Comparative computational performance Analysis of shell and tube heat exchanger with and without SiO2 nanofluid

Abhimanyu Kumar[1], Animesh singhai[2]

[1]Research Scholar, Department of Mechanical Engineering Trinity Institute of Technology and Research Bhopal, India
[2]Asst. Professor, Department of Mechanical Engineering Trinity Institute of Technology and Research Bhopal, India

---***---

***Abstract*—Considerable amount of work has been done to deal the exergy balance aspects in thermal engineering field. The present study aims the computational comparative analysis of performance parameters of a concentric shell and tube heat exchanger with and without nanoparticles under different mass flow rates of cold fluid. The results reported significant improvement in maximum heat transfer rate, overall heat transfer coefficient, LMTD and effectiveness with the use of Nanoparticles in lined with previous studies.**

Keywords*—*heat exchanger, CFD analysis, nanofluid, SiO2, solidworks

1. INTRODUCTION

Heat Exchanger is a device used for energy transfer between fluids for industrial purposes. Heat exchanger is a broadly used term for a category of devices. The devices such as evaporators, recuperators, condensers, and any more fall under the category of heat exchanger. Heat exchangers are classified based on various aspects, such as: [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

A variety of techniques are used in order to improve the performance of heat exchanger. The performance of heat exchanger is measured by the amount of heat exchanged in a given time between the two streams of fluids. The techniques are classified in broad 2 categories. They are termed as Active heat transfer enhancement techniques, and passive heat transfer enhancement techniques. In active heat transfer enhancement techniques, additional power is supplied to get the desired increase in heat transfer rate, whereas in passive heat transfer techniques, heat transfer enhancement is achieved by changing the shape of the pipes or by changing the quality of working fluids or materials used.[2]

1.5 NANOFLUIDS:

A nanofluid is a mixture of a base liquid with nano size particles of either metal oxides, or carbides, which improves the four necessary properties of the base fluid which are density, viscosity, thermal conductivity, and specific heat. These improvement in properties allow fluid to transfer more heat in comparison to the base fluid. The nano particle used for our research purpose is silicon dioxide (SiO_2), whose properties are calculated and represented in Table 1. [3]

2. INTRODUCTION TO SOLIDWORKS

Solidworks is a software used for virtual modelling and analysis of systems used for engineering designs. It is a product of Dassault systems. The software tool basically used for virtual modelling for representation of design. Analysis can be done in software for finding out optimum 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 solve the matter and present the results. In numerical ways, the most distinction is an additional step referred to as mesh generation. This can be the step that divides the advanced model into little components that become resolvable in Associate in Nursing otherwise too advanced scenario. Below describes the processes in word slightly additional adjust to the software system. [4]

2.1.1 Virtual Modelling

Construct a two or three dimensional virtual model of your project for the representation of the object and test it using the work plane coordinates system within Flow simulation-SOLIDWORKS.

2.1.2 Assigning material

Now that the part is modelled, outline a library of the mandatory materials that compose the item (or project) being modelled. This includes thermal and mechanical properties

2.1.3 Generate Mesh

At this point SOLIDWORKS understands the makeup of the part. Now define how the Modelled system should be broken down into finite pieces in order to perform the calculation of a infinitesimal object and then the system will use the iterative method to integrate the results for the complete system.

2.1.4 Problem set-up

Once the system is fully designed, the last task is to set-up the system with constraints, such as physical loadings or boundary conditions. Here we will be providing flow rates of fluid, gravity effect and type of differential equation that the problem is depending upon.

2.1.5 Generate Solution

Here the software requires information about the type of analysis that it has to undertake (steady state/transient). The software also runs a sample of 10 iterations in order to check that whether the solution will converge to a unique value or not.

2.1.6 View Results/Reports (post Processing)

Post Processing is the technique of getting the solution represented in the format you desire. SOLIDWORKS provides various ways in which the solution can be presented in, and you can choose from among them such as tables, graphs, and contour plots. [5]

3. METHODOLOGY

3.1 CFD PROCESS ANALYSIS:

The results are simulated with the help of SOLIDWORKS 22 software and a Computational Fluid Dynamics (CFD) analysis is performed in order to get the validation of the results. The simulation is carried out as described by a block diagram shown in fig 1 [6]

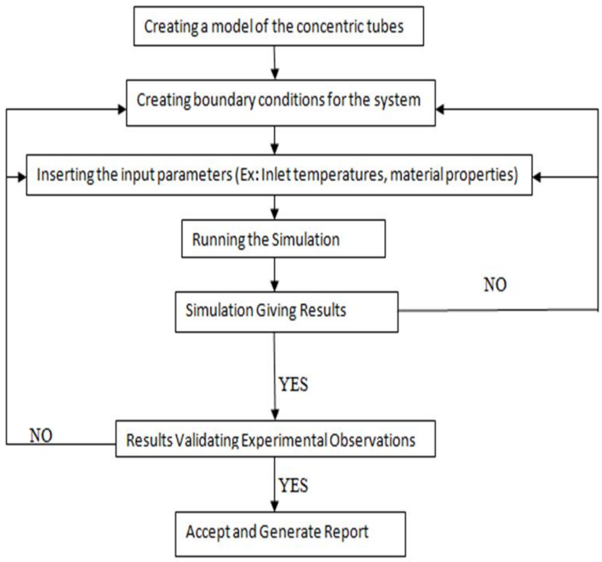

Fig 1 CFD Process [7]

3.2 COMPUTATIONAL PROCEDURE:

1. A concentric shell and Tube heat exchanger is virtually designed in SolidWorks software, 2022 version. The dimensions of the heat exchanger are as per the experimental base paper.

2. The inner tube has an inner diameter of 12mm and outer diameter of 14mm, whereas the shell is made of inner diameter of 17mm and outer diameter of 18mm respectively.

3. The material used for both the tubes are copper with its standard properties at given temperature. The inlet temperature of cold fluid is kept at 303K and inlet temperature of hot fluid is kept at 343K. The mass flow rate of hot fluid flowing through the annuus of both the 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.

4. The initial readings of this virtual model is validated with experimental results of our base paper. The water-water heat exchanger results are calculated, and data is presented for heat transfer rate, effectiveness, and LMTD values.

5. A Nano-Fluid is defined in virtual software whose properties are calculated based on standard formulas as mentioned ahead. The cold water flowing through annulus is replaced by this nano fluid while keeping the inlet temperature and its mass flow rate same. The calculations are found for this arrangement as well. Also, the nano fluid is checked for various values of volume fraction, and the best suitable volume fraction is used for the calculations.

6. The results are compared on the basis of heat transfer rate, LMTD, overall heat transfer coefficient and effectiveness of heat exchanger.

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

Cp(s): Specific heat of solid

Cp(w): Specific heat of water

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

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

5. Results

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

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

The properties of nano fluid which are required to be inserted in solidworks software are calculated. The four necessary properties are Density of nano fluid, specific heat of nano fluid, Viscosity of nano fluid and thermal conductivity of nano fluid. The above tabulated calculations are made for volume fraction 0.4 and 0.3 respectively for all the flow rates of 0.05, 0.1, 0.15, 0.2 kg/s respectively.

5.2 Generated Report:

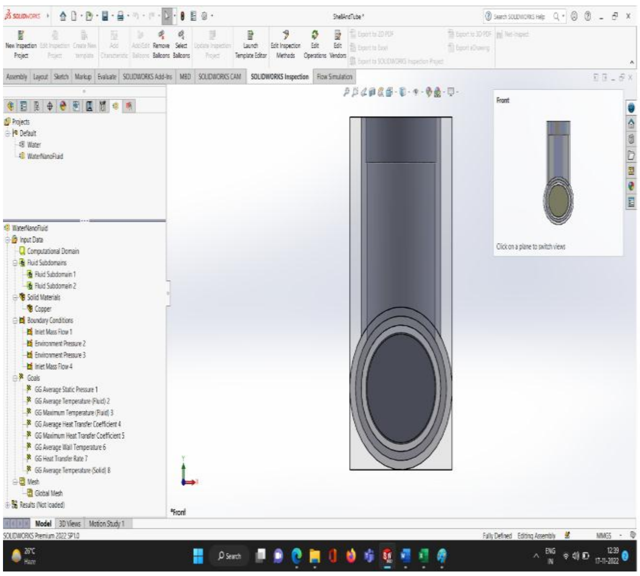

Fig 2 Front View of Model of the Shell and Tube Heat Exchanger

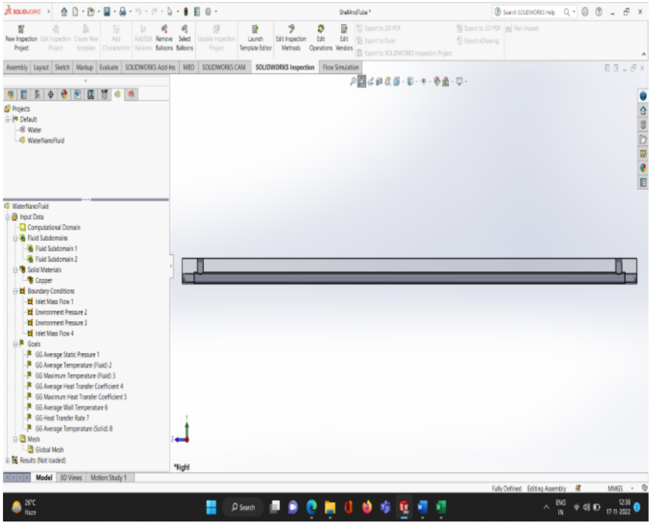

Fig 3 Side View of Shell and Tube model

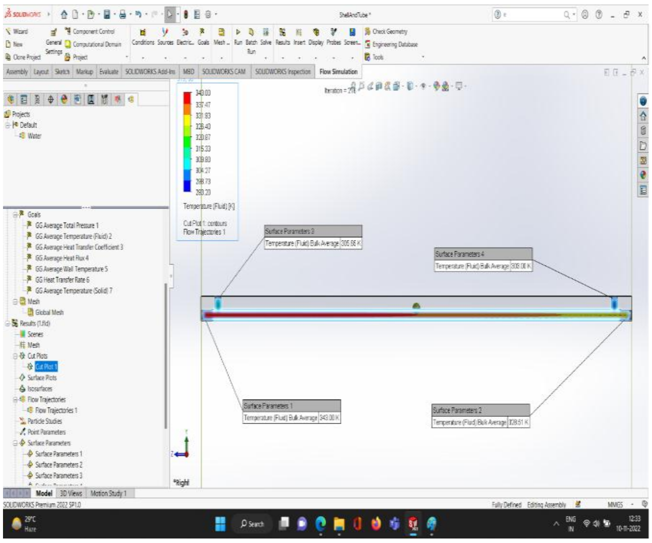

Fig 4 Outlet Temperature (in case of water-water heat exchanger) as displayed by software

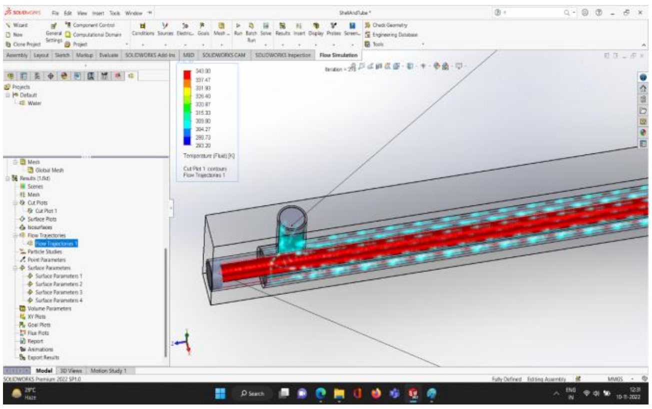

Fig 5 Flow Trajectories of Temperature of Hot Fluid flowing inside the tube on a Clip plane

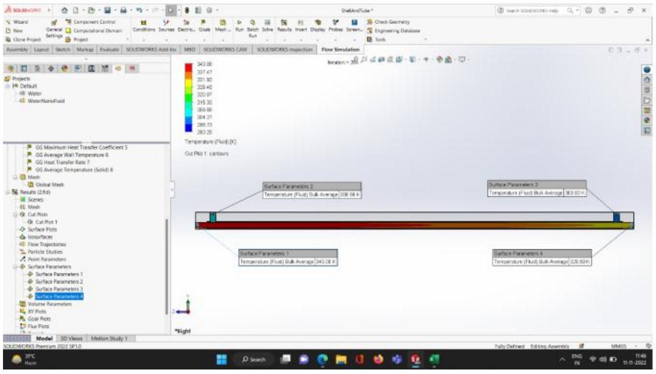

Fig 6 Outlet Temperature (in case of water-Nano-Fluid heat exchanger) as displayed by software

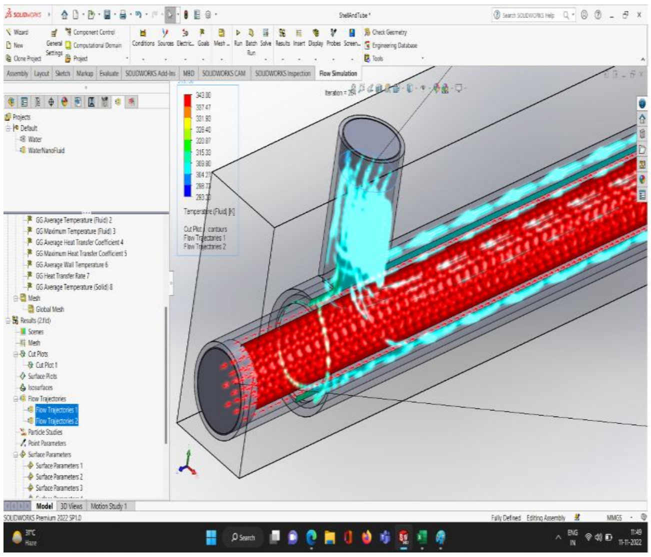

Fig 7 Flow Trajectories (Water-Nano-Fluid) flowing inside the tube on a Clip plane

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

Fig 8 shows the comparative values of heat transfer rates of concentric circular plane tubes without any inserts, with water flowing as hot fluid in both the cases but in case of cold fluid, one arrangement has water flowing as cold fluid and the next time, the SiO2 nano fluid with volume fraction of 0.4 is flowing as cold liquid respectively. The comparison shows that the maximum value of heat transfer rate for the same flow rates is achieved for water-nanofluid arrangement at 0.2kg/s with a value of 5016.026 watts.

5.4 Comparison of Overall Heat Transfer coefficient based on Computational analysis

Fig 9 shows the comparative values of Overall Heat transfer coefficient of concentric circular plane tubes without any inserts, with water-water arrangement and water-nanofluid arrangement respectively. The comparison shows that the maximum value of Overall Heat transfer coefficient for the same flow rates is achieved water-nanofluid arrangement at 0.2kg/s with a value of 13039.99291 (Watts/(m^2-K)).

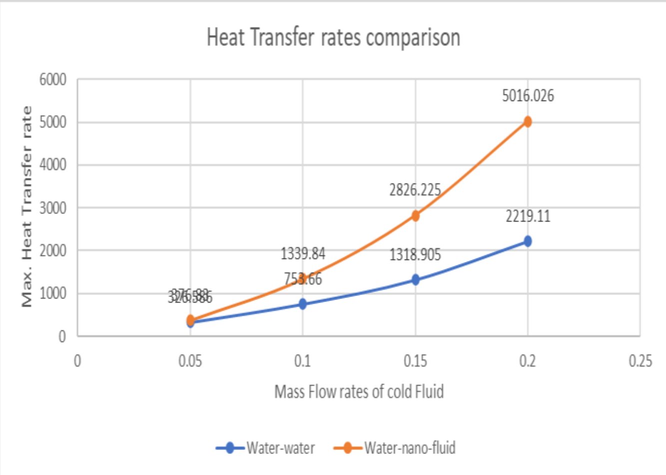

Fig 8 Rate of Heat Transfer versus mass flow rate of Hot Fluid in Counter Flow arrangement

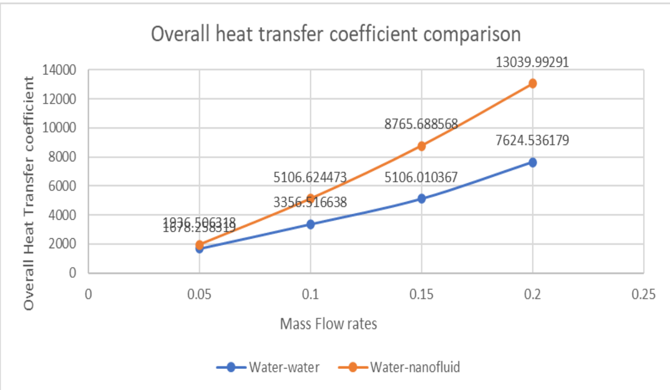

Fig 9 Overall Heat transfer coefficient versus mass flow rate of Cold Fluid in Counter Flow arrangement

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

Fig 10 shows the comparative values of LMTD of concentric circular plane tubes without any inserts, with water-water and water-nanofluid arrangement respectively. The comparison shows that the maximum value of LMTD for the same flow rates is achieved for water-nanofluid arrangement, and it was at its maximum on 0.2kg/s with a value of 9.21088.

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

Fig 11 shows the comparative values of effectiveness of concentric circular plane tubes without any inserts, with counter flow arrangement in water-water and water-nanofluid system respectively. The comparison shows that the maximum value of effectiveness for the same flow rates is achieved for water-nanofluid.

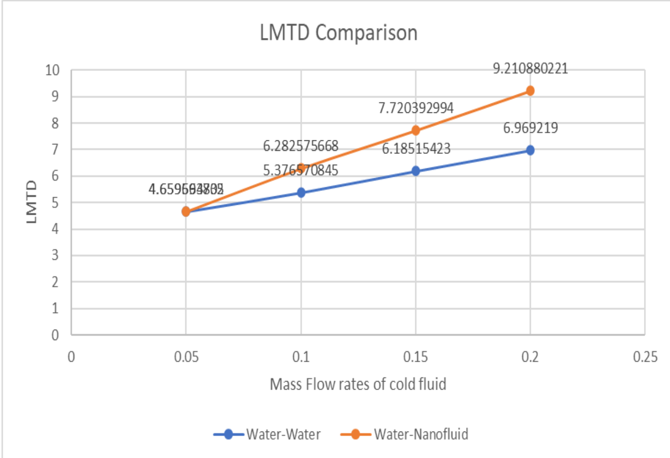

Fig 10 LMTD versus mass flow rate of cold Fluid in Counter Flow arrangement

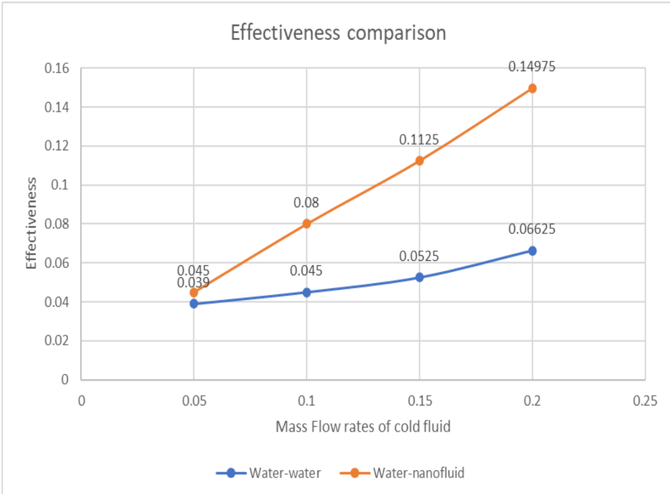

Fig 11 Effectiveness versus mass flow rate of Hot Fluid in Counter Flow arrangement

6. CONCLUSION:

1) In this research work the properties of SiO2 nanofluid were found out and defined in software for various values of concentration factor. The performance of nanofluid is observed to be optimum at concentration factor of 0.4, which was selected to calculate the performance of heat exchanger.

2) In the present research work it is found out that the overall heat transfer coefficient is having a maximum value of 7624.53 Watts/m^2k for the counter flow arrangement of water-water type heat exchanger which is 42% less than the value we obtained for water-nanofluid arrangement, which has a value of 13039.99 Watts/m^2K.

3) It is noted that LMTD for water-nanofluid arrangement was found to be 9.21 K which is greater than water-water arrangement by 24%.

4) The effectiveness of water-nanofluid arrangement was also found to be maximum with a value of 0.149 which is more than that of water-water heat exchanger arrangement by 56% at a volume flow rate of 0.2kg/s of cold water.

5) The maximum heat transfer rate was noted to be increased by an amazing amount of 55% for a mass flow rate of 0.2kg/s water-nanofluid arrangement in comparison to the water-water arrangement which had a value of 2219.11 Watts for the same working conditions.

REFERENCES

[1] Chaiyanan Kamsuwan, Xiaolin Wang, Lee Poh Seng , Cheng Kai Xianc , Ratchanon Piemjaiswang, Pornpote Piumsomboona, Yotsakorn Pratumwal, Somboon Otarawanna, Benjapon Chalermsinsuwan (2022). Simulation of nanofluid micro-channel heat exchanger using computational fluid dynamics integrated with artificial neural network, 9th International Conference on Power and Energy Systems Engineering (CPESE 2022), Doshisha University, Kyoto, Japan, (2022).

[2] Vedant Irabatti, Yash Patil, Sandeep Kore, Vaishnavi Barangule, Abhishek Kothe (2022). Comprehensive review of spiral heat exchanger for diverse applications. Materials Today: Proceedings (2022).

[3] S. Raja, MS. Sivahari Shankar, P. Mathan Kumar , C. Rajaganapathy (2022). Heat transfer analysis and enhancement in shell and tube heat exchanger using copper oxide Nano particles; Materials Today: Proceedings (2022).

[4] Pavushetti Abhilash, Udutha Raghupati, Raghavan Nanda Kumar (2021). Design and CFD analysis of hair pin heat exchanger using aluminium and titanium carbide nanofluids; Materials Today: Proceedings (2021).

[5] N. Parthiban, M. Rajkumar, S.N. Murugesan (2021). Experimental study of comparison in performance of heat exchanger with and without silicon dioxide nano particle used in cold fluid. Materials Today: Proceedings (2021).

[6] Shu-Rong Yana, Hazim Moria , Samira Pourhedayat , Mehran Hashemian (2020). A critique of effectiveness concept for heat exchangers; theoretical-experimental study, International Journal of Heat and Mass Transfer (2020).

[7] J.I. Corcoles , J.D. Moya-Rico, A.E. Molina, J.A. Almendros-Ib anez (2020). Numerical and experimental study of the heat transfer process in a double pipe heat exchanger with inner corrugated tubes. International Journal of Thermal Science (2020).

[8] Miftah Altwieb, Krzysztof J. Kubiak, Aliyu M. Aliyu, Rakesh Mishra (2020). A new three-dimensional CFD model for efficiency optimisation of fluid-to-air multi-fin heat exchanger. Thermal Science and Engineering Progress (2020).

[9] A. Zargoushi, F. Talebi, S.H. Hosseini (2019). CFD modeling of industrial cold box with plate-fin heat exchanger: Focusing on phase change phenomenon. International Journal of Heat and Mass Transfer (2019).

[10] Chamil Abeykoon (2019). Compact heat exchangers – Design and optimization with CFD. International Journal of Heat and Mass Transfer 146 (2020) 118766

[11] P.C. Mukesh Kumar, M. Chandrasekar (2019). CFD analysis on heat and flow characteristics of double helically coiled tube heat exchanger handling MWCNT/water nanofluids. Heliyon 5 (2019) e02030

[12] A. Natarajan, R. Venkatesh, S. Gobinath, L. Devakumar, K. Gopalakrishnan (2019) CFD simulation of heat transfer enhancement in circular tube with twisted tape insert by using nanofluids. Materials Today: Proceedings (2019).