Comparative Computational analysis of performance parameters for shell and tube heat exchanger using helically twisted insert and SIO2 nanofluid

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Abstract— **Exergy balance aspects are always a prime concern encountered in the thermal engineering field face. Present research deals with the study of a concentric shell and tube heat exchanger performance parameters i.e. heat transfer rate using Nanofluid and a geometry change as compared to base fluid. Based on the experimental model of the research under consideration, the numerically validated results of a virtual shell and tube heat exchanger satisfies model used for present study. Using same conditions under the research considered the system is provided with liquids that are both hot and cold, with temperatures of 343K and 303K, respectively. When using water as the working fluid, readings were observed at a flow rate ranging from 0.05 kg/s to 0.2 kg/s for the cold fluid. The nanofluid made of SiO2 nanoparticles instead of water as the working fluid for the same analysis was also carried out under the identical boundary conditions. For the best results, this nanofluid's volume fraction was varied and calculated. The same calculations were carried out for this system using the nanofluid with a volume fraction of 0.4. The obtained results demonstrated that SiO2 nanofluid significantly improves performance. On the other hand, in order to increase the heat transfer coefficient by causing turbulence in the flow of hot fluid, a geometrical change in the form of a helical insert is made. The insert has an effective length of 950 mm and a pitch length of 2.5 inches. For each of the three scenarios, performance parameters like maximum heat transfer rate, overall heat transfer coefficient, and LMTD are calculated and compared. Performance Evaluation Criterion is also evaluated which provides the relative improvement of heat transfer rate w.r.t the additional power loss for creating that turbulence. Scatter plots show that the effectiveness of the heat exchanger is improving.**

Keywords—heat exchanger, CFD analysis, nanofluid, SiO2, solidworks, helical inserts

1. INTRODUCTION

Using a heat exchanger, heat energy can be transferred from one fluid to another that is in direct or indirect contact with one another. Heat exchangers are used in a wide variety of commercial and industrial settings. boilers, air coolers, chilling towers, evaporators, condensers, etc. Additionally, autos employ heat exchangers in the form of radiators, intercoolers, and oil coolers inside engines. Additionally, heat exchangers are frequently utilized in the chemical and process industries to transfer heat between two fluids that are in one state or two states.: [1]

1.1. According to Type of contact

1. Direct Contact Type
2. Transfer Type Heat Exchanger
3. Regeneration type Heat Exchanger

1.2. According to shapes

1. Tubular Heat Exchanger
2. Shell and Tube Heat Exchanger
3. Finned tube Heat Exchanger

1.3. According to direction of flow of fluids

1. Parallel flow
2. Counter flow
3. Cross flow

1.4 Heat Transfer Enhancement

The improvement of heat transfer rate is one of the key considerations in the design of a heat exchanger in order to make the heat exchanger for mechanical and chemical devices and plants more and more compact. Techniques for improving heat transfer are often divided into two categories. As can be observed, the rate of heat transfer in turbulent flow is always higher than the rate of heat transfer in laminar flow. By creating turbulence in a fluid flow, the rate of heat transfer can be increased. The geometric heat transfer coefficient (general heat transfer coefficient) depends on a number of factors, including the orientation of the heat exchanger, its geometry, the characteristics of the fluid flow, the kind of fluid (such as turbulent or laminar), the material of the tube, etc. Two things can cause turbulence.[2]

1.5 NANOFLUIDS:

The four essential properties of a base fluid—density, viscosity, thermal conductivity, and specific heat—are enhanced by the presence of nanosized particles of either metal oxides or carbides in a nanofluid. These improvement in properties permit liquid to move more intensity in contrast with the base liquid. Silicon dioxide (SiO2) is the nanoparticle used in our study. Its properties are calculated and shown in Table 1. [3]

2. INTRODUCTION TO SOLIDWORKS

Solidworks is a product utilized for virtual displaying and investigation of frameworks utilized for designing plans. Dassault Systems produced it. The software tool primarily serves to represent design through virtual modeling. Software analysis is available for determining optimal values.

2.1 STEPS FOR SOLVING A GENERAL PROBLEM IN SOLIDWORKS:

Similar to solving any problem analytically, you need to define

(1) problem domain,
(2) Virtual model,
(3) Boundary conditions and
(4) Physical properties.

You then present your solution to the problem. In terms of numbers, an additional step known as mesh generation makes the most difference. This is the step that breaks up the advanced model into smaller pieces that can be solved in an Associate in Nursing scenario if it is not too advanced. The procedures are described below in word with slight adjustments for the software system. [4]

2.1.1 Virtual Modelling

Utilizing the work plane coordinate system in Flow simulation-SOLIDWORKS, create a two- or three-dimensional virtual model of your project for the object's representation and test it.

2.1.2 Assigning material

Create a list of necessary materials that make up the modelled item (or project) now that the part has been modeled. Mechanical and thermal properties are included.

2.1.3 Generate Mesh

SOLIDWORKS knows the part's composition at this point. Now, specify how the Modeled System should be broken down into smaller, more manageable pieces in order to calculate an infinitesimal object. The system will use the iterative method to combine the results for the entire System.

2.1.4 Problem set-up

The final step is to set the system up with constraints like physical loadings or boundary conditions after it has been fully designed. In this section, we will provide the fluid's flow rates, the effect of gravity, and the kind of differential equation on which the problem is based.

2.1.5 Generate Solution

In this case, the software needs to know what kind of analysis it needs to do—steady state or transient. In addition, the software performs a sample of ten iterations to determine whether the solution will converge to a unique value.

2.1.6 View Results/Reports (post Processing)

The process of obtaining the solution in the desired format is known as post processing. You have a variety of options for how the solution can be presented in SOLIDWORKS, including tables, graphs, and contour plots [5]

3. METHODOLOGY

3.1 CFD PROCESS ANALYSIS:

SOLIDWORKS 22 software is used to simulate the results, and a Computational Fluid Dynamics (CFD) analysis is carried out to verify the results. The simulation is carried out as depicted in fig. 1, a block diagram. [6]

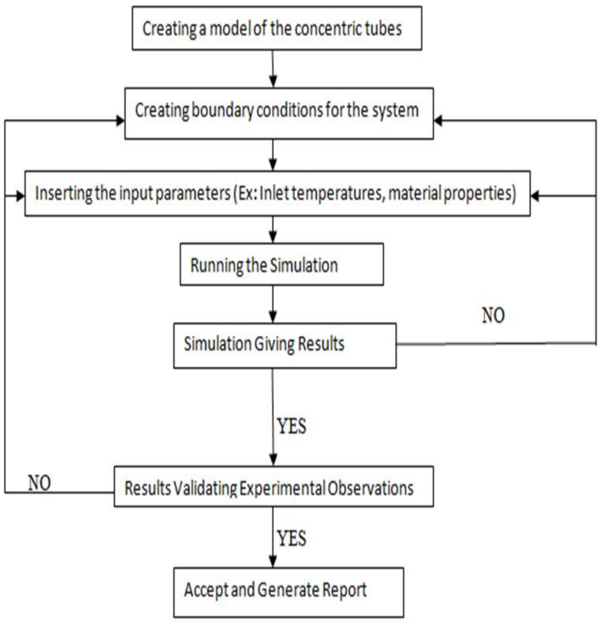

Fig 1 CFD Process [7]

3.2 COMPUTATIONAL PROCEDURE:

1. In SolidWorks 2022, a virtual concentric shell and tube heat exchanger can be virtually designed. The experimental base paper's dimensions apply to the heat exchanger.

2. The inner tube has a diameter of 12 millimeters and the outer tube has a diameter of 14 millimeters, while the shell has a diameter of 17 millimeters and an outer diameter of 18 millimeters, respectively.

3. Copper is the material that was used to make both of the tubes, and it has the same properties at any temperature. The mass flow rate of hot fluid flowing through the annuus of both tubes is kept constant at a value of 0.05kg/s, whereas the mass flow rate of cold fluid flowing through the annulus is varied from 0.05kg/s, 0.1kg/s, 0.15kg/s, and 0.2kg/s, respectively. The inlet temperatures of the cold fluid are kept at 303K and the inlet temperature of the hot fluid is kept at 343K.

4. Our foundational paper's experimental findings serve as validation for this virtual model's initial designs. Heat transfer rate, effectiveness, and LMTD values are calculated and presented for the water-water heat exchanger results.

5. The properties of a Nano-Fluid are determined using the aforementioned standard formulas in virtual software. The virus water coursing through annulus is supplanted by this nano liquid while keeping the gulf temperature and its mass stream rate same. The calculations are also discovered for this arrangement. Additionally, various volume fraction values of the nano fluid are examined, and the most appropriate volume fraction is used in the calculations.

6. The heat transfer rate, LMTD, overall heat transfer coefficient, and heat exchanger efficiency are used to compare the outcomes.

7. A helically twisted insert of pitch length 2.5-inch has been placed inside the inner tube of shell and tube heat exchanger. The insert has been placed in order to create turbulence in the flow of fluid, which in turns increase the value of heat transfer coefficient resulting in improvement of performance of heat exchanger. The geometric parameters and fluid parameters oof the system is kept same as it were in simple shell and tube heat exchanger.

8. Performance Evaluation Criterion is calculated between simple heat exchanger and helically inserted heat exchanger, to justify the use of inserts.

4. MATHEMATICAL AND ANALYTICAL PROCEEDURE

4.1 Calculation of Properties of nanofluid

As discussed above, the nanofluid is considered on 4 different properties of fluid. They are calculated as follows: [8]

4.1.1. Volume Fraction:

A Nano-Fluid is made up of a solution of a dissolving liquid, and nano particles of any suitable metal, oxides or carbides. The concentration of these particles in this base fluid is of importance because it changes the properties of nano fluid.

$$\text{Volume Fraction} = \frac{\text{Mass of nano paticle/Density of Nano Particle}}{\text{mass of nano particle/Density of nano particle} + \text{mass of base fluid/Density of base fluid}}$$

4.1.1. Density of Nano Fluid:

Due to the addition of two different densities of materials, the resultant density of solution changes and it can be calculated as shown.

$$\rho nf = \Phi \times \rho s + (1 - \Phi)\rho w$$

Where,

ρnf: Density of nano fluid.

Φ: Volume Fraction

ρw: Density of water

ρs: Density of solid

4.1.2. Specific heat of nano fluid:

This is the net heat that one kg of nano fluid will be requiring in order to raise its temperature to 1K.

$$Cp(nf) = \frac{(\Phi \times \rho s \times Cp(s) + (1-\Phi) \times (\rho w \times Cp(w))}{\Phi \times \rho s + (1-\Phi)\rho w}$$

Where,

Cp(nf): Specific heat of nano fluid

4.1.3 Viscosity of nano fluid:

This is the resistance to flow that is caused by shear stress in the nano fluid.

$$\mu(nf) = \mu(w) \times (1 + 0.25 \times \Phi)$$

where,

μ(nf): Dynamic viscosity of nano Fluid.

4.1.4 Thermal conductivity of Nano Fluid:

$$K(nf) = \frac{((Ks + 2Kw + 2(Ks - Kw)(1+\beta)^3 \times \Phi) * Kw)}{(Ks + 2Kw - 2(Ks - Kw) \times (1+\beta)^3 \times \Phi)}$$

4.1.5 Performacne parameters of Heat exchanger

A. Heat Transfer Rate:

Heat Transfer Rate of Hot Fluid:

As the inlet and outlet temperature of both the fluids are known then, we can find out the rate of heat transfer of hot fluid by the following expression.

Q= mc Cp (Tco – Tci)

B. Heat Transfer Rate of Cold Fluid:

With the help of the temperatures of cold fluid inlet and outlet we can find out the heat gained by cold fluid by the following expression.

Q = mh Cp (Thi – Tho)

The heat gained by cold fluid must be exactly equal to the heat lost by the hot fluid in fully adiabatic boundary condition. But since the surface cannot be fully adiabatic thus, we consider rate of heat loss by hot fluid as the actual heat transfer rate of the system.

C. Logarithmic Mean Temperature Difference:

At different section along the length of circular tubes the temperature difference between hot fluid and cold fluid will be different, as the hot fluid will continuously be losing heat to cold fluid. Logarithmic mean temperature difference is the equivalent temperature difference which can be used to calculate heat transfer rate of the heat exchanger if it is substituted in the general equation of heat transfer in Heat exchanger. We find out the logarithmic mean temperature difference for every case by using the following expression.

$$\Delta T_{lm} = \frac{(\Delta T_2 - \Delta T_1)}{ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} = \frac{(\Delta T_1 - \Delta T_2)}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

Where,

ΔT_2 = T_1 (Hot fluid inlet temperature) – T_4 (Cold fluid exit temperature)

ΔT_1 = T_2 (Hot fluid exit temperature) – T_3 (Cold fluid inlet temperature)

ΔT_{lm} = Logarithmic mean temperature difference.

D. Overall Heat Transfer Coefficient:

The overall heat transfer coefficient is a measure of the overall ability of a series of conductive and convective barriers to transfer heat. It is commonly applied to the calculation of heat transfer in heat exchangers, but can be applied equally well to other problems.

For our case of heat exchanger, since we already know the value of heat transfer rate thus we can use the following equation to determine the value of Overall Heat Transfer Coefficient.

$$\boldsymbol{Q = UA\Delta T_{lm}}$$

U = Overall heat transfer coefficient (Watts/m^2K).

E. Effectiveness of Heat Exchanger:

It is a dimensionless parameter and defined as the ratio of actual heat transfer rate '$Qactual$' by heat exchanger to maximum possible heat transfer rate '$Qmax$' it is denoted by 'ε'.

The value of effectiveness of the heat exchanger can also be determined for each case by using the following expression. [9] [10] [11] [12]

$$\varepsilon = \left(\frac{Qact}{Q\max}\right) = \left(\frac{mcCpc(Tco - Tci)}{Q\max}\right) = \left(\frac{mhCph(Thi - Tho)}{Q\max}\right)$$

Where,

Q_{max} = maximum heat transfer possible

$$Q_{max} = C_{min} * (T_{hot\ Inlet} - T_{cold\ inlet})$$

F. Performance Evaluation Criterion:

This expression gives us the increase in heat transfer rate w.r.t. to the additional input power required for gaining that enhancement in heat transfer rate.

PEC = Improvement in heat transfer/additional drop in pressure

5. Results

5.1 Properties of SiO2 Nano Fluid as calculated based on above formula

Calculations are made on the nano fluid properties that must be entered into SolidWorks software. The density of the nano fluid, its specific heat, its viscosity, and its thermal conductivity are the four essential properties. For each of the flow rates of 0.05, 0.1, 0.15, and 0.2 kg/s, the aforementioned calculations were performed for the volume fractions of 0.4 and 0.3, respectively.

Table 1: Properties of Nano Fluid

Nano Fluid Property Table							
S.No	mfC (kg/s)	Volume Fraction	mf(Nanoparticle in kg/S)	Density of SiO2 Nano Fluid	Specific Heat of NanoFluid (J/kg-K)	Viscosity of NanoFluid	Knf (W/m-K)
1	0.05	0.4	0.08860	1658.2	1977.121819	0.002	1.259864
2	0.05	0.3	0.05696	1492.9	2346.076294	0.00175	1.034068
3	0.1	0.4	0.17720	1658.2	1977.121819	0.002	1.259864
4	0.1	0.3	0.11391	1492.9	2346.076294	0.00175	1.034068
5	0.15	0.4	0.26580	1658.2	1977.121819	0.002	1.259864
6	0.15	0.3	0.17087	1492.9	2346.076294	0.00175	1.034068
7	0.2	0.4	0.35440	1658.2	1977.121819	0.002	1.259864
8	0.2	0.3	0.22783	1492.9	2346.076294	0.00175	1.034068

5.2 Generated Report:

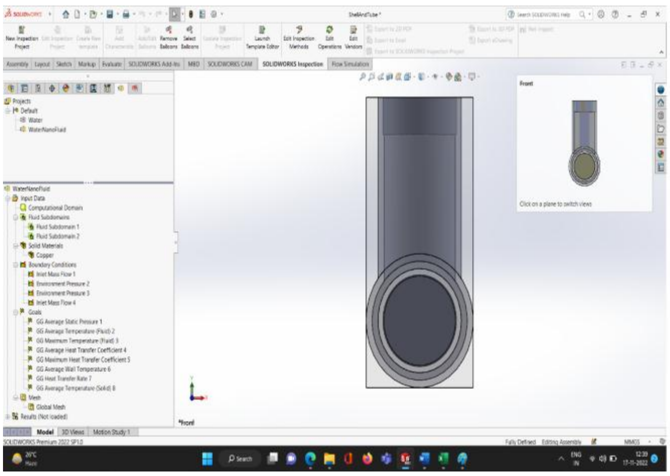

Fig 2 Front View of Model of the Shell and Tube Heat Exchanger

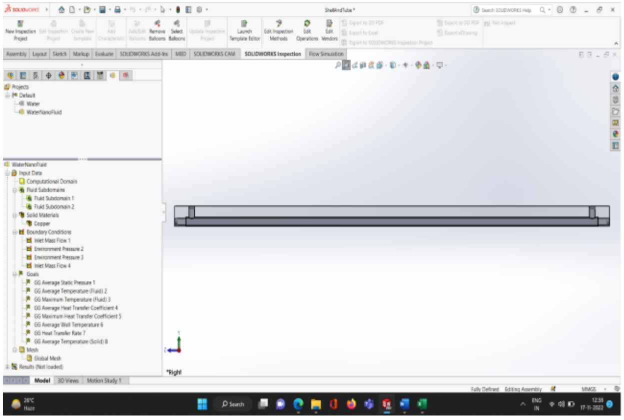

Fig 3 Side View of Shell and Tube model

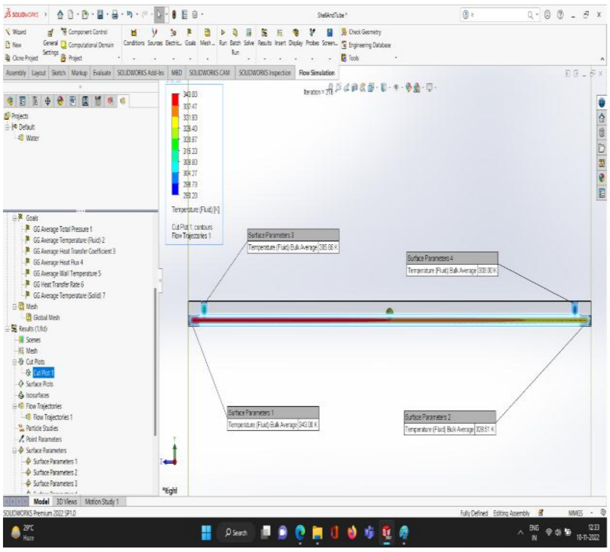

Fig 4 Outlet Temperature (in case of water-water heat exchanger) as displayed by software

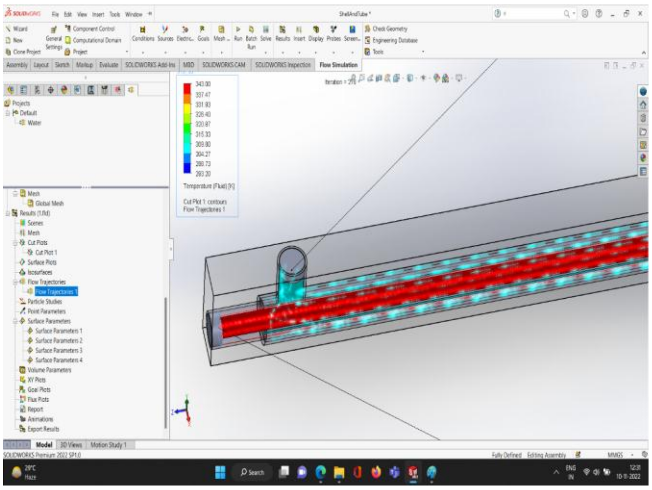

Fig 5 Flow Trajectories of Temperature of Hot Fluid flowing inside the tube on a Clip plane

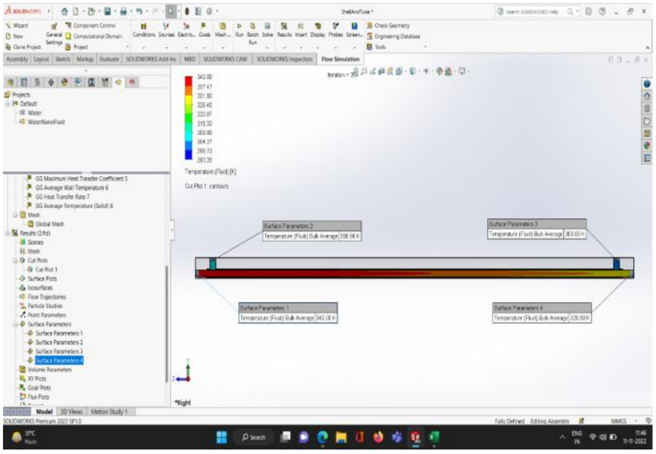

Fig 6 Outlet Temperature (in case of water-Nano-Fluid heat exchanger) as displayed by software

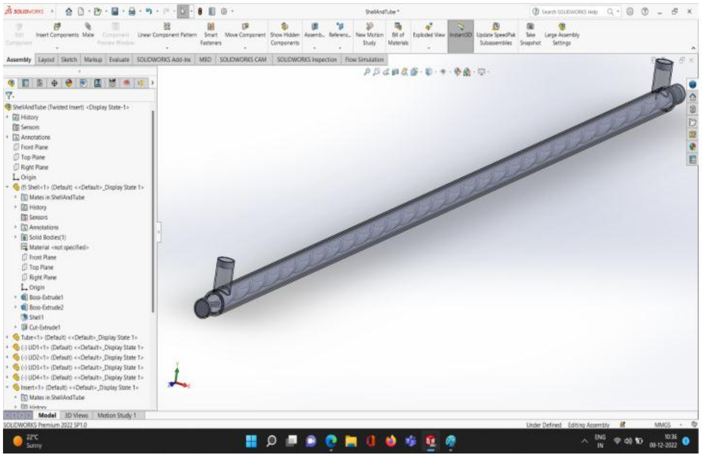

Fig 8(b) Assembly of helical insert in shell and tube heat exchanger

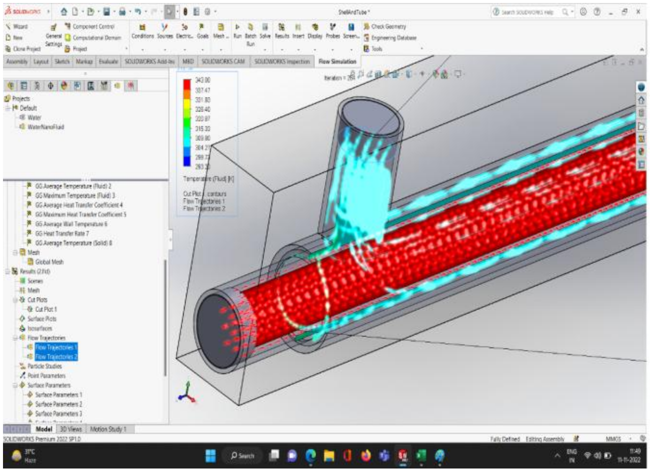

Fig 7 Flow Trajectories (Water-Nano-Fluid) flowing inside the tube on a Clip plane

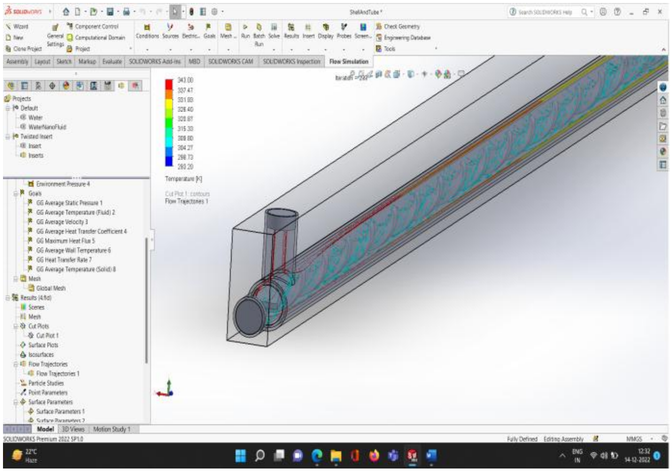

Fig 9 (a) Close view of Flow Trajectories (Water-water-helical insert) flowing inside the tube on a Clip plane

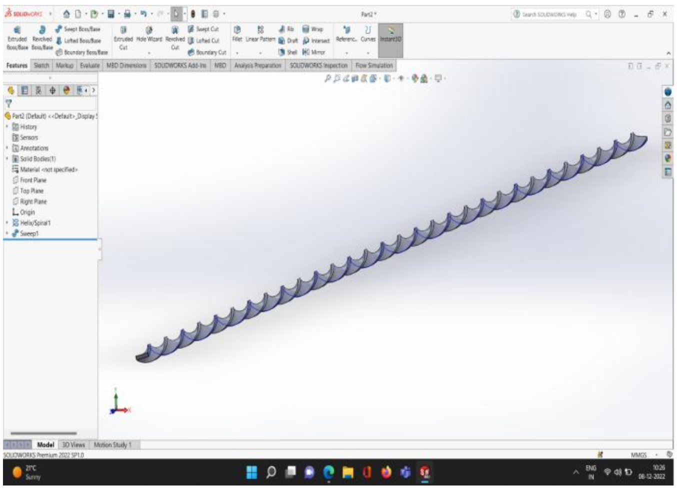

Fig 8(a) Virtual model of helically twisted shaped insert

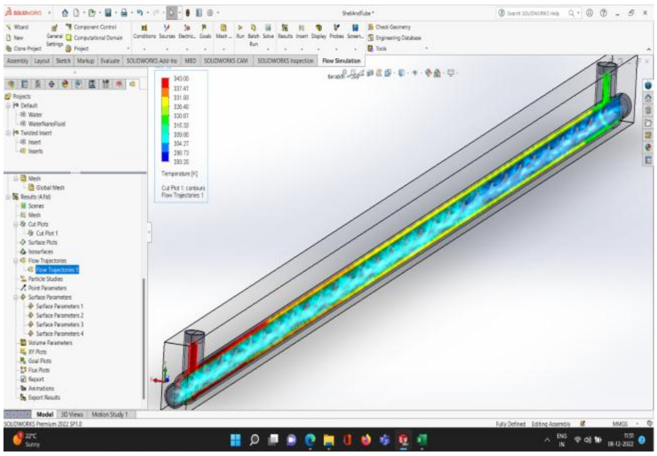

Fig 9 (b) Flow Trajectories (Water-water-helical insert) flowing inside the tube on a Clip plane

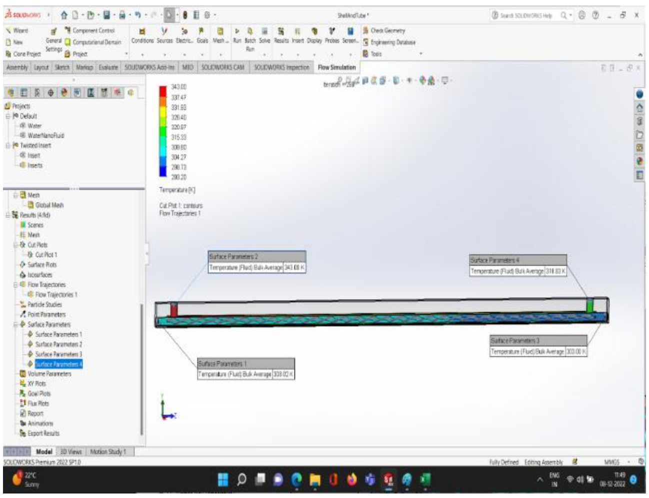

Fig 10 Outlet Temperature (in case of water-water-helical insert heat exchanger) as displayed by software

5.3 Comparison of Heat Transfer Rate of water heat exchanger with nano-fluid heat exchanger.

The heat transfer rates of concentric circular plane tubes without insert and with insert are compared in Figure 11. In the case of cold fluid, one arrangement has water flowing as cold fluid, and the next time, the SiO2 nano fluid with a volume fraction of 0.4 is flowing as cold liquid, respectively. In both cases, water flows as a hot fluid. The correlation shows that the most extreme worth of intensity move rate for a similar stream rate is accomplished for water-nanofluid game plan at 0.2kg/s with a worth of 5016.026 watts whereas the system having helical insert also showed great progress in comparison to simple heat exchanger.

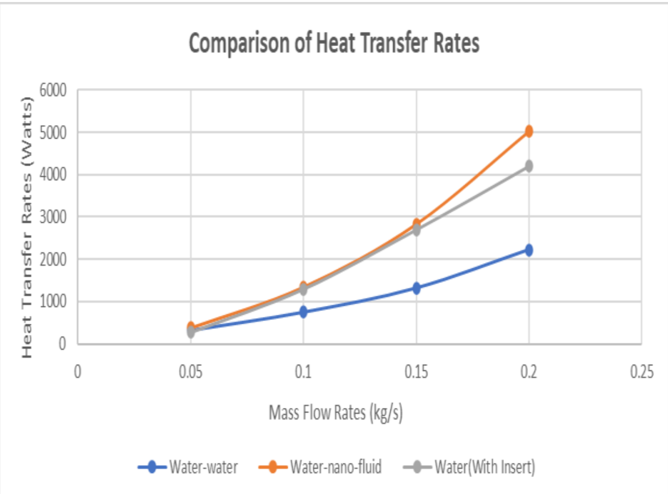

Fig 11 Rate of Heat Transfer versus mass flow rate of Hot Fluid in Counter Flow arrangement

5.4 Comparison of Overall Heat Transfer coefficient based on Computational analysis

The overall heat transfer coefficients of concentric circular plane tubes with and without inserts, in the water-water arrangement and the water-nanofluid arrangement, respectively, are compared in Figure 12. The comparison reveals that, for the same flow rates, the water-nanofluid arrangement achieves a value of 13039.99291 (Watts/(m2-K)) for the overall heat transfer coefficient, whereas the water system with helical insert achieved a value of 8254.945 (Watts/(m2-K)).

5.5 Comparison of LMTD based on Computational analysis of all the cases

Fig 13 shows the relative upsides of LMTD of concentric round plane cylinders with next to no supplements, with water-endlessly water nanofluid course of action individually. The comparison demonstrates that the water-nanofluid arrangement achieves the same LMTD value for the same flow rates, with a maximum of 9.21088 at 0.2 kg/s. The increase in the temperature difference between the inlet and exit is the cause of this growth. because LMTD is directly correlated with temperature changes at the inlet and exit. As a result, the mass flow rate also increases. The helical insert with a pitch length of 2.5 inches and a value of 12.19386 K achieves the highest possible LMTD value.

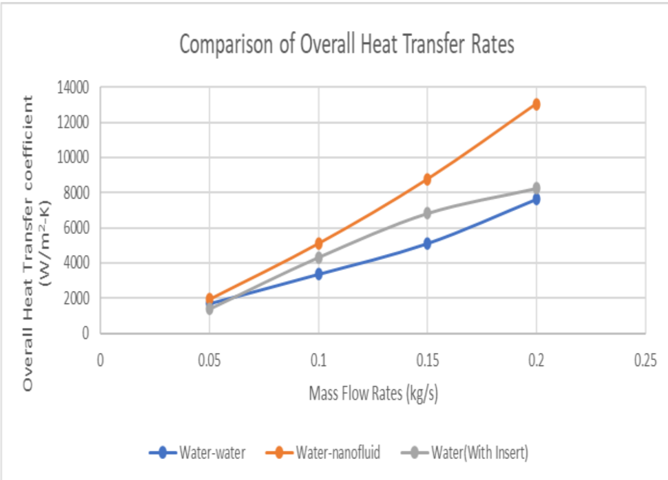

Fig 12 Overall Heat transfer coefficient versus mass flow rate of Cold Fluid in Counter Flow arrangement

5.6 Comparison of Effectiveness based on Computational analysis of all the three cases

In the water-water and water-nanofluid systems, the effectiveness of concentric circular plane tubes without inserts and with a counterflow arrangement is compared in Figure 14, respectively. The comparison demonstrates that water with inserts achieves the highest value of effectiveness for the same flow rates at 0.2 kg/s.

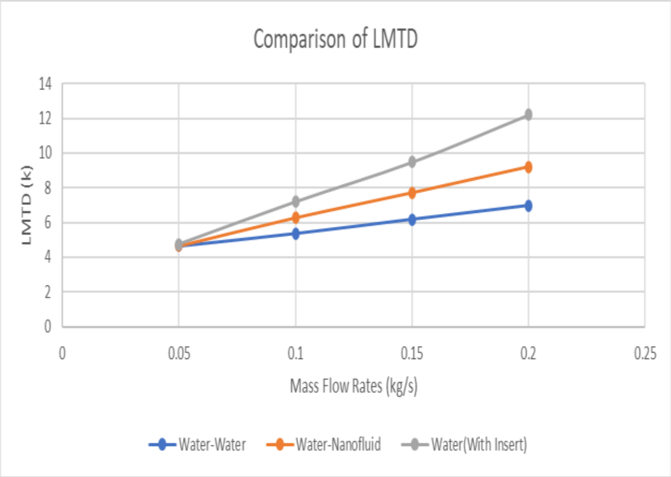

Fig 13 LMTD versus mass flow rate of cold Fluid in Counter Flow arrangement

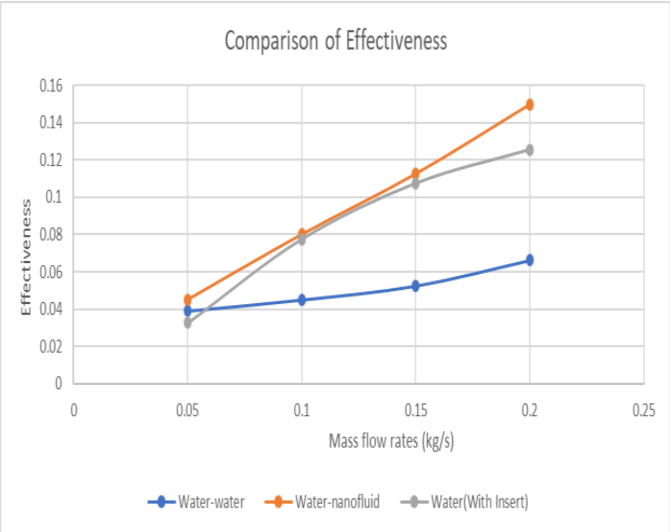

Fig 14 Effectiveness versus mass flow rate of Hot Fluid in Counter Flow arrangement

6. CONCLUSION:

1) In this investigation, the properties of the SiO2 nanofluid were discovered and characterized in programming for various fixation factor advantages. Nanofluid performance was found to be best at the concentration of 0.4, which was chosen for the heat exchanger's performance calculation.

2) The current investigation reveals that the counter flow arrangement of a water-water heat exchanger has a maximum heat transfer coefficient of 7624.53 Watts/m2k, which is 42% lower than the value we obtained for a water-nanofluid arrangement, which is 13039.99 Watts/m2K, and is 36% higher than the heat exchanger with twisted inserts.

3) It should be mentioned that the LMTD for the water-nanofluid arrangement was found to be 9.21 K, which is higher than the LMTD for the water-water arrangement by 24% but lower than the LMTD for the water-water arrangement with a helical insert by 24%, which is 12.19 K.

4) The effectiveness of the water-nanofluid arrangement was also found to be maximum with a value of 0.149, which is higher than the effectiveness of the water The water-water case with helical inserts has a maximum value of 0.1255, which is 16% lower than the nanofluid case.

5) When compared to the water-water arrangement, which had a value of 2219.11 Watts for the same working conditions, the maximum heat transfer rate was noted to have increased by an astonishing 126% for a mass flow rate of 0.2 kg/s for the water-nanofluid arrangement. The same heat transfer rate is 54% higher than what helical-inserted tubes can achieve after consideration of Performance evaluation criterion.

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