}]$

Heat transfer rate through Cold fluid: $Q_C = m_c C_{pc}[T_{co}-T_{ci}]$

Average Heat transfer rate: $Q_a = \frac{Q_H+Q_C}{2}$

Logarithmic Mean Temp. Difference (LMTD):

For parallel flow condition: $$\text{LMTD } (\Delta T_m) = \frac{[T_{hi}-T_{ci}]-[T_{ho}-T_{co}]}{\ln \frac{T_{hi}-T_{ci}}{T_{ho}-T_{co}}}$$

For counter flow condition: $$\text{LMTD } (\Delta T_m) = \frac{[T_{hi}-T_{co}]-[T_{ho}-T_{ci}]}{\ln \frac{T_{hi}-T_{co}}{T_{ho}-T_{ci}}}$$

The Overall Heat Transfer Coefficient: $U = \frac{Q_a}{A\Delta T_m}$

Effectiveness of heat exchanger: $$\eta = \frac{\text{Actual Heat Transfer Rate}}{\text{Maximum Possible Heat Transfer Rate}} = \frac{m_c C_{pc}(T_{co}-T_{ci})}{C_{min}(T_{hi}-T_{ci})}$$

where $C_{min}(C_h) = m_h C_{ph}$ or $C_{min}(C_c) = m_c C_{pc}$ (which ever is smaller)

Here Q is heat transfer rate(Watts), ΔT_m is Logarithmic Mean Temp. Difference (LMTD), T is temperature (K) ,U is overall heat transfer coefficient (W/m^2 K) and η is effectiveness of heat exchanger(%).The subscripts h is for hot,c is for cold ,hi is for hot inlet ,ci is for cold inlet ,ho is for hot outlet, co is for cold outlet, H is hot fluid and Cis cold fluid.

5.Results and Discussion

5.1 Numerical Results

In Table 5 Von-misses stress results observed during simulation and theoretical results calculated are depicted.

Table 5. ANSYS and Theoretical results for Stress Analysis of H.E. tube

Materials	Von-mises stress , σ_{vm} in MPa		Variation in ANSYS and theoretical value
	Theoretical value	*ANSYS value*	
Steel	0.092	0.09097	1.11%
Copper	0.092	0.09091	1.18%
Aluminium	0.092	0.09098	1.10%

Table 6. ANSYS and Theoretical results for strain and deformation in H.E. inner tube

Materials	**Theoretical value**		**ANSYS value**		**Variation in Strain values**	**Variation in Δd values**
	Strain, ε	**Diametric deformation, Δd (mm)**	**Strain, ε**	**Diametric deformation, Δd (mm)**		
Steel	5e-07	6.35e-07	4.8e-07	6.32e-07	2.2%	0.4%
Copper	8.2e-07	1.058e-06	7.9e-07	1.038e-06	3.2%	1.8%
Aluminium	1.4e-06	1.8142e-06	1.3e-06	1.7e-06	2.17%	1.2%

Table 7. Thermophysical properties of Heat Transfer fluids

Coolant with Nano Particle Volume concentration	Specific heat (J/kg-K)	Density (kg/m^3)	Dynamic viscosity (kg/m-s)	Thermal Conductivity (W/m-K)	Prandtl number
Water	4184	1000	0.000815	0.6145	5.54916
CuO-water (0.2%)	1952.4	2064	0.0012225	1.700	1.404005
CuO-water (0.4%)	1238.98	3128	0.00163	2.8268	0.714425
CuO-water (0.5%)	1037.8	3660	0.00183375	3.6935	0.515247
CuO-water (0.8%)	678.66	5256	0.002445	10.343	0.160429
CuO-water (1%)	540	6320	0.0028525	53.74	0.028663

In Table 6 strain and deformation results observed during simulation and theoretical results calculated are depicted. The variation in ANSYS and theoretical values for von-misses stress ,strain and deformations is less than 3% which is acceptable for the project.

In Table 7 , thermophysical properties of CuO Nanofluid prepared in varying volume concentrations of 0.2 ,0.4 ,0.5 ,0.8 & 1% are calculated .As depicted in Table7, the density and thermal conductivity of fluid increases with increase in volume concentration of nanofluid ,the specific heat , dynamic viscosity & Prandtl number of the fluid decreases. The specific heat is highest at 0.8% CuO-water nanofluid so good performance of heat exchanger could be achieved at 0.8% volumetric cocncentration..

The Overall Heat Transfer Coefficient (U) of concentric tube heat exchanger operated in parallel and counter flow setup was calculated using standard equations and also obtained by performing CFD analysis using ANSYS which are depicted in Table 8 and Table 9.

Table 8. Comparison of U value for parallel flow setup

Heat transfer medium	Overall Heat transfer coefficient (U) in W/m^{2}K (theoretical value)	Overall Heat transfer coefficient (U) in W/m^{2}K (CFD value)	Variation in theoretical and CFD value
Plain water -water	377.1	385	2.05%
CuO-water nanofluid (0.2%)	588.2	601.6	2%
CuO-water nanofluid (0.4%)	596	617	3.4%
CuO-water nanofluid (0.5%)	611.04	629.88	2.97%
CuO-water nanofluid (0.8%)	646	654.337	1.25%
CuO-water nanofluid (1%)	589.6	595.7	1.2%

Table 9. Comparison of U value for Counter flow setup

Heat transfer medium	Overall Heat transfer coefficient (U) in W/m^{2}K (Theoretical value)	Overall Heat transfer coefficient (U) in W/m^{2}K (CFD value)	Variation in theoretical and CFD value
Plain water -water	440.9	467.196	5.6%
CuO-water nanofluid (0.2%)	589.65	606.23	2.73%
CuO-water nanofluid (0.4%)	600.68	619.53	3%
CuO-water nanofluid (0.5%)	626.1	637.95	1.9%
CuO-water nanofluid (0.8%)	653	656.7	0.6%
CuO-water nanofluid (1%)	608.93	631	3.5%

5.2 Graphical Results

In Figure 3 and 4 ,comparison between overall heat transfer coefficient for parallel and counter flow heat exchanger with variation in CuO nanofluid concentration based on experimental and CFD simulation results are shown. It could be observed that counter flow arrangement of heat exchanger has shown better heat transfer in both the cases with increase in volume concentration of nanofluid than parallel flow heat exchanger .In both experimental and simulation cases, the overall heat transfer of exchanger increases upto 0.8% concentration of CuO nanofluid and then it drops at 1% ,hence 0.8% concentration is where optimum performance shall be achieved.

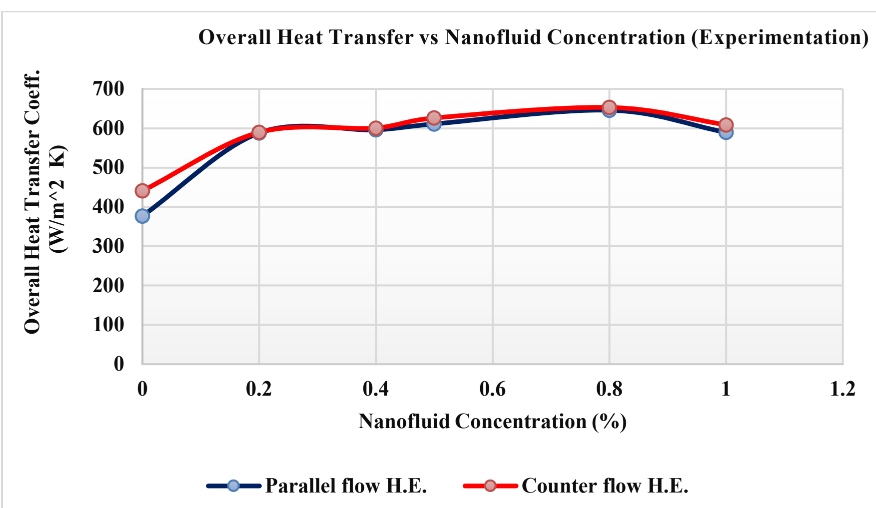

Figure 3. Comparison of U value in Parallel & Counter flow H.E. for varying Nanofluid Concentration based on Experimentation

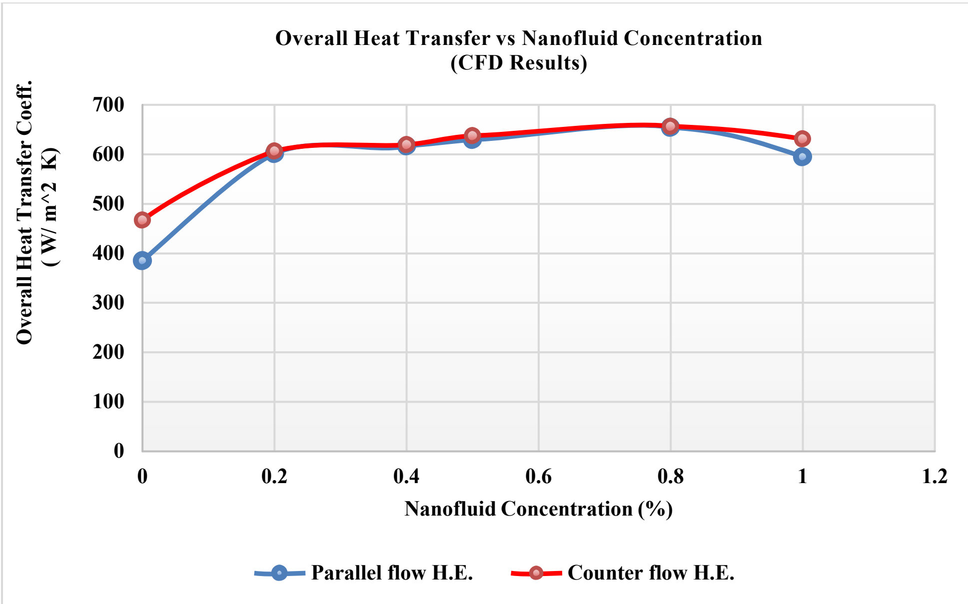

Figure 4. Comparison of U value in Parallel & Counter flow H.E. for varying Nanofluid Concentration based on CFD Results

5.3 Proposed Improvements

Optimum performance of heat exchanger is achieved at 0.8% as per CFD analysis output thus the overall heat transfer coefficient (U) of heat exchanger observed during parallel and counter flow analysis at 0.8% CuO nanofluid is 654.337 W/m^2-K and 665.631 W/m^2-K as depicted in Figure 5 .

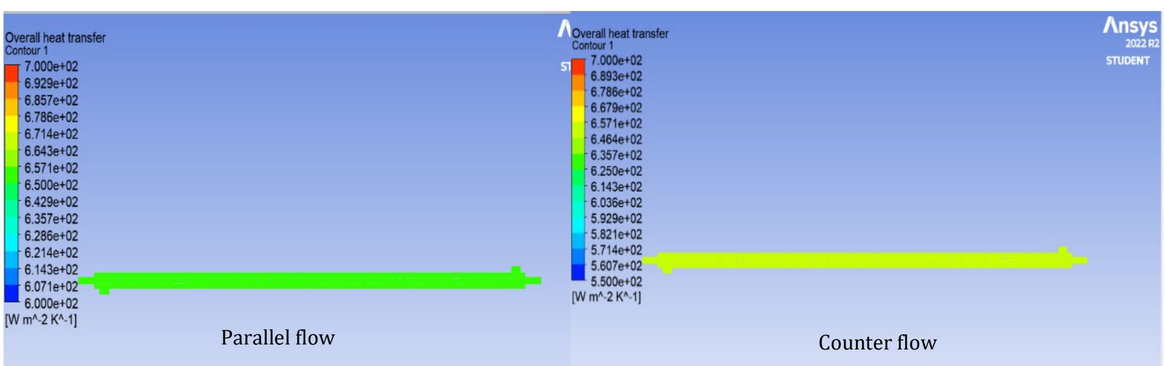

Figure 5. Overall Heat transfer Coeff. of H.E. using CuO (0.8%) in Parallel and Counter flow

In Figure 6 ,effectiveness (η) of heat exchanger calculated is depicted. It has been observed in the figure that counter flow heat exchanger has more effectiveness than parallel flow heat exchanger. It is also noted that the effectiveness of heat exchanger increases with increase in nanofluid concentration .

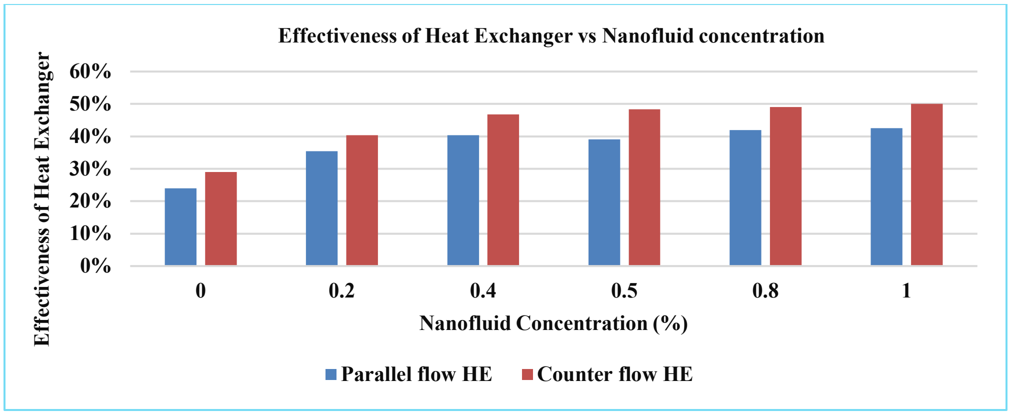

Figure 6. Effectiveness of Parallel & Counter flow H.E. with varying Nanofluid concentration

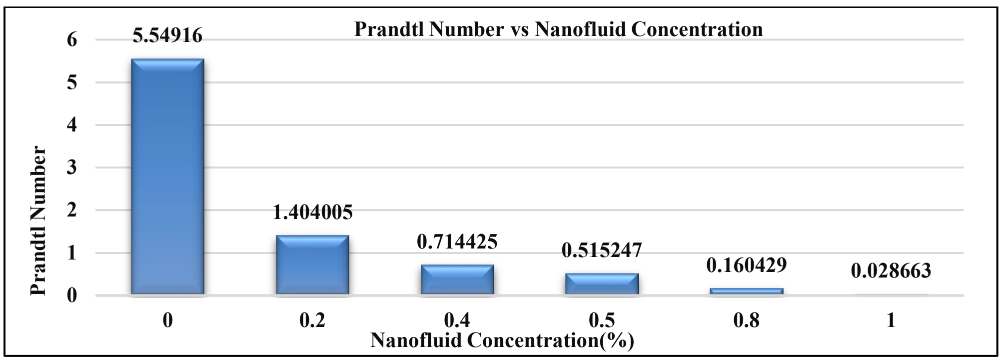

Figure 7. Prandtl number for different concentrations of Nanofluid

In Figure 7, bar graph is depicted showing the decrease in Prandtl number with increase in CuO nanoparticle concentration in base fluid (water). This decrease in Prandtl number with increase in volume concentration of nanofluid indicates free flowing behavior of heat transfer fluid with high thermal conductivity, hence better performance.

5.4 Validation

In Figure 8 and 9, comparison of U in parallel and counter flow between experimental and CFD results of heat exchanger are shown with variation of Nanofluid volume concentration. In both cases, the U value increases up to 0.8% conc. & then drops slightly at 1.0% conc. The variation in U value noted at 0.8% volume conc. of CuO nanofluid between theoretical and analysis results in parallel flow is 1.25% and counter flow is 0.6% which lies under acceptable range. The overall variation in theoretical value and CFD value has been observed to be less than 4% for parallel flow and be less than 6% for counter flow which is thus an acceptable limit for the project.

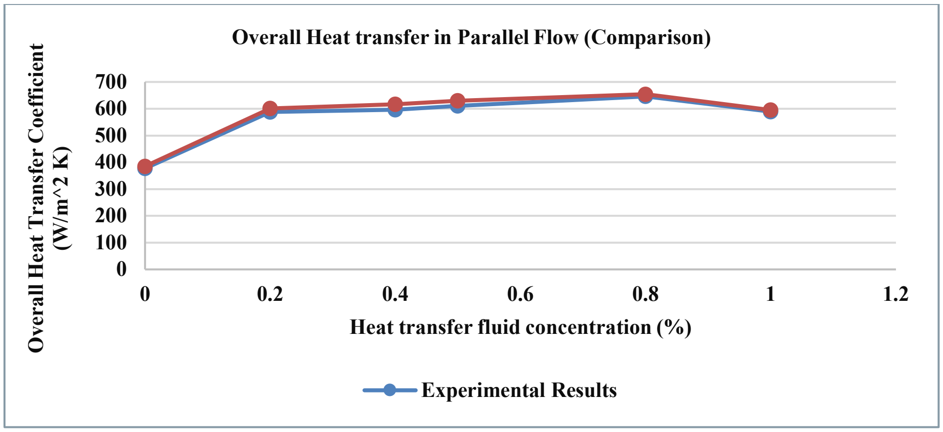

Figure 8. Comparison of Experimental & CFD based U value for Parallel flow HE with varying Nanofluid concentration

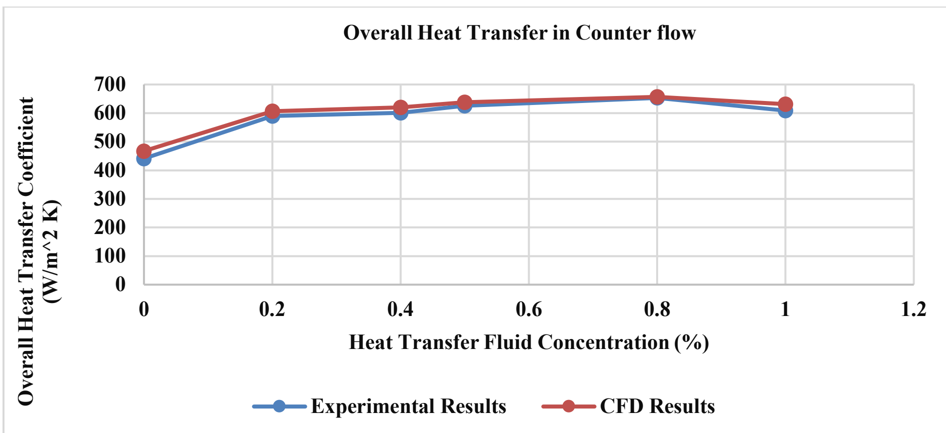

Figure 9. Comparison of Experimental & CFD based U value for Counter flow HE with varying Nanofluid concentration

6.Conclusions

The deformation observed in steel is 6.35e-07 mm, copper is 10.58e-07 mm and aluminium 18.14e-07 mm with aluminium having maximum deformation and steel having minimum deformation induced when compared with other materials.Copper has highest thermal conductivity of 385 W/m-K with minimum strain and deformation value after steel ,thus it is best suited material to be considered for inner tube of H.E. for its better performance.

The maximum effectiveness observed in Parallel flow Heat exchanger with nanofluid usage is found to be 42.5% for 1% vol. concentration and in counter Counter flow Heat exchanger is found to be 50% for 1% vol. concentration of nanofluid. Heat transfer is found to increase with increase in volume concentration up to 0.8% and then decreases for both Parallel and Counter flow Heat exchanger.The maximum value of U that is obtained at 0.8% volume concentration in parallel flow is 646 w/m^{2}K and in counter flow is 653 W/m^{2}K.

Optimum performance of heat exchanger is thus obtained at 0.8% volume concentration of CuO nanofluid in Counter flow arrangement with an effectiveness of 49.03 % .Addition of CuO nanoparticles in right amount can thus improve the heat transfer coefficient, thermal conductivity as well as effectiveness of heat exchanger.Prandtl Number is found to decrease from a value of 5.55 for zero concentrated base fluid to a value of 0.028 due to increase in nanofluid concentration indicating free flowing behavior of fluid with high thermal conductivity.

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