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Design & Development of Triple Pipe Concentric Heat Exchanger

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Abstract: In this numerical and experimental study, a triple concentric tube heat exchanger (TCTHE) is designed and fabricated which consists of two copper tubes and one steel tube of diameter 12 mm, 26 mm and 40 mm respectively and the length of the tubes are 1380 mm, 1350 mm and 1300 mm, respectively. The thickness of the outer, middle and inner tubes are 1 mm. The objective of this study is to reduce the length and material cost as well as increase the heat transfer surface area by adding an intermediate tube to the double concentric tube heat exchanger. The performance of the heat exchanger and mass flow rates are estimated and analyzed. From the experimental and ANSYS results, found that overall heat transfer coefficient of the equivalent double concentric tube heat exchanger is compared with that of the TCTHE and found better performance. For the same heat transfer area, the length of the heat exchanger is 65.17% reduced compared to double tube heat exchanger.
Keywords: Heat exchanger, Triple concentric tube, Overall heat transfer coefficient, Logarithmic mean temperature difference.

I. INTRODUCTION

Heat exchanger is used to transfer heat from one fluid to another. The basic component of a heat exchanger can be observed as a tube with one fluid running through it and another fluid flowing on the outside. The simple context of heat exchanger is one for which the hot and cold fluids move in the same or opposite directions in a concentric tube construction. In the parallel-flow arrangement, the hot and cold fluids enter at the same end, flow in the same direction, and leave at the same end. In the counter flow arrangement, the fluids enter at opposite ends, flow in opposite directions, and leave at opposite ends. In the TPCHE, there are three sections: central tube, inner annular space and outer annular space. Heat transfer mediums are passed through the central tube and outer annular space and a thermal fluid is passed through an inner annular space as shown in Fig. 1.

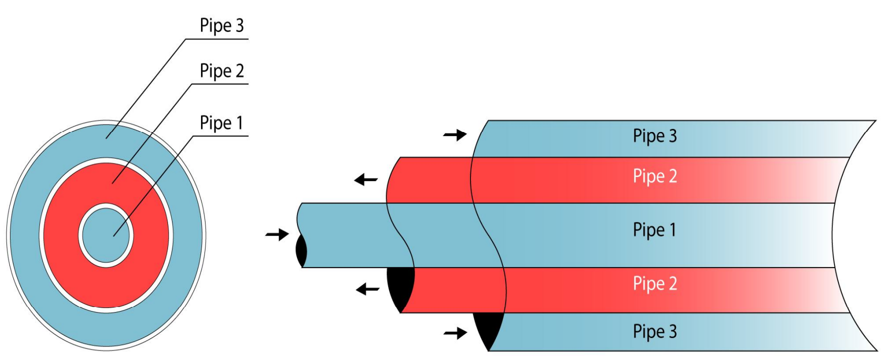

Fig1. Triple pipe concentric assembly with fluid direction

II. LITERATURE REVIEW

A. Review of triple concentric heat exchanger
B. Experimental Analysis of a Triple Concentric Tube Heat Exchanger
C. Design Development and Heat Transfer Analysis of a Triple Concentric Tube Heat Exchanger
D. Thermal-hydraulic characteristics and optimization of a liquid-to-suction triple-tube heat exchanger
E. Sizing of triple concentric pipe heat exchanger

III. NUMERICAL DESIGN PROCEDURE

In the present work, at first a TCTHE is designed by LMTD method by considering a known set of input values as given in table 1.Then by finding the length, drawing the TCTHE setup by using Illustartor as shown in figure 1.

Table I
Input Parameters for Calculation of TPCHE

Input parameters	Symbols	Values
Hot water inlet temperature, ˚C	T_{Hi}	60
Hot water outlet temperature, ˚C	T_{Ho}	48
Cold water (C1) inlet temperature, ˚C	Tc_{1i}	27
Cold water (C2) inlet temperature, ˚C	Tc_{2i}	27
Volumetric flow rate of hot water, lit/hr	$\dot{V}_H$	150
Volumetric flow rate of cold water (C1), lit/hr	$\dot{V}_{c1}$	100
Volumetric flow rate of cold water (C2), lit/hr	$\dot{V}_{c2}$	100
Diameter of central pipe, mm	d_1	12
Diameter of intermediate pipe, mm	d_2	26
Diameter of outer pipe, mm	d_3	40
Thickness of each pipe, mm	t	1
Specific heat of hot water, $j/_{kg.k}$	C_{PH}	4183
Thermal conductivity of copper, $W/_{m.k}$	K_{copper}	401

NOTATION

A Heat transfer area (m2)
Cp Specific heat (J/kg K)
d Diameter (m)
k Thermal conductivity
$\dot{m}$ Mass flow rate (lit/sec)
Pr Prandlt number
Q Heat flow rate (W)
Re Reynolds number
T Temperature (oC)
U Overall heat transfer coefficient (W/m2 K)
*Uo1*Overall heat transfer co-efficient based on outside area of central tube (W/m2 K)
Ui2 Overall heat transfer co-efficient based on inside area of middle tube (W/m2K)
v Volumetric flow rate (m3/s)
V Linear velocity (m/s)
ρ Density (kg/m3)
μ Dynamic viscosity (Pa.s)
α Coefficient of heat transfer (W/m2 K)
Δ Difference

$\dot{m}_{c1} = \dot{m}_{c2} = 0.02772 \, kg/sec$

$\dot{m}_{H} = 0.04124 \, kg/sec$

The outlet temperatures of cold water streams (C1 & C2) are calculated by steady state energy balance equation.

$$\dot{Q}_H = \dot{Q}_{c1} + \dot{Q}_{c2}$$

$$\dot{m}_H C_{PH}(T_{Hi} - T_{Ho}) = \dot{m}_{c1} C_{Pc1}(T_{c1o} - T_{c1i}) + \dot{m}_{c2} C_{Pc2}(T_{c2o} - T_{c2i}) \quad \text{.....................................(1)}$$

0.04124*4183(60-48) = 0.02772*4183(T_{c1o} -27) + 0.02772*4183(T_{c2o} -27)

8331.52 = 115.95*T_{c1o} + 115.95*T_{c2o}

$\boxed{T_{c1o} = T_{c2o} = 35.92°C}$

A. Inner Tube Heat Transfer Co-efficient

1) Bulk Mean Temperature Of Cold Water Is Given As

$$T_{B1} = \frac{T_{Ci} + T_{Co}}{2} = 31.46°C$$

Thermo physical properties of cold water at T_b =304.96 K

Properties	Symbols	Values
Density	$\rho c1$	995.20 kg/m^3
Thermal conductivity	$Kc1$	0.6052 $W/m.k$
Specific heat	$Cpc1$	4183 $j/kg.k$
Viscosity	$\mu c1$	0.007748 $Pa \cdot S$
Pradantl number	$\Pr c1$	5.357

2) Linear Velocity of cold water C1

$$Vc1 = \frac{\dot{m}_{c1} * 4}{\rho c1 * \Pi * d_1^2} = \frac{0.02772 * 4}{995.20 * \Pi * (0.012)^2}$$

$$Vc1 = 0.246 \, m/\sec$$

3) Reynolds no.

$$\mathrm{Re}_{c1} = \frac{\rho_{c1} * Vc1 * d_1}{\mu_{c1}} = \frac{995.20 * 0.246 * 0.012}{0.0007748}$$

$$\mathrm{Re}_{c1} = 3791.72$$

4) *Nusselt* no.

$$Nu_{c1} = \frac{(\frac{f}{2}) * (Re_{c1} - 1000) * Pr_{c1}}{1 + 12.7 * (\frac{f}{2})^{1/2} (Pr_{c1}^{2/3} - 1)}$$

$$= \frac{(\frac{0.01054}{2}) * (3791.72 - 1000) * 5.357}{1 + 12.7(\frac{0.01054}{2})^{1/2} * ((5.357)^{2/3} - 1)}$$

$$Nu_{c1} = 27.17$$

5) *Convective Heat Transfer Co-efficient*

$$\alpha_{c1} = \frac{Nu_{c1} * K_{c1}}{d_1} = \frac{27.17 * (0.6052)}{0.012}$$

$$\alpha_{c1} = 1370.27 W/m^2 K$$

B. Intermediate Tube Heat Transfer Co-Efficient

Bulk mean temperature of hot water is given as:

$$T_{B2} = \frac{T_{Hi} + T_{Ho}}{2} = \frac{60 + 48}{2} = 54°C$$

Thermo physical properties of cold water at T_b =327.5 K

Properties	Symbols	Values
Density,	ρ_H	986.16 kg/m^3
Thermal conductivity,	K_H	0.6349 $W/m.k$
Specific heat,	C_{PH}	4182 $j/kg.k$
Viscocity,	μ_H	0.0005127 $Pa \cdot s$
Pradantl number,	Pr_H	3.3776

Linear velocity of Hot water

$$V_H = \frac{\overset{\circ}{m}_H * 4}{\rho_H * \Pi * (d_2^2 - D_1^2)} = \frac{0.04124 * 4}{986.16 * \Pi * ((0.026)^2 - (0.014)^2)}$$

$$V_H = 0.1109 m/\sec$$

Reynolds no.

To obtain Reynolds number Hydraulic Diameter

$$d_{h2} = d_2 - D_1 = 0.026 - 0.014$$

$$d_{h2} = 0.012m$$

$$\mathrm{Re}_H = \frac{\rho_H * V_H * d_{h2}}{\mu_H} = \frac{986.16 * 0.1109 * 0.012}{0.0005127}$$

$$\mathrm{Re}_H = 2559.74$$

Nusselt no.

$$Nu_H = 2.718 * \mathrm{Re}_H^{0.597} * \mathrm{Pr}_H^{1/3} * (\frac{d_{h2}}{1.193})^{2/3}$$

$$Nu_H = 2.718 * (2559.74)^{0.597} * (3.3776)^{1/3} * (\frac{0.012}{1.193})^{2/3}$$

$$Nu_H = 20.58$$

Convective Heat Transfer Co-efficient

$$\alpha_H = \frac{Nu_H * K_H}{d_{h2}} = \frac{20.58 * (0.6349)}{0.012}$$

$$\alpha_H = 1088.85 W/m^2 K$$

C. Outer Tube Heat Transfer Co-Efficient

Bulk mean temperature of cold water is given as**:**

$$T_{B3} = \frac{T_{c1i} + T_{c20}}{2} = \frac{27 + 35.92}{2} = 31.46°C$$

Thermo physical properties of cold water at T_b =304.96 K

Properties	Symbols	Values
Density,	$\rho c1$	995.20 kg/m^3
Thermal conductivity,	$Kc1$	0.6052 $W/m.k$
Specific heat,	$Cpc1$	4183 $j/kg.k$
Viscosity,	$\mu c1$	0.007748 $Pa \cdot s$
Prandatl number,	$\Pr c1$	5.357

Linear velocity of Cold water C2

$$V_{c2} = \frac{\dot{m}_{c2} * 4}{\rho_{c2} * \Pi * (d_3^2 - D_2^2)} = \frac{0.02772 * 4}{995.20 * \Pi * ((0.040)^2 - (0.028)^2)}$$

$$V_{c2} = 0.04346\, m/\sec$$

1) Reynolds no

To obtain Reynolds number Hydraulic Diameter

$$d_{h3} = d_3 - D_2 = 0.040 - 0.028$$

$$d_{h3} = 0.012m$$

$$\mathrm{Re}_{c2} = \frac{\rho_{c2} * V_{c2} * d_{h3}}{\mu_{c2}} = \frac{995.20 * 0.04346 * 0.012}{0.0007748}$$

$$\mathrm{Re}_{c2} = 669.87$$

2) Nusselt no

$$Nu_{c2} = 0.51 * \mathrm{Re}_{c2}^{0.5} * \mathrm{Pr}_{c2}^{1/2} * (\frac{\mathrm{Pr}_{c2}}{\mathrm{Pr}_{co2}})^{0.25}$$

$$Nu_{c2} = 0.51 * (669.87)^{0.5} * (5.357)^{1/3} * (1)^{0.25}$$

$$Nu_H = 23.09$$

3) Convective Heat Transfer Co-efficient

$$\alpha_{c2} = \frac{Nu_{c2} * K_{c2}}{d_{h3}} = \frac{23.09 * (0.6052)}{0.012}$$

$$\alpha_H = 1164.50\, W/m^2 K$$

D. Overall Heat Transfer Co-Efficient

1) Based On Outside Area Of Central Pipe

$$\frac{1}{U_{o1}} = \frac{D_1}{d_1 * \alpha_{c1}} + \frac{D_1 * \ln(\frac{D_1}{d_1})}{2 * K_{copper}} + \frac{1}{\alpha_H}$$

$$\frac{1}{U_{o1}} = \frac{0.014}{0.012 * (1370.27)} + \frac{0.014 * \ln(\frac{0.014}{0.012})}{2 * 401} + \frac{1}{1088.85}$$

$$U_{o1} = 564.30\, W/m^2 K$$

2) *Based On Inside Area Of Intermediate Pipe*

$$\frac{1}{U_{i2}} = \frac{d_2}{D_2 * \alpha_{c2}} + \frac{D_2 * \ln(\frac{D_2}{d_2})}{2 * K_{copper}} + \frac{1}{\alpha_H}$$

$$\frac{1}{U_{i2}} = \frac{0.026}{0.028 * (1164.50)} + \frac{0.026 * \ln(\frac{0.028}{0.026})}{2 * 401} + \frac{1}{1088.85}$$

$$U_{o1} = 564.30 W/m^2 K$$

3) *Based On Inside Area Of Intermediate Pipe*

$$m_H * C_{PH} * (T_{Hi} - T_{Ho}) = U_{i1} * \Pi * D_1 * L * \Delta T_{im1} + U_{i2} * \Pi * d_2 * L * \Delta T_{im2}$$

$$m_H * C_{PH} * (T_{Hi} - T_{Ho}) = U_{i1} * \Pi * D_1 * L * \frac{((T_{Hi} - T_{c1o}) - (T_{Ho} - T_{c1i}))}{\ln(\frac{(T_{Hi} - T_{c10})}{(T_{Ho} - T_{c1i})})} + U_{i2} * \Pi * d_2 * L * \frac{((T_{Hi} - T_{c2o}) - (T_{Ho} - T_{c2i}))}{\ln(\frac{(T_{Hi} - T_{c20})}{(T_{Ho} - T_{c2i})})}$$

$$0.04124 * 4182 * (60 - 48) = (564.30) * \Pi * 0.014 * L * \frac{((60 - 35.92) - (48 - 27))}{\ln(\frac{24.08}{21})} + (582.27) * \Pi * (0.026) * L * \frac{((60 - 35.92) - (48 - 27))}{\ln(\frac{24.08}{21})}$$

$$2069.58 = L * (558.55 + 1070.11)$$

$$L_{TTHE} = 1.270 m$$

⇨ Length of triple pipe heat exchanger is 1.270 meter.

E. Double Pipe Heat Exchanger Calculations

The area enclosed by solid rectangle represents triple tube heat exchanger. In case of triple tube heat exchanger, three fluid streams enter and leave the exchanger. On the other hand, there are only two fluid streams entering and leaving the dashed box, one being the hot fluid and the other being the cold fluid. This is similar to double tube heat exchanger with the flow beings in a counter-current mode and hence is an equivalent double tube heat exchanger that can be used to replace the triple tube heat exchanger.

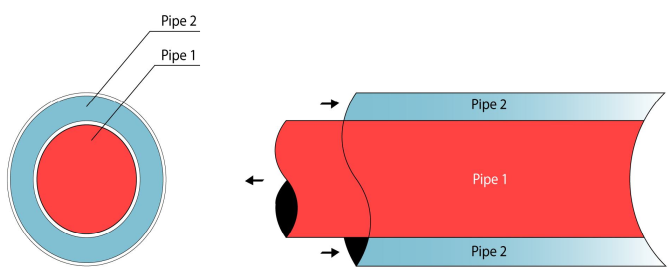

Fig2. Double pipe concentric assembly with fluid direction

Here,

$$\mathring{m}_c = 0.02772 \, {}^{kg}\!/_{\sec}$$

$$\mathring{m}_H = 0.04124 \, {}^{kg}\!/_{\sec}$$

$$T_{Co} = 44.85°C$$

1) Logarithmic Mean Temperature Difference

$$\Delta T_m = \frac{((T_{Hi} - T_{c1o}) - (T_{Ho} - T_{ci}))}{\ln(\frac{(T_{Hi} - T_{co})}{(T_{Ho} - T_{ci})})}$$

$$\Delta T_m = \frac{((60 - 48) - (48 - 27))}{\ln(\frac{(60 - 48)}{(48 - 27)})}$$

$$\Delta T_m = 16.082°C$$

2) Heat Transfer rate,

$$\dot{Q} = \mathring{m}_H * C_{PH} * (T_{Hi} - T_{Ho})$$

$$\dot{Q} = (0.04124) * (4183) * (60 - 48)$$

$$\dot{Q} = 2070.08W$$

3) Logarithmic mean Area,

$$A_{im1} = \Pi * \frac{(D_1 - d_1)}{\ln(\frac{D_1}{d_1})} * L$$

$$A_{im1} = \Pi * \frac{(0.028 - 0.026)}{\ln(\frac{0.028}{0.026})} * 1.270$$

$$A_{im1} = 0.1076m^2$$

$$A_{im2} = \Pi * \frac{(D_2 - d_2)}{\ln(\frac{D_2}{d_2})} * L$$

$$A_{im2} = \Pi * \frac{(0.042 - 0.040)}{\ln(\frac{0.042}{0.040})} * 1.270$$

$$A_{im2} = 0.1635m^2$$

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Logarithmic mean area of Double pipe heat exchanger is equal to sum of the two logarithmic mean area of triple pipe heat exchanger

$$A_{im} = A_{im1} + A_{im2}$$
$$A_{im} = 0.1076 + 0.1635$$

$$A_{im} = 0.2711 m^2$$

F. Overall Heat Transfer Co-Efficient

$$U = \frac{\dot{Q}}{A_{im} * \Delta T_{im}} = \frac{2070.08}{(0.2711)*(16.082)}$$

$$U = 474.80 W/m^2 K$$

G. Length of Double pipe heat exchanger

$$A_{im} = \Pi * d_1 * L_{DTHE}$$
$$0.2711 = \Pi * (0.026) * L_{DTHE}$$

$$L_{DTHE} = 3.3189 m$$

Double pipe Heat exchanger	L_{DTHE}	**3.3189 m**
Triple pipe Heat exchanger	L_{TPCHE}	**1.2700 m**

As per assumed inputs calculations is performed for Triple pipe concentric heat exchanger and also for double pipe heat exchanger and comparing both heat exchangers length we achieved **61.74%** Reduction in length of TPCHE as compared to DTHE.

IV. ANSYS IMPLEMENTATION & CFD ANALYSIS

The geometry using the calculated geometrical dimensions. The software used for CFD analysis is ANSYS Workbench. Modelling was done in ICEM; meshing was done using ICEM only; simulations were carried out in FLUENT. CFD Post was used for respective graphics of temperature contours, streamlines, volume rendering, planar heat distribution graphics, etc.

A. Modeling

Model of the TPCHE was created in ICEM. The dimensions of the model were as specified in Table 1. However, the length of the TPCHE was rounded off to 2m. The model is as shown in Figure 3.

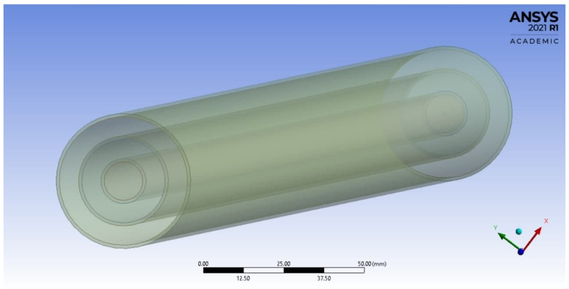

Fig3. Model of TPCHE

B. Meshing

Block meshing was used to mesh our geometry. Block meshing uses blocks to cover the whole geometry. These blocks are then split. Meshing was done using block meshing and the total mesh count was adjusted to around 2.5 lakhs so that the simulation is run in our system conveniently. The meshing is shown in Figure 4.

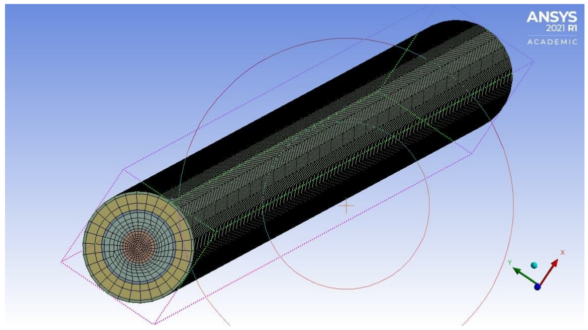

Fig4. Meshed model of TPCHE

C. Simulation

The simulation of the model was run in ANSYS. The k-Ɛ realizable model was used to solve the simulation. Boundary conditions were specified; various other requirements like temperature inlets and outlets, flow velocity, material properties of all material used viz. Copper for 2 tubes and stainless steel for outer tube, water. Our main aim was to check the overall heat transfer rate on all the surfaces.

D. Temperature Contours

Temperature contours for flow of water in the innermost tube, temperature contour for flow of oil in the intermediate tube and that of water in the outermost annulus is shown in figure 5,6 and 7.

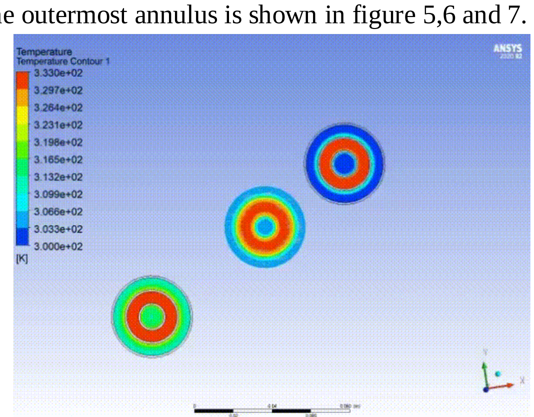

Fig5. Temperature gradients of water at 3 stages

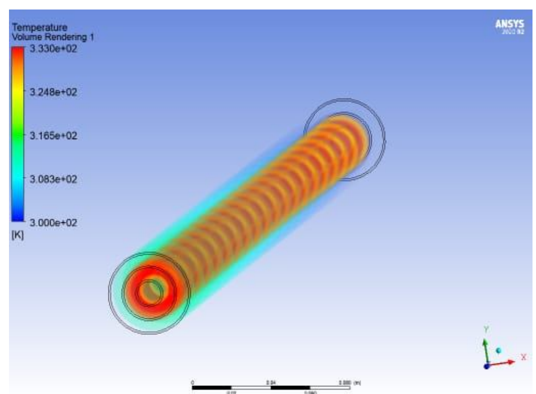

Fig6. Temperature Variation of hot water

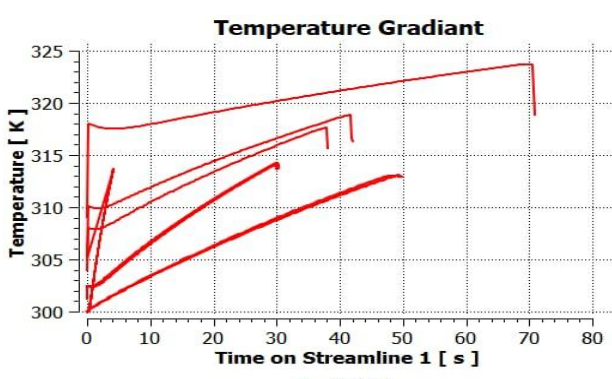

Fig7. Temperature gradient graph

E. CFD Results

Above discussion much talks about the results achieved by CFD analysis. However, the overall heat transfer co-efficient results are given in graph figures 8 and 9. We see results are close to analytical calculations. The minute difference might be due to calculation errors like rounding off, etc. However, our aim seems achieved through CFD. Thus, CFD results permit us to go ahead with fabrication.

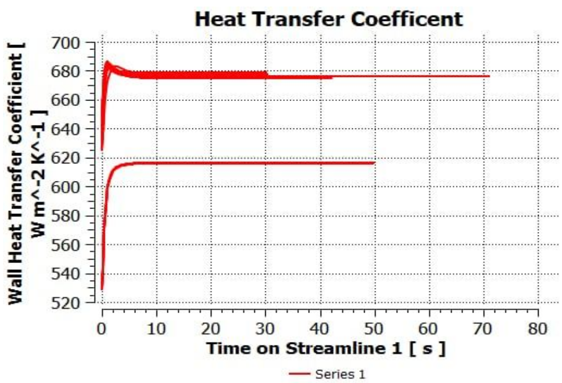

Fig8. Actual heat transfer coefficient graph

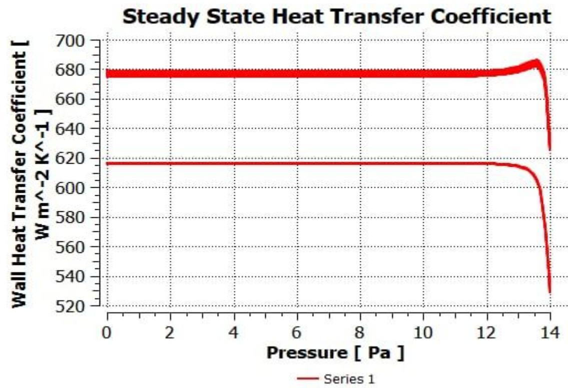

Fig9. Steady State heat transfer coefficient graph

V. FABRICATION, SYSTEM INTEGRATION AND EXPERIMENTAL INVESTIGATION

Experimentation on the TPCHE was carried out in order to predict the thermal performance of the three concentric tube heat exchanger, the outlet temperatures of the fluid flowing through the heat exchanger are to be seen. Experiment was conducted by fabricating the triple tube heat exchanger subjected to one fluid i.e. water ; cold water flowing in inner tube and outer annulus and hot water flowing through inner annulus of the heat exchanger. A triple concentric tube heat exchanger was fabricated for experimentation. The Two tubes used are made of Copper and one is made of Stainless steel. Outside diameters of the three tubes are 0.0127 m, 0.0254 m and 0.0381 m respectively with thickness of each tube as 1 mm only. The fluids are pumped from two different tanks to the heat exchanger. The arrangement of flow of different fluids is called CW-HW-CW (Cold Water- Hot Water - Cold Water). The flow is counter current i.e. water flows in one direction and oil flows in the opposite direction.

Hot water is at inlet temperature 60^{O}C. The Hot water and Cold water starts flowing from the tank through the pump, and enters the heat exchanger inlet. Digital thermometer is used to measure the readings on inlet and outlet water temperatures. Experimental setup is as indicated in figure 10.

Fig10. Experimental Setup

A. Results of Experimentation

The set of experimental results in terms of temperature variations of different fluids along the length of the heat exchanger for counter current flow under CW-HW-CW arrangement for temperature variation in hot water and cold water is presented in table 2

Table III
Experimental temperature results

TPCHE TEMPERATURE (℃)				
Reading No.	Hot Water		Cold Water	
	Inlet	Outlet	Inlet	Outlet
1	60	44	28	33
2	59	44	28	33
3	58	43	28	32
4	58	44	28	33

VI. RESLUTS AND CONCLUSION

A. The Analytical, CFD and experimental results are as shown in Table 3.

Table IIIII
Comparison of all Temperature results (^{O}C)

	Analytical		CFD		Experimental	
Area	T inlet	T outlet	T inlet	T outlet	T inlet	T outlet
Cold Water (inner tube) ℃	27	35.92	27	35.92	28	33
Hot Water (intermediate tube) ℃	60	48	60	48	58	44
Cold Water (outer tube) ℃	27	35.92	27	35.92	28	32
Overall Heat transfer coefficient $W/m^2 K$	564.30		650		560	

B. Conclusion

The following study we carried out to achieve higher heat transfer rate as compare to double pipe heat exchanger and reduction in material usage and cost. by this study we may get errors in analytical methods so from results we get through analytical method we designed heat exchanger from that geometries run simulation and got 12% of errors between CFD analysis and analytical method, and from experimental investigations by fabrication of system according to geometries according to analytical calculations we got 61.74% of reduction in length.

VII. ACKNOWLEDGMENT

We would like to take this opportunity to bestow our acknowledgements to all the persons who have directly or indirectly been Involved into our work and help us to complete the project. It is the result of many hands, and countless hours from many people. Our thanks go to all those who helped, whether through their comments, feedback, edits or suggestions. We express a deep sense of gratitude for providing a suitable environment, where we can implement our work. Moreover, we would like to thank our guide Prof. Vishal Tailor who has helped us throughout our project development.

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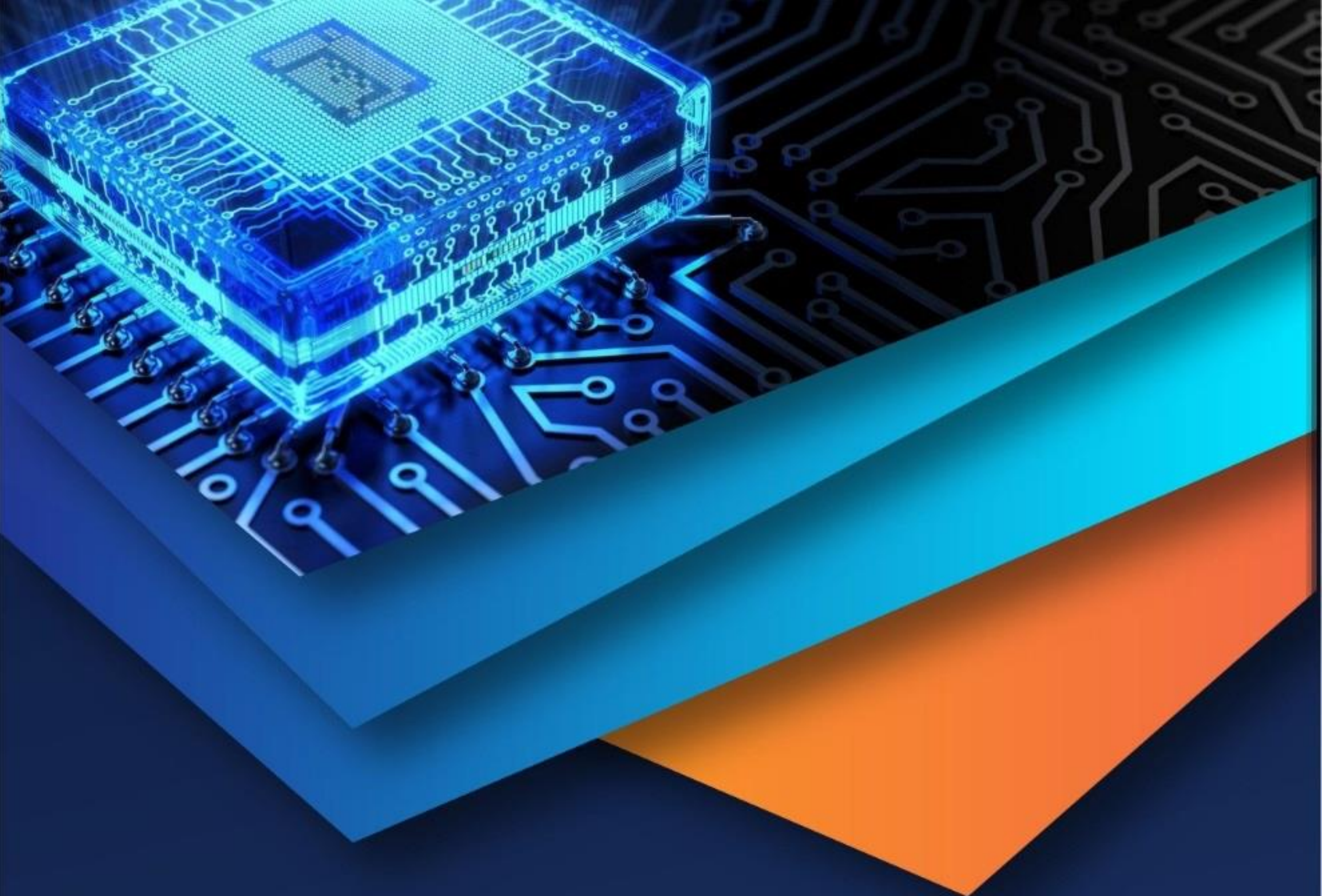

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