Thermal Design, CFD Analysis and Experimentation of Single Stream, Single Phase, Double Helix Helical Coil Heat Exchanger

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Abstract : The importance of coil in shell heat exchanger is recognized in many industrial applications ranging from petrochemical, pharmaceuticals steam and water sampling system (SWAS). The presented study is focused on the thermal design, CFD analysis and experimentation of single stream, single phase, and double helix helical coil heat exchanger. The thermal design is prepared by using the basic equations and the correlations. It focuses mainly on parameter like heat duty, pressure drop, heat transfer area, Overall heat transfer coefficient, length of coil, number of turns, Reynolds number, Prandtl's number, etc.

CFD analysis has been carried out for a coil in shell single stream, single phase, and double helix helical coil heat exchanger. The analysis is done using Star CCM +12.06. Experiment is carried out on heat exchanger, consisting of helical coil with a length of 3 m and tube diameter 1" (25.4mm). The experiment is performed under controlled environmental condition. The hot water flows at sample side and cold water at the cold side. The temperature for the water inlet is fixed at 29.5 deg C whereas the hot water inlet is almost kept at 55 deg C.The key points for the analysis are the outlet temperatures, heat duty and pressure drops for cold side.

During experimentation, in first case both the mass flow rates of hot and cold side are kept contant.Then the outlet temperature of hot as well as cold side, heat duty and pressure drop are monitored. In second case of experimentation, the mass flow rate of cold side is varied up to 500 lph.Then the effect on heat duty and pressure drop is studied. The result obtained from the experiment is stored in data acquisition system which gives the outputs such as heat duty, flow rates, drop in pressure and temperature for the heat exchanger.

Index Terms - Coil in Shell Heat Exchanger, Thermal Design, Parametric Analysis, Data Acquisition System

I. INTRODUCTION

In most Industries, the designing and thermal evaluation of heat exchangers is generally carried out in order to reduce cost, material and energy and to obtain maximum heat transfer. The main challenge in heat exchanger design is to make it compact and to get maximum heat transfer in minimum space. The passive enhancement technique using coiled tube has significant ability in enhancing heat transfer by developing secondary flow in the coil. Due to enhanced heat transfer the study of flow and heat transfer in helical coil tube is of vital importance. Heat exchange between flowing fluids is one of the most important physical process of concern, and a variety of heat exchanger are used in different type of installations, as in process industries, compact heat exchangers, nuclear power plant, HVACs, food processing, refrigeration, etc. The purpose of constructing a heat exchanger is to get an efficient method of heat transfer from one fluid to another, by direct contact or by indirect contact.

In a heat exchanger the heat transfer through radiation is not taken into account as it is negligible in comparison to conduction and convection. Conduction takes place when the heat from the high temperature fluid flows through the surrounding solid wall. The conductive heat transfer can be maximized by selecting a minimum thickness of wall of a highly conductive material. But convection is plays the major role in the performance of a heat exchanger. Forced convection in a heat exchanger transfers the heat from one moving stream to another stream through the wall of the pipe. The cooler fluid removes heat from the hotter fluid as it flows along or across.

Helical coils give better heat transfer characteristics, since they have lower wall resistance & higher process side coefficient. The whole surface area of the curved pipe is exposed to the moving fluid, which eliminates the dead-zones that are a common drawback in the shell and tube type heat exchanger. The spring-like coil of the helical coil heat exchanger eliminates thermal expansion and thermal shock problems, which helps in high pressure operations. Fouling is comparatively less in helical coil type than shell and tube type because of greater turbulence created inside the curved pipes.

However, for highly reactive fluids or highly corrosive fluid coils cannot be used, instead jackets are used. Cleaning of vessels with coils is more difficult than the cleaning of shells and jackets. Coils play a major role in selection of agitation system. Sometimes the densely packed coils can create unmixed regions by interfering with fluid flow. The design of the helical tube in tube type heat exchanger is also a bit complex and challenging.

In this paper, there is explanation in brief about the literature study, thermal design which explains the theoretical formulation, cfd analysis which is based on numerical methods and gives visualization of how actual process is going to take place, experimental analysis which gives idea regarding actual performance of the heat exchanger and at last conclusions.

Applications: Heating systems, Steam water analysis system (SWAS), Refineries, Petrochemical industries.

II. LITERATURE REVIEW

The first attempt has been made by Dean, et al.[1] to describe mathematically the flow in a coiled tube. A first approximation of the steady motion of incompressible fluid flowing through a coiled pipe with a circular cross-section is considered in his analysis. It was observed that the reduction in the rate of flow due to curvature depends on a single variable, K, which is equal to 2(Re) 2r/R, for low velocities and small r/R ratio. Naphon,et al. [2] investigated the thermal performance and pressure drop of a shell and helical coiled tube heat exchanger with and without helical crimped fins. He summarized the phenomenon of heat transfer and flow characteristics of single-phase and two-phase flow in curved tubes including helically coiled tubes and spirally coiled tubes.

Yasuo Mori,et al. [3] presented a research on effect of forced convection on heat transfer in curved pipes. In this present work analysis is made about the pipe inlet condition under uniform wall temperature from temperature field. The result shows for both laminar and turbulent region, approximation for the Nu number in curved coil remains same under uniform heat flux as well as wall condition. Swapnil Ahire, et al.[4] presented a detail investigation on fabrication and analysis of counter flow helical coil heat exchanger Concluded that heat transfer coefficient and overall heat transfer coefficient increases with increase in Reynolds number which is due to increase in velocity of fluid.

A.T Ananthanpillai et al. [5] has explored the design and development of a novel high-performance, compact, counter flow heat exchanger design to utilize cold water to reduce the operating temperature of hot water. He found that helical heat exchangers offer significant advantage in heat exchange over straight tubular heat exchangers due to better mixing caused by the secondary flow in the helical coils.R.K.Patil et al. [6] have presented paper on the design of helical coil heat exchanger to find out the heat transfer coefficients on shell and coil side. They have suggested various correlations taking the reference of standard books such as D.Q.Kern,R.K Shaha.etc.

Shiva Kumar, et al. [7] carried out the experiment on helical coil and straight tube heat exchanger and validate the results using CFD.Results indicated that helical heat exchangers showed 11% increase in the heat transfer rate over the straight tube. Simulation results also showed 10% increase in nusselt number for the helical coils.J.S Jayakumar, et. al, 2008 [8] carried out an experimental study of fluid to fluid heat transfer though a helical coiled tube. Heat transfer characteristics were also studied using CFD code fluent. They observed CFD predictions match reasonably with experimental results for all operating conditions.

Nasser Ghorbanifar,et al.[9], carried out an experiment on study of thermal performance of shell-and-coil heat exchanger. They investigated mixed convection heat transfer in a coil-in-shell heat exchanger and experimental readings are taken for various Reynolds and Rayleigh numbers, various tube-to-coil diameter ratios and dimensionless coil pitch.C. E. Kalb et al.[10]**,** presented a detail investigation on Fully developed heat transfer to viscous flow in curved circular tubes, the investigation is based on numerical solution of the constant-property continuity, Navier-Stokes, and thermal-energy equations. Results for the boundary condition of axially uniform wall heat flux with peripherally uniform wall temperature are presented for Dean Number, Prandtl number and curvature of the tube.

It is observed that most of the researches use various types of co-relations for heat transfer coefficient. In the present study the coil in shell heat exchanger is designed taking the reference of correlations mentioned and verified. Experimentation is also carried out to check whether the correlations matches or not.

III. THERMAL DESIGN

i. Nomenclature:

Tci	Cold fluid inlet temperature
Tco	Cold fluid outlet temperature
mc	Cold fluid mass flow rate
Cpc	Specific heat of cold fluid
µc	Dynamic viscosity of cold fluid
kc	Thermal conductivity of cold fluid
ρc	Density of cold fluid
(Do)sh	Outside diameter shell
ts	Thickness of shell
(Di)sh	Inside diameter shell
(Do)dum 1	Outside diameter of dummy 1
(t)dum 1	Thickness of dummy 1
(Di)dum 1	Inside diameter of dummy 1
(Do)dum 2	Outside diameter of dummy 2
Rs	Shell side resistance
Thi	Hot fluid inlet temperature
Tho	Hot fluid outlet temperature
mh	Hot fluid mass flow rate
Cph	Specific heat of hot fluid
µh	Dynamic viscosity of hot fluid
kh	Thermal conductivity of fluid in coil
kt	Thermal conductivity of coil material
ρh	Density of hot fluid
(do)t	Outside diameter of tube

(x)t	Thickness of tube
(di)t	Inside diameter of tube
P	Pitch of coil
(davg)coil 1	Average diameter of helical coil 1
(di)coil 1	Inside diameter of helical coil 1
(do)coil 1	Outside diameter of helical coil 1
(davg)coil 2	Average diameter of helical coil 2
(di)coil 2	Inside diameter of helical coil 2
(do)coil 2	Outside diameter of helical coil 2
Panu,1	Wetted perimeter of annulus 1
Aanu,1	Area of annulus 1
Dh1	Hydraulic diameter of annulus 1
Aanu,2	Area of annulus 2
Panu,2	Wetted perimeter of annulus 2
Dh2	Hydraulic diameter of annulus 2
Dh	Average hydraulic diameter for shell
v	Velocity of fluid through shell
Re	Reynolds number
Pr	Prandtl's number
Nu	Nusselt number
ho	Shell side heat transfer coefficient
Gs	Mass velocity
f	Friction factor
(ΔPmajor)sh	Shell side major pressure loss
(ΔPminor)sh	Shell side minor pressure loss(head loss)
(ΔPtotal)sh	Shell side total pressure drop
Ac	Cross sectional area of tube
P	Wetted perimeter of tube
Dh	Hydraulic diameter of tube
u	Velocity of fluid through tube
Jh	Colburn factor
hi	Heat transfer coefficient based on inside diameter of tube
ho	Heat transfer coefficient based on outside diameter of tube
hic	Corrected heat transfer coefficient based on inside diameter of tube

ii. Detailed thermal design:

The detailed thermal design is as follows:

A] Parameters which must be known:

❖ Shell Side -

1. Annulus 1-

- Area of annulus-

$$A_{annu,1} = \{\frac{\pi}{4}\left({D_{i_{sh}}}^2 - {D_{o_{dum\,1}}}^2\right) - \left({d_{o_{coil\,1}}}^2 - {d_{i_{coil\,1}}}^2\right)\}$$

- Wetted Perimeter-

$$P_{wet} = \pi * (D_{i_s} + d_{o_{coil\,1}} + d_{i_{coil\,1}} + D_{o_{dum\,1}}$$

- Hydraulic Diameter-

$$\left(D_{hyd}\right)_{Annu,1} = \frac{4 * A_{annu,1}}{(P_{wet})_{annu,1}}$$

2. Annulus 2-

- Area of annulus-

$$A_{annu,2} = \{\frac{\pi}{4}\left({D_{i_{dum\,1}}}^2 - {D_{o_{dum\,2}}}^2\right) - \left({d_{o_{coil\,2}}}^2 - {d_{i_{coil\,2}}}^2\right)\}$$

- Wetted Perimeter-

$$P_{wet} = \pi * (D_{i_{dum\,1}} + d_{o_{coil\,2}} + d_{i_{coil\,2}} + D_{o_{dum\,2}}$$

- Hydraulic Diameter-

$$(D_{hyd})_{annu,2} = \frac{4 * A_{annu,2}}{(P_{wet})_{annu,2}}$$

3. Average hydraulic diameter-

$$(D_{hyd})_{sh} = \frac{(D_{hyd})_{Annu,1} + (D_{hyd})_{annu,2}}{2}$$

4. Velocity of fluid –

$$V = \frac{\dot{m}_c}{\rho * \frac{\pi}{4} * \left[(D_{avg})_{hyd}\right]^2}$$

5. Reynolds Number-

$$Re = \frac{\rho * V * (D_{avg})_{hyd}}{\mu}$$

6. Prandtl's Number-

$$P_r = \frac{\mu * C_p}{K}$$

❖ Coil Side –

1. Cross-sectional area of tube-

$$(A_c)_{tube} = \frac{\pi}{4}\left(d_{i_{tube}}{}^2\right)$$

. Wetted Perimeter-

$$(P_{wet})_{tube} = \pi * (d_{i_{tube}})$$

3. Hydraulic Diameter-

$$D_{hyd,1} = \frac{4 * (A_c)_{tube}}{(P_{wet})_{tube}}$$

B] Calculation of heat transfer coefficient :

❖ Shell Side -

If ,Re<10000,then use,

$$\frac{h_o * (D_{avg})_{hyd}}{K} = 0.6 * R_e{}^{0.5} * P_r{}^{0.31}$$

Otherwise**,**

$$\frac{h_o * (D_{avg})_{hyd}}{K} = 0.36 * R_e{}^{0.55} * P_r{}^{0.333} * (\frac{\mu}{\mu_w})^{0.14}$$

❖ Coil Side -

1. Heat Transfer Coefficient based on inside diameter of tube–

$$hi = J_h * \frac{K_h}{d_{i_{tube}}} * (P_r)^{\left(\frac{1}{3}\right)}$$

2. Corrected Heat Transfer Coefficient –

$$h_{i_c} = h_i * (1 + 3.5 * \frac{d_i}{(D_{avg})_{hyd}})$$

C] Pressure Drop Calculations:

❖ Shell Side –

1. Pressure drop through shell ΔP_s,

$$\Delta Ps = \frac{f * G_t^{\,2} * L * n}{5.22 * 10^{10} * D_e * \emptyset_s * s}$$

2. Reverse pressure loss, ΔP_r

$$\Delta P_r = \frac{4n}{s} * \frac{V^2}{2g}$$

3. Total pressure loss through shell,

$$\Delta P_T = \Delta P_s + \Delta P_r$$

D] Determine required area,A:

1. Heat Duty,Q

$$Q = m_h * C_{p_h} * (T_{h_I} - T_{h_o})$$

2. Overall heat transfer coefficient,U,

$$\frac{1}{U} = \frac{1}{h_o} + \frac{do}{2K_m} * \ln\left(\frac{do}{di}\right) + \frac{do}{h_{i_c} * di}$$

3. LMTD,ΔTlm,

$$\Delta T_{lm} = \frac{(T_{h_i} - T_{c_o}) - (T_{h_o} - T_{c_i})}{\ln\frac{(T_{h_i} - T_{c_o})}{(T_{h_o} - T_{c_i})}}$$

4. Corrected LMTD,(ΔTlm)c,

$$(\Delta T_{lm})c = 0.99 * \Delta T_{lm}$$

5. Heat transfer area required, A

$$A = \frac{Q}{U * (\Delta T_{lm})c}$$

E] No of turns of coil required, N

$$N = \frac{A}{\pi * d_o * (\frac{L}{N})}$$

F] Height of cylinder needed,

$$H = (n * p) + d_o$$

IV. CFD ANALYSIS

Computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical analysis and data structures to solve and analyze problems that involve fluid flows. Computers are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by conditions. Solution initialization is done by the STAR CCM + 12.06.

The Navier stokes equations form the basis of all CFD problems. In the continuity equation, energy equation and Navier-stoke momentum equation governs the flow of the fluid in the curve tubes. Continuity Equation gives the conservation of mass and is given by,

$$\partial\rho/\partial t + d\rho U1/dx1 + d\rho U2/dx2 + d\rho U3/dx3 = 0$$

$$\partial y/\partial x + \partial V/\partial x = 0$$

And for constant density,

$$\partial\rho/\partial t = 0$$

The momentum balance, (Navier-Stokes equations) follows Newton's 2nd law [7].The two forces acting on the finite element are the body and the surface forces. In CFD programmes, the momentum equation is given as,

$$\rho*(udU/dx + vdV/dx) = -\rho g - (\partial\rho)/\partial x + \mu*(d2y/dx2)$$

The governing energy equation is given by:

$$\rho cp*(udT/dx + vdV/dy) = k*(d2T/dy2)$$

Turbulence is created because of the unstable nature of the fluid flow. The flow becomes turbulent for higher Reynolds number. In this model the k-ε (turbulent kinetics energy "k" and the turbulent dissipation "ε") model is used. The time constant for turbulence is determined from the turbulent kinetic energy and dissipation rate of turbulent kinetic energy

$$\tau = k/\varepsilon$$

Computational fluid dynamics (CFD) study of the system starts with the construction of desired geometry and mesh for modelling the dominion. Generally, geometry is simplified for the CFD studies. Meshing is the discretization of the domain into small volumes where the equations are solved by the help of iterative methods. Modelling starts with the describing of the boundary and initial conditions for the dominion and leads to modelling of the entire system. Finally, it is followed by the analysis of the results, conclusions and discussions [8].

i. Geometry:

The model of double helix helical coil heat exchanger is built in Solid Edge V19,as per the specification given in table no1.The fluid volume extraction from the heat exchanger is done in Star CCM 12.06. It is a counter-flow heat exchanger. First, the internal volume is extracted from the coil in 3D CAD Model Section. This model is bought in the main screen by closing 3D CAD Model Section.

The geometry with different named sections is as shown below-

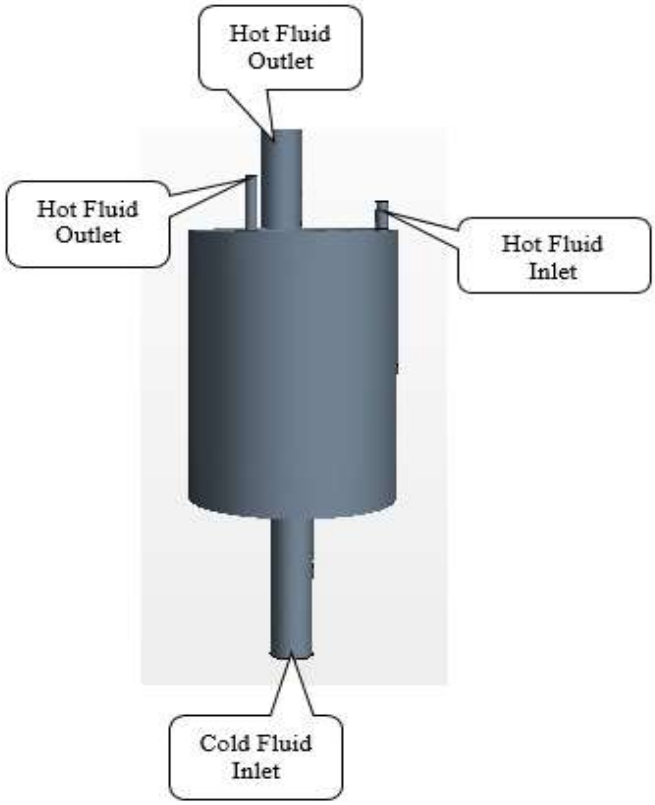

Fig 1.Geometry used for simulation with named sections.

Fig.2 Opaque view of geometry in Star CCM.

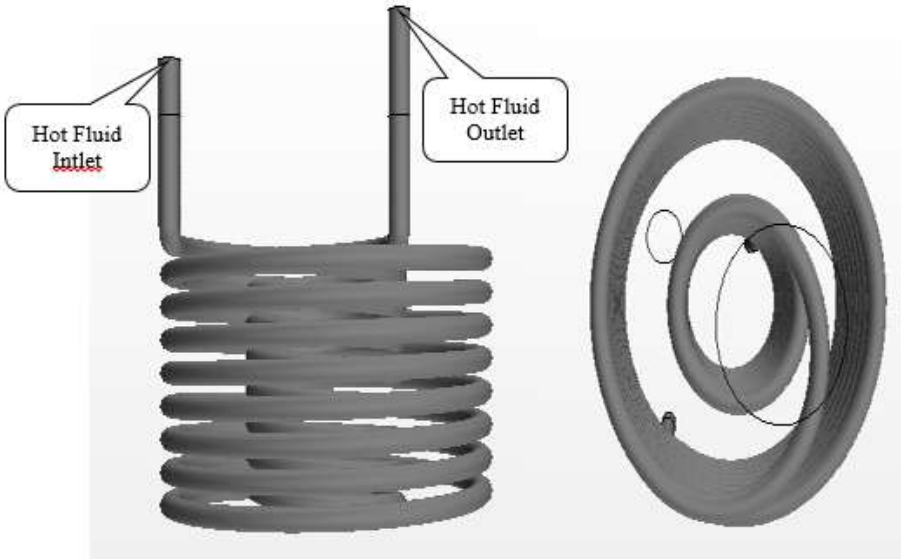

Fig 3.Coil used in assembly

Fig 1 shows the complete assembly of the shell and coil heat exchanger. The inlets and outlets are labelled for both hot and cold side. Fig 2 shoes the coil used in the assembly. The inlets and outlets are as per defined in the figure. There are two vies which gives the complete idea of the coil structure. Fig 3 shows the opaque view of the assembly. With this one can get the clear idea regarding assembly.

ii. Meshing:

In the development of CFD models, the development of a good quality computational mesh is considered the most critical step. The computational mesh must not only accurately describe the flow geometry, but it also must appropriately discretize the volume for both the closure models and solvers to be applied. For meshing of the geometry, it necessary to define the base size. In this project, many cases are studied by considering various base sizes. Once the base size is decided then target surface size and the minimum surface sizes are fixed. The target surface size and minimum surface size are selected on the basis of relative percentage of base size. Various sets of target surface sizes and minimum surface sizes are also studied. For meshing parameters like polyhedral mesh, thin mesh etc. are selected. Along with this prism layer are also added. The prism layer is added as there is tube section in the geometry and we want the fine mesh in that region so that the simulation error decrease. The following figures shows the meshed geometry and its section respectively. From cross-section we come to know that the prism layers are particularly taken for the tube as the tube thickness is the smallest thick part in the geometry.

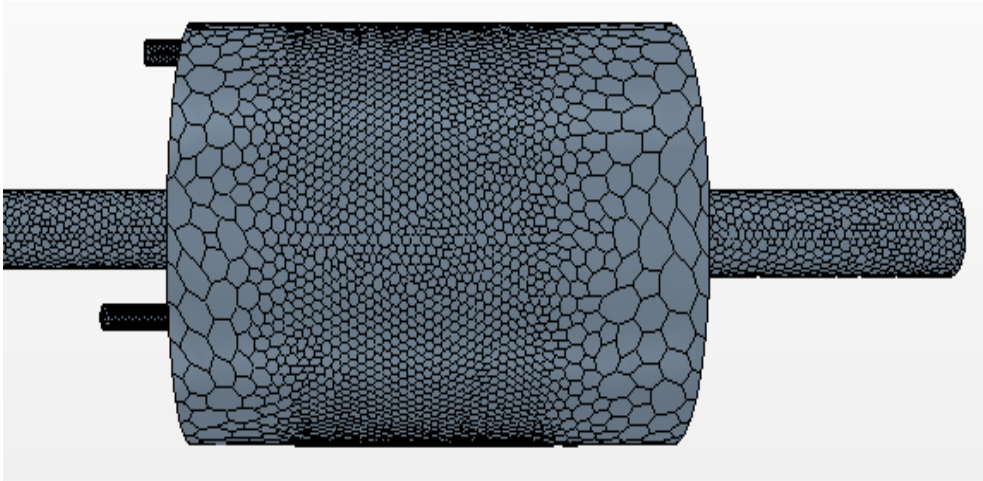

Fig.4.Mesh with base size 8 mm.

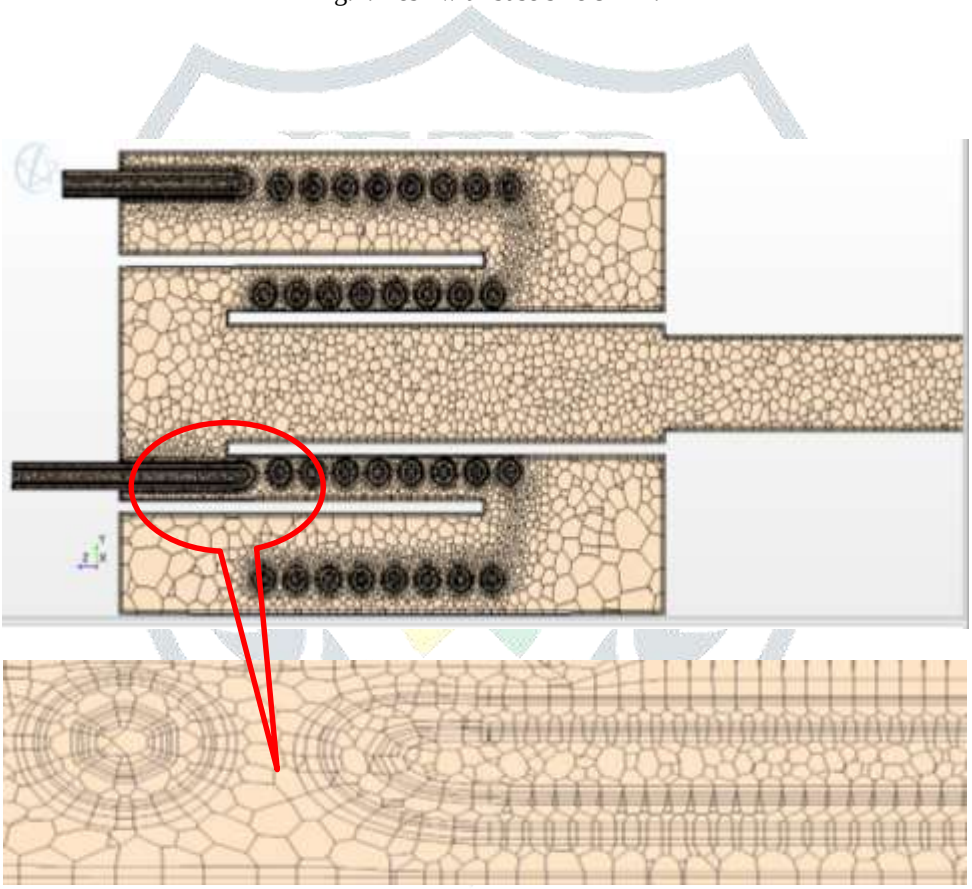

Fig.5.Cross Section of the mesh.

iii. Boundary Conditions:

Boundary conditions are used according to the need of the model. The inlet and outlet conditions are defined as mass flow inlet and pressure outlet. As this is a counter-flow with one coil and one shell there are two inlets and two outlets. The walls are separately specified with respective boundary conditions. No slip condition is considered for each wall. Except the coil and shell walls each wall is set to zero heat flux condition. The details about all boundary conditions can be seen in the table as given below.

Table 1.Boundary Conditions

Element	Boundary condition type	Mass flow magnitude(kg/s)	Temperature (deg C)
Coil_in	Mass flow inlet	0.006944	55
Coil_out	Pressure outlet	-	-
Shell_in	Mass flow inlet	0.029166	29.5
Shell_out	Pressure outlet	-	-

iv. Models:

Energy is set to ON position. The pressure based realizable K-€ turbulent model is selected under the solution setup. The following models are selected for the analysis:

For liquid:

a) Three Dimensional
b) Steady
c) Liquid-water
d) Segregated Fluid Flow
e) Constant Density
f) Turbulence
g) K-Epsilon Turbulence
h) Segregated Fluid temperature

For Fluid:

a) Three Dimensional
b) Steady
c) Solid-Stainless Steel
d) Segregated Solid energy
e) Constant Density.

v. Simulation Analysis:

The simulation is done using Star CCM+ 12.06 version.Scalers and vectors are plotted to understand the physical phenomenon of heat transfer. The scalers and the vectors are as shown below:

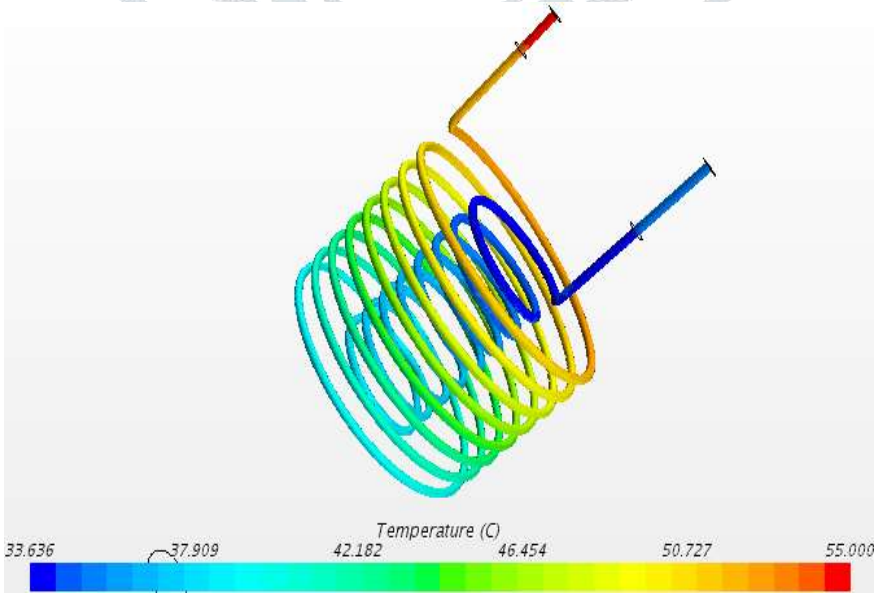

Fig.6.Scaler Scene of Coil

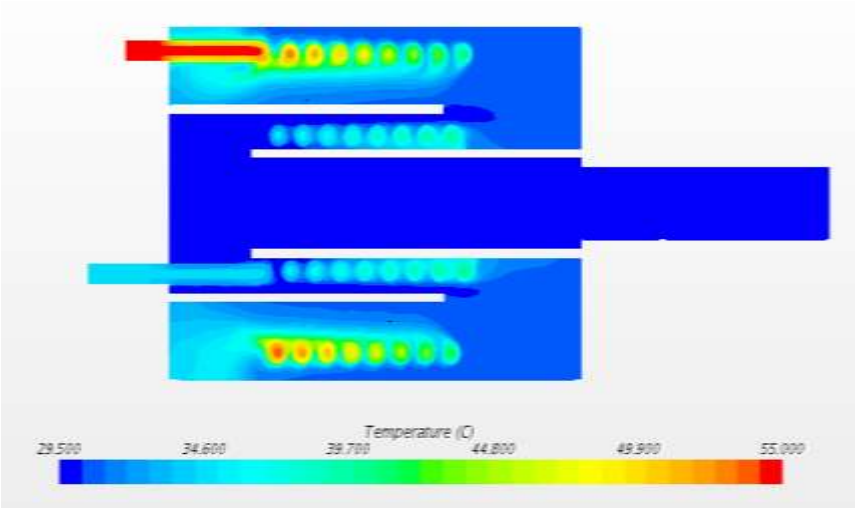

Fig.7.Scaler Scene of cross-section of geometry

From fig 6 and fig 7,we come to know that there is uniform temperature distribution of the heat transfer.

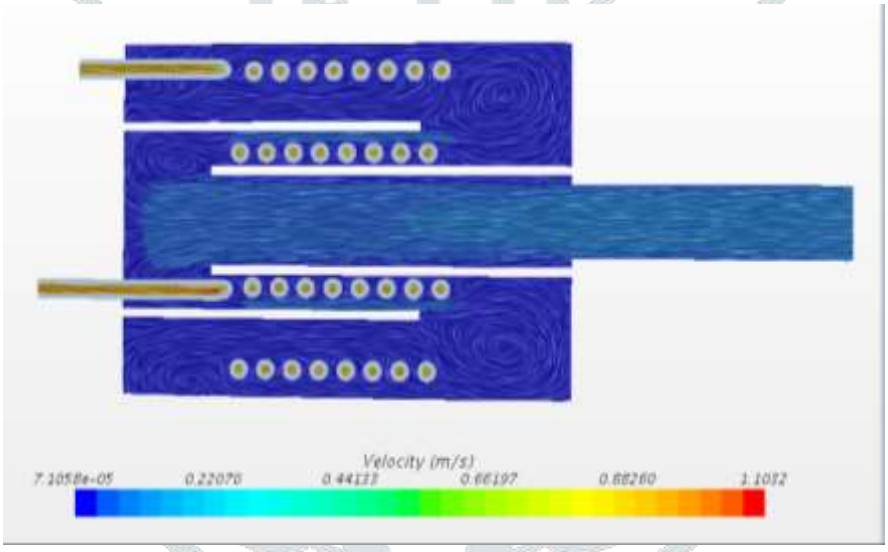

Fig 8.Vector Scene for Velocity Contour

The vector scene for velocity contour is as shown in fig 8.From that we come to know that there is eddies formation at the corners. These eddies are responsible for more turbulance.As more turbulence takes place there is more heat transfer between cold fluid and hot fluid. This can be understood better by studying the fig 7 and fig 8 together.

V. EXPERIMENTATION

Experiment was conducted on a coil in shell heat exchanger test rig. A experimental setup of coil in shell is shown in Figure.1

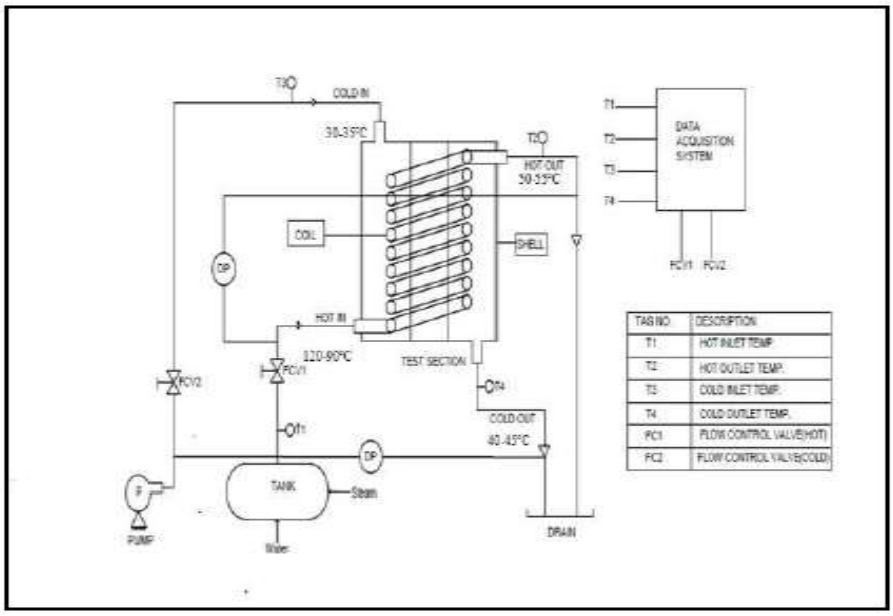

Fig.9. Experimental setup of Coil in shell heat exchanger.

i. Experimental Procedure:

The setup primarily consists of three major parts viz., coil in shell heat exchanger, and flow control valves and data acquisition system. The inlet as well as outlet of both the fluids is arranged in such a way that they produce a counter flow pattern for the experimentation. Experimental Procedure

1. Ensure all the power, fluid line, and drain line connections are checked
2. Open the cooling water flow control valve check the cooling water flow, temperature and pressure is sufficient.
3. In case leakage is observed in the cooling water supply line stops the flow rate and check for the leakage.
4. Start the cooling water supply and adjust the supply flow rate as per the requirement.
5. Operate rotameter and adjust the desired sample flow rate of rotameter.
6. In case sample flow rate is not achieved, operate the pressure regulator and check for the sample flow rate.
7. Check for the sample outlet temperature for every 15min.If the outlet is desired stop the procedure else vary the sample flow rate and check for the outlet temperature. 8. Reading is taken from the data acquisition system.

Experiment was conducted on a coil in shell heat exchanger, and flow control valves and data acquisition system. During experimentation, in first case both the mass flow rates of hot and cold side are kept contant.Then the outlet temperature of hot as well as cold side, heat duty and pressure drop are monitored. In second case of experimentation, the mass flow rate of cold side is varied up to 500 lph.Then the effect on heat duty and pressure drop is studied.

VI. RESULTS AND DISCUSSION

After the experimentation analysis of result is done. The major concern is on the heat duty and pressure drop. The CFD results are also studied. The graphs are plotted for the respective as follows-

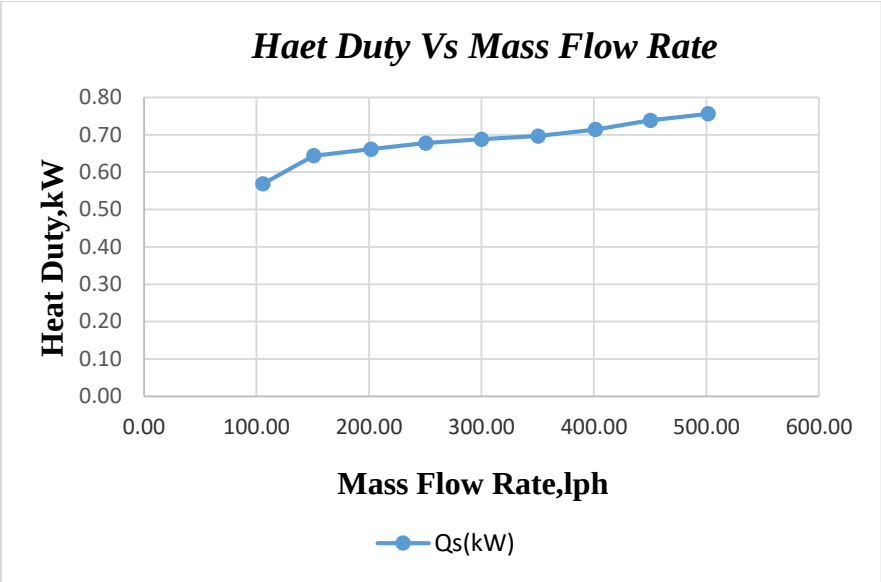

Fig.10 Heat Duty Vs Mass Flow Rate

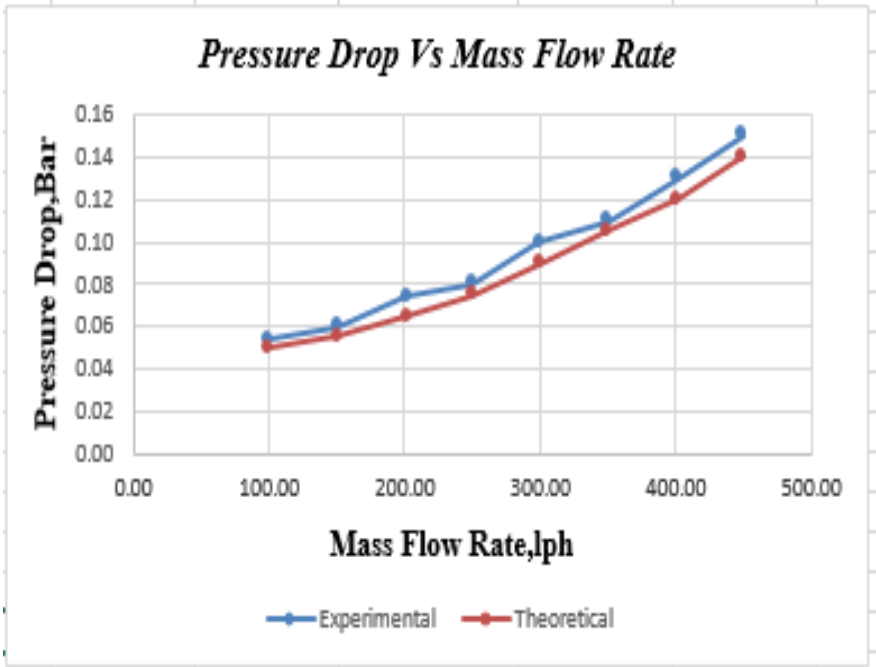

Fig.11Pressure Drop Vs Mass Flow Rate

Surface Average of Temperature on Volume Mesh

Part	Value (C)
HOT WATER: Outlet	3.525609e+01
Total:	3.525609e+01

Fig 12.CFD result for Hot Water Outlet

Surface Average of Temperature on Volume Mesh

Part	Value (C)
COLD WATER: Outlet	3.404915e+01
Total:	3.404915e+01

Fig13. CFD result of Cold Water Outlet

Difference of Total Pressure: Inlet/Outlet

Total Pressure Drop: -5.165275e-02 (bar)

Fig 14.CFD result of pressure drop

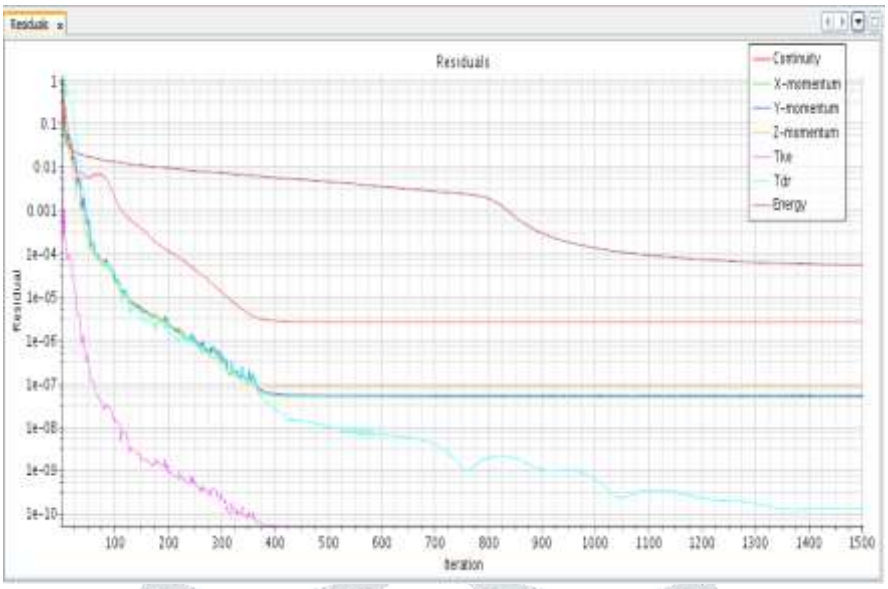

Fig 15.Residuals in simulation.

Table 2.Summary of Results

Sr No.	Parameter	UoM	Thermal Design	CFD	Experimental
	Hot side		***Hot water***	***Hot Water***	***Hot Water***
1	Mass Flow Rate	Kg/hr.	25	25	25.27
2	Inlet Temp.	deg C	55	55	55.29
3	Outlet Temp.	deg C	35	35.25	37.21
4	Heat Duty	kW	0.580	0.573	0.531
	Cold Side		***Cold Water***	***Cold Water***	***Cold Water***
5	Mass Flow Rate	Kg/hr	105	105	105.51
6	Inlet Temp.	deg C	29.5	29.5	29.56
7	Outlet Temp.	deg C	34.5	34.04	33.89
8	Pressure Drop	Bar	0.05	0.05263	0.05487

VII. CONCLUSION

Thermal design and parametric analysis of coil & shell heat exchanger of study under consideration and has following conclusions:

- The thermal design procedure gives the sizing and parametric analysis for coil in shell heat exchanger.
- For gradual change in mass flow rate of cold side, heat duty varies logarithmically.
- The pressure drop varies polynomially for gradual variation in mass flow rate of cold side.
- CFD and experimental results for hot water outlet, cold water outlet, and pressure drop are well within accepted range. This proves that, there is very less deviation between the analytical, computational and experimental results.

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REFERENCES

[1] N.Dean, F.A. Holland, Friction factors for coils, Institution of Chemical Engineering Transactions 48 (1907) T156–T161.

[2] P. Naphon, Thermal performance and pressure drop of the helical-coil heat exchangers with and without helically crimped fins, International Communications in Heat and Mass Transfer 34 (3) (2007) 321–330.

[3]Mori, Y and Nakayama, W, 1967a, Study of forced convective heat transfer in curved pipes (2nd report), Int. J. Heat Mass Transfer, 10, 37-59.

[4] S.Ahire, Development of heat transfer coefficient correlation for concentric helical coil heat exchanger, International Journal of Thermal Sciences 48 (12) (2009) 2300–2308.

[5] A.T Ananthanpillai et al., Natural convection heat transfer from helical coiled tubes, International Journal of Thermal Sciences 43 (2004) 359–365.

[6]R. K. Patil, B.W.Shende, P.K.Ghosh, "Designing a helical coil Heat Exchanger", Chemical Engineering Journal, December 1982.

[7] S.Shivakumar"Analysis of heat transfer enhancement in coiled-tube heat exchangers", *International Journal of Heat and Mass Transfer*, Vol. 44,pp. 3189-3199.

[8]Manna, R., Jayakumar, J.S. and Grover, R.B., 1996, Thermal Hydraulic design of a condenser for a natural circulation system, J. Energy, Heat and Mass Transfer, 18, 39-46

[9]N. Ghorbani, H. Taherian, M. Gorji-Bandpy, Designing Shell-and-Coil Mixed Convection Heat Exchangers, Proceedings of 2008 ASME Summer Heat Transfer Conference, Jacksonville, Florida, August 2008.

[10] C.Kalb "Turbulent heat transfer to near-critical water in a heated curved pipe under the conditions of mixed convection", *International Journal of Heat and Mass Transfer*, Vol. 42(16), pp. 3147.