Design and Modelling of Shell and tube Heat exchanger with Cut-Segmental Baffles

G. Sanjeethkumar[1] Dr. T. Alwarsamy[2]
[1]PG Scholar [2]Professor
[1,2]Department of Mechanical Engineering
[1,2]Government College of Technology, Coimbatore – Tamil Nadu, India

Abstract— The transfer of heat from one fluid to another fluid is an important operation for most of the process in chemical industries by using a heat transfer equipment. The equipment which is used for heat transfer process is generally known as heat exchangers. The heat exchangers are normally classified depending on the transfer process occurring in them. Shell and tube heat exchanger (STHE) the most common type of heat exchanger which is used in Oil refineries. This project work is focused on the study of STHE, their types, design considerations and their modes of failure which were used in Oil refineries in detail. The thermal performance and pressure drop are considered as major factors for the design and evaluation of STHE. The main objective characteristic of Shell and tube heat exchanger design is the procedure for specifying the design of heat exchanger, their heat transfer surface area, pressure drops and checking whether the assumed design satisfies the requirements. The Shell and tube heat exchanger and baffles such as single segmental baffle, double segmental baffle and helical baffle is designed as per ASME Boiler and Pressure Vessel Code, Section VIII and Tubular Exchanger Manufacturers Association (TEMA) standards. The modelling of the designed STHE with various baffles is carried out by using Solid Works software. In this work, the existing model of STHE is designed with different baffles and modelled.

Key words: Shell and tube heat exchanger (STHE), Tubular Exchanger Manufacturers Association (TEMA), American Society of Mechanical Engineers (ASME)

I. INTRODUCTION

The Shell and tube heat exchangers are generally built of a bundle of round tubes mounted in a cylindrical shell with the tube axis parallel to that of the shell. One fluid flow inside the tubes, the other flows across and along the tubes. The major components of this exchanger are tubes, shell, front end head, rear end head, baffles, and tube sheets. A variety of different internal constructions are used in shell and tube exchangers depending on the desired heat transfer and pressure drop performance and the methods employed to reduce the thermal stress, to prevent leakages, to provide for ease of cleaning, to contain operating pressures and temperatures, to control corrosion, to accommodate highly asymmetric flows, and so on. Shell and tube exchangers are classified and constructed in accordance with the widely used TEMA standards and ASME boiler and pressure vessel codes. TEMA has developed a notation system to designate major types of shell and tube exchangers. In this system, each exchanger is designated by a three-letter combination, the first letter indicating the front-end heat type, the second the shell type, and the third the rear-end head type. Some common shell and tube exchangers are AES, BEM, AEP, CFU, AKT, and AJW. The three most common types of shell and tube heat exchangers are

1) Fixed tube sheet design,
2) U-tube design, and
3) Floating-heat type.

In all the three types, the front-end head is stationary while the rear end head can be either stationary or floating, depending on the thermal stresses in the shell, tube, or tube sheet, due to temperature differences as a result of heat transfer. The exchangers are built in accordance with three mechanical standards that specify design, fabrication, and materials of unfired shell and tube heat exchangers. Class R is for the generally severe requirements of petroleum and related processing applications. Class C is for generally moderate requirements for commercial and general process applications. Class B is for chemical process service.

TUBULAR EXCHANGER MANUFACTURERS ASSOCIATION (TEMA): The Tubular Exchanger Manufacturers Association (TEMA) is trade association of leading manufacturers of shell and tube heat exchangers, who have pioneered the research and development of heat exchangers for over sixty years. TEMA has established and maintains a set of construction standards for heat exchangers, known as the TEMA standard. The TEMA standards have achieved worldwide acceptance as the authority on shell and tube heat exchanger mechanical design. TEMA is a progressive organization with an eye towards the future. Members are market aware and actively involved, meeting several times a year to discuss current trends in design and manufacturing. The internal organization includes various subdivisions committed to solving technical problems and improving equipment performance. This cooperative technical effort creates an extensive network for problem solving, adding value from design to fabrication. The current edition of the TEMA standard is the Ninth Edition, published in 2007. Worldwide, the TEMA standard is used as the construction standard for most shell and tube heat exchangers.

Su Thet Mon Than et al., (2008) designed the shell and tube heat exchanger and obtained a high heat transfer rate without exceeding the allowable pressure drop by using MatLAB and AutoCAD software. The arrangement of tubes is in triangular pattern which permits the use of more tubes. The segmental baffle is used with cut-out portion of 25 percent cut of the open shell area.

Deepak Kumar Kushwaha et al., (2015) reviewed and studied about the heat exchangers used in oil refineries, their design consideration and common type of heat exchanger failures. The design of the shell and tube exchanger is carried out by using Kern's method for the preliminary design and provides conservative results.

A. Sahoo et al., (2016) reported modeling and control of a real time shell and tube heat exchanger, mathematically modeled the heat exchanger using system identification methods and experimentally evaluated the effectiveness of two PID controller tuning methods such as Internal Model Control (IMC) and relay auto-tuning for temperature control. The experimental results show that the IMC based PID controller makes the system reach the desired set point than relay auto tuned PID controller.

Pranita Bichkar et al., (2017) shows the evaluation of shell and tube heat exchanger in which thermal performance and pressure drop are considered as major factors. It illustrates that both the thermal performance and pressure drop are dependent on the path of fluid flow and types of baffles in different orientations.

Mir Majid Etghani et al., (2017) illustrates that numerical model of shell and tube heat exchanger is investigated to assess heat transfer coefficient and exergy loss. The design parameters such as pitch coil, tube diameter, hot and cold fluid flow rate involved in the considerations for the heat exchanger performance. Design optimization of the shell and tube exchanger is carried out by using Taguchi method.

P.J. Fule et al., (2017) investigated the convective heat transfer rate of CuO-water nanofluid at various volume % (0.1–0.5) in a helical coiled tube at various Reynolds number. An increase in the loading of CuO nano-particles in base fluid shows a significant enhancement in the heat transfer coefficient of nanofluid. As the flow rate of the CuO nanofluid was increased, there is an increase in heat transfer coefficient significantly.

Emad M.S. El-Said et al., (2018) presented an experimental study on thermo-hydraulic analysis and performance evaluation of shell and multi-tube heat exchanger with two air injection methods; cross and parallel injection. The result show that, the air bubble injection can play an important role in the augmentation of the performance of horizontal shell and multi-tube heat exchanger with baffles for cross and parallel injection from the shell side.

In reference with the literature, the shell and tube heat exchanger which were used in the oil refineries were arranged in parallel for reducing the temperature of the crude oil for further processing. In shell and tube heat exchanger without the baffle arrangement, the shell side fluid is not forced towards the tube side fluid which reduces the heat transfer rate and the effectiveness of the heat exchanger.

The main objective of this project work is the designing of Shell and tube heat exchanger with single and double segmental baffle assuming no phase change occurs in the fluids flowing inside the heat exchanger. To model the designed values of shell and tube heat exchanger by using the SolidWorks tool.

II. DESIGNING OF SHELL AND TUBE HEAT EXCHANGER

The following steps are discussed briefly to demonstrate the multidisciplinary approach of heat exchanger design as a component and as part of a system for an overall optimum solution. The important design aspects of the shell and tube heat exchanger are as follows.

Step 1: Assumed tube diameter and thickness of the tube using the Birmingham Wire Gauge (BWG) with reference[1]
Tube outer diameter = 0.0160 m.
Tube thickness (BWG) = 0.0025 m.
Tube inner diameter = 0.0135 m.

Step 2: Assumed fouling factor based on inside and outside tubes,
h_{di} = 0.003 and h_{do}=0.003

Step 3: Assumed copper, stainless steel as a material for the construction of tubes and shell.

Step 4: Assumed inlet and exit temperatures of hot and cold streams and mass flow rate of cold stream (subscripts *c* and *h* refer to cold and hot streams).
$T_{c,in} = 25^0C$ $T_{h,in} = 350^0C$ $T_{c,out} = 75^0C$ $T_{h,out} = 200^0C$
cp_c = 4187 J/kgK cp_h = 2407 J/kgK m_c = 77.96 kg/s
Use the heat duty equation

$$Q = m_c\, cp_c\,(T_{c,out} - T_{c,in}) = m_h\, cp_h\,(T_{h,out} - T_{h,in})$$

$$m_h\, 2407\,(350\text{-}200) = (77.96)(4187)(75\text{-}25)$$

$$m_h = 45.20 \text{ (kg/s)}$$

$$Q = 16319460 \text{ W}$$

Step 5: Assumed flow is counter flow, Log Mean Temperature Difference (LMTD)

$$LMTD = \frac{(350-75)-(200-25)}{ln\frac{(350-75)}{(200-25)}}$$

LMTD = 221.25.

Step 6: Temperature correction factor (for 1 Shell – 2 tube pass exchanger)

$$F_t = \frac{\sqrt{R^2+1}\, ln\frac{(1-S)}{(1-RS)}}{(R-1)ln\frac{2-S[R+1-\sqrt{R^2+1}]}{2-S[R+1+\sqrt{R^2+1}]}} \qquad R=\frac{(350-200)}{(75-25)}, \quad [R=3]$$

$$S=\frac{(75-25)}{(350-25)}, \ [S=0.154]$$

$$F_t = \frac{\sqrt{3^2+1}\, ln\frac{(1-0.154)}{(1-(3)(0.154))}}{(3-1)ln\frac{2-(0.154)[3+1-\sqrt{3^2+1}]}{2-(0.154)[3+1+\sqrt{3^2+1}]}}, \ (F_t = 2.459)$$

Step 7: The mean temperature difference,
$DT_m = F_t \times LMTD$ = (2.459)(221.25)
DT_m = 544.054 K

Step 8: Assumed overall heat transfer coefficient,
U = 1200 (W/m^{2}K)

Step 9: Provisional Area, $A = \frac{q}{(U \times DT_m)}$

$$= \frac{16319460}{(1200 \times 544.054)}$$

A = 24.9966 m^2

Step 10: Based on the assumed tube diameter (ID and OD at a given BWG) and tube length, L.

Number of tubes, $N_t = \frac{A}{(\pi \times d_o L)}$

$$= \frac{24.9966}{(\pi \times (0.016)(1.750))}$$

N_t = 284

Step 11: Calculate tube pitch and the bundle diameter

$P_t = 1.25\, d_o$ $D_b = d_o\left[\frac{N_t}{K_1}\right]^{\frac{1}{n_1}}$

$= 1.25\,(0.016)$ $= (0.016)\left[\frac{284}{0.156}\right]^{\frac{1}{2.291}}$

P_t = 0.02 m D_b = 0.52 m.

Step 12: Assumed the fixed tube end, therefore Bundle diameter clearance (BDC=0.012m)

Step 13: Shell diameter, $D_s = D_b + BDC$.

$= (0.52) + (0.012)$

$D_s = 0.532$ m.

Step 14: Baffle spacing, $B_s = 1.4\ D_s$.

$= (1.4)(0.532)$

$B_s = 0.3508$ m

Step 15: Area for cross-flow,

$$A_s = \frac{[Pt - do]\ Ds\ Bs}{Pt}.$$

$$= \frac{[0.02 - 0.016]\ (0.532)\ (0.2128)]}{(0.02)}$$

$A_s = 0.02264\ m^2$.

Step 16: Shell-side mass velocity

$$G_s = \frac{\text{shell−side flow rate [kg/s]}}{As}$$

$$= \frac{77.96}{0.02264}$$

$G_s = 3443.46\ kg/m^2s$

Velocity of shell fluid = 3.443 m/s.

Step 17: Shell equivalent diameter for a square pitch arrangement,

$$D_e = \frac{1.27}{d_o}\ [p_t^2 - 0.785 d_o^2]$$

$$= \frac{1.27}{0.016}\ [0.02^2 - 0.785(0.016)^2]$$

$D_e = 0.01580$ m.

Step 18: Shell-side Reynolds number

$$R_e = \frac{G_s d_e}{\mu}$$

$$= \frac{(3443.46)(0.0158)}{(0.000547)}$$

$R_e = 99463.74 = 10^5$.

Step 19: Prandtl number, $P_r = \frac{\mu C_p}{k}$

$$= \frac{(0.000547)(4.187)}{(0.64)}$$

$P_r = 0.00358$.

Step 20: Shell-side heat transfer coefficient,

$$N_u = \frac{h_s d_e}{k_f} = j_h Re Pr^{0.33} \left[\frac{\mu}{\mu_w}\right]^{0.14}$$

$$\frac{h_s d_e}{k_f} = (10)^{-2.9}(99463.74)(0.00358)^{0.33}\left(\frac{0.000547}{0.00091}\right)^{0.14}$$

$$\frac{h_s\ (0.0158)}{0.64} = 18.176$$

$h_s = 736.24\ W/m^2K$.

Step 21: Shell side pressure drop,

$$\Delta P_s = 8 j_f \left[\frac{D_s}{d_e}\right]\left[\frac{L}{l_B}\right]\left[\frac{\rho \mu_s^2}{2}\right]\left[\frac{\mu}{\mu_w}\right]^{-0.14}$$

$$= 8(10^{-1.7})\left[\frac{(0.532)}{(0.0158)}\right]\left[\frac{1.75}{0.2128}\right]\left[\frac{(1000)(3.443)}{2}\right]\left[\frac{0.000547}{0.00091}\right]^{-0.14}$$

$\Delta P_s = 8.1708$ kpa

Step 22: Number of tubes per pass,

$$Nt_{pp} = \frac{N_t}{Number\ of\ passes}$$

$$= \frac{284}{2}$$

$Nt_{pp} = 142$

Step 23: Tube-side mass velocity,

$$G_m = \frac{tube\text{−}side\ flow\ rate\ [kg/s]}{Nt_{pp}\left[\frac{\pi d_i^2}{4}\right]}$$

$$= \frac{45.20}{(142)\frac{3.14(0.0135)^2}{4}}$$

$G_m = 2224.91\ kg/m^2s$

Velocity of tube fluid = 3.0066 m/s

Step 24: Prandtl and Reynolds numbers for fluids inside tubes

$P_r = \frac{\mu C_p}{k}$ $\quad R_e = \frac{\rho_i d_i v}{\mu_i}$

$= \frac{(0.01)(2.407)}{(0.13)}$ $\quad = \frac{(740)(0.0135)(3.0066)}{(0.01)}$

$P_r = 0.185$ $\quad R_e = 3003.60$

Step 25: Calculate heat transfer coefficient h_i by using the following relation

$$h_i = 0.023\ \frac{k_f}{d_i} Re^{0.8} Pr^{0.33}\left[1 + \frac{d_i}{L}\right]^{0.7}$$

$$= 0.023\ \frac{0.13}{0.0135}(3003.60)^{0.8}(0.185)^{0.33}\left[1 + \frac{0.0135}{1.750}\right]^{0.7}$$

$h_i = 81.27\ W/m^2K$.

Step 26: The tube-side pressure drop may be calculated using the following relation

$$\Delta P_t = \left[1.5 + N_t\left[2.5 + \frac{8 j_f L}{d_i} + \left[\frac{\mu}{\mu_w}\right]^{-m}\right]\right]\left[\frac{\rho_i v^2}{2}\right]$$

$$= \left[1.5 + 284\left[2.5 + \frac{8(10)^{-1.7}(1.75)}{0.0135} + \left[\frac{0.01}{0.000547}\right]^{-0.14}\right]\right]\left[\frac{(1000)(3.0066)^2}{2}\right]$$

$\Delta P_t = 3.0631$ kpa.

The calculated dimension of the shell and tube heat exchanger with cut segmental baffles is tabulated and it is shown in the table 1 with their dimensions.

S.No.	PARTS		DIMENSIONS
1.	Shell	Outer Diameter	540 mm
		Inner Diameter	532 mm
		Length	1750 mm
		Flange thickness	30 mm
		Shell side fluid flow Outer Diameter	135 mm
		Shell side fluid flow Inner Diameter	115 mm
2.	Shell Cover	Outer Diameter	570 mm
		Inner Diameter	532 mm
3.	Head Cover	Outer Diameter	570 mm
4.	Baffles	Thickness	12.7 mm
		Baffles Spacing	350 mm
5.	Tube Bundles	Tube Outer Diameter	16 mm
		Tube Inner Diameter	13.5 mm
		Tube thickness	2.5 mm
		Tube Sheet Diameter	520 mm
		Tube Pitch	20 mm
		Tube Bundle Diameter	520 mm
		Bundle Diameter Clearance	12 mm
6.	Total Number Of Tubes		284
7.	Number of passes		2
8.	Number of tubes per pass		142
9.	Total heat transfer surface area		24.996 m^2
10.	Area of Cross flow in Shell		0.02264 m^2

Table 1: Calculated dimensions of Shell and tube heat exchanger with cut-segmental baffles

III. MODELLING OF SHELL AND TUBE HEAT EXCHANGER

The Modelling of shell and tube heat exchanger is carried out with the specified and designed values obtained in the calculation. The complete modelling of shell and tube heat exchanger involves modelling of individual parts and assembling the parts to obtain the real 3D model of the shell and tube heat exchanger by using solid works tool.

The fig. 1 represents the 2D front view, top view and right side view of the shell of the heat exchanger.

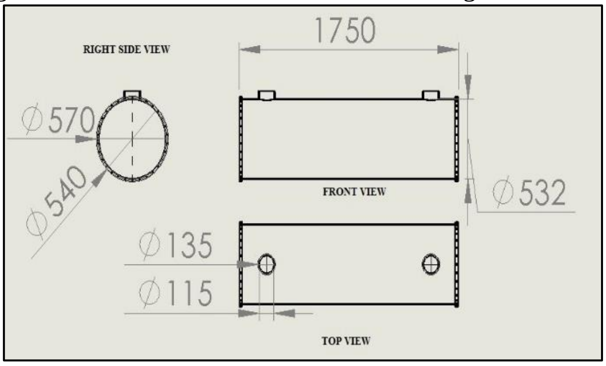

Fig. 1: 2-D Front view, Top view and Right side view of Shell

The fig.2 represents isometric view of the tube bundle holding the tubes of the heat exchanger.

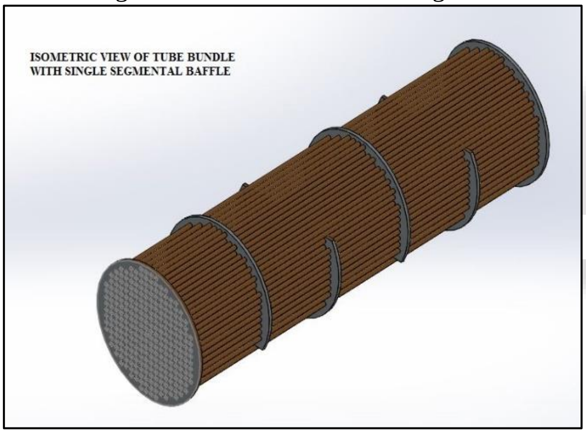

Fig. 2: Isometric view of tube bundle with single segmental baffle

The fig. 3 represents the arrangement of single cut segmental baffle.

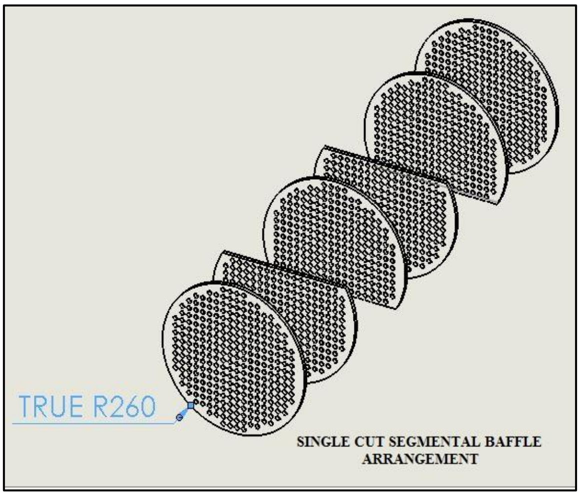

Fig. 3: Single cut segmental baffle arrangement with tube sheets

The fig. 4 represents the front view and top view of the shell cover in 2-D.

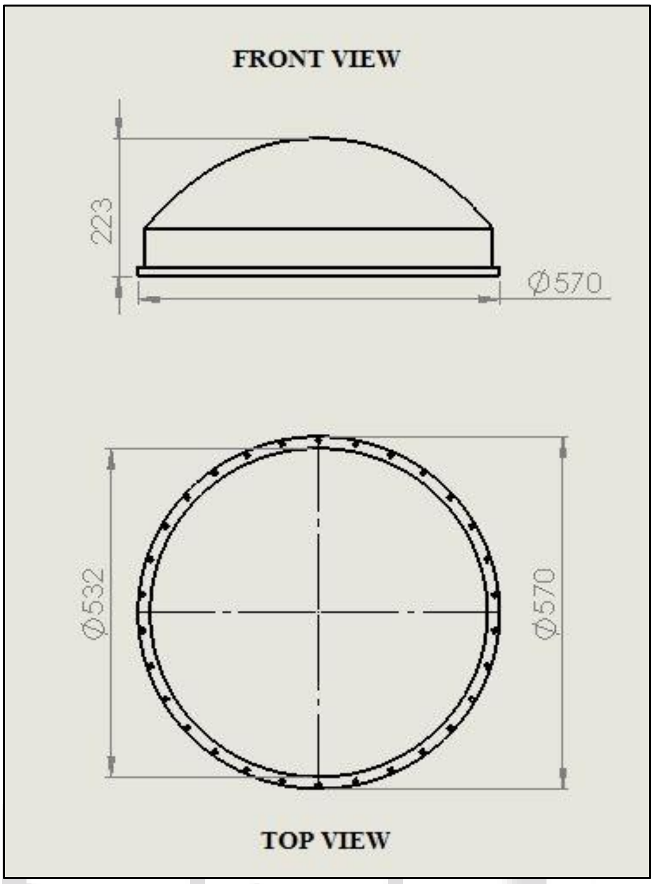

Fig. 4: 2-D Front View and Top View of the Shell cover

The fig. 5 represents the front view, top view and left side view of the head cover in 2-D.

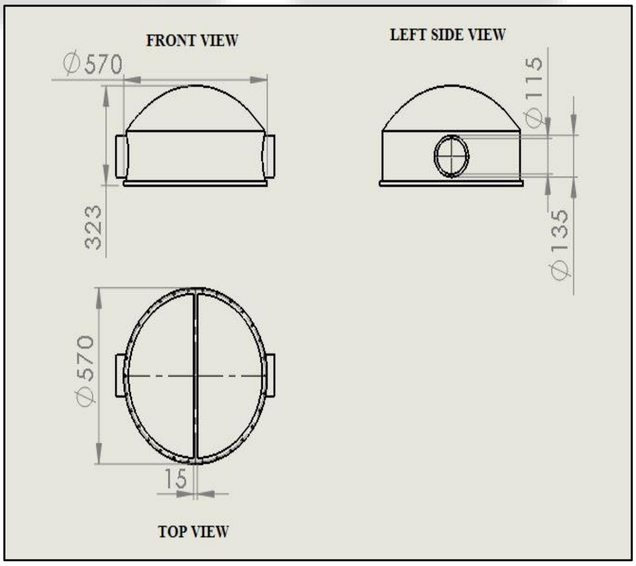

Fig. 5: 2-D Front view, Top view and Left side view of the head cover

The fig. 6 represents the isometric cut sectional view of the shell and tube heat exchanger with single segmental baffle arrangement inside the heat exchanger.

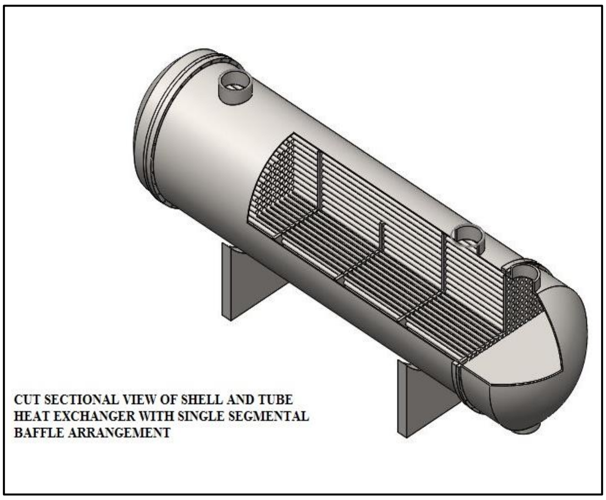

Fig. 6: Cut-sectional view of modelled shell and tube heat exchanger with single segmental baffle arrangement

The fig. 7 represents the isometric cut sectional view of the shell and tube heat exchanger with double segmental baffle arrangement inside the heat exchanger.

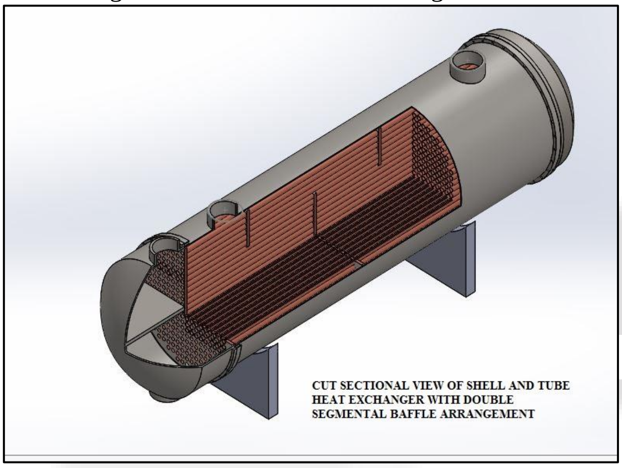

Fig. 7: Cut-sectional view of modelled shell and tube heat exchanger with double segmental baffle arrangement

IV. CONCLUSION

The flow rates, temperatures, and physical properties such as specific heat capacity, thermal conductivity of the fluids flowing in the heat exchanger are fixed. The fluid velocity, heat transfer coefficient and optimum pressure drop that takes place inside the shell side and tube side are calculated by using the standard formula for design the shell and tube heat exchanger. The property of the designed shell and tube heat exchanger is given in the table 2.

PHYSICAL PROPERTIES	SHELL SIDE	TUBE SIDE
Fluid	Water	Oil
Flow rate (kg/s)	77.96	45.20
Fluid Density (kg/m^3)	1000	740
Fluid Velocity (m/s)	3.443	3.0066
Specific Heat Capacity (J/kg K)	4187	2407
Viscosity (cps)	0.494	1.000
Thermal Conductivity (W/m K)	0.61	0.105
Inlet temperature (ºC)	25	350
Outlet temperature (ºC)	75	200
Allowable ΔP (k pa)	8.1708	3.0631
Reynolds Number	99463.74	3003.60
Prandtl Number	0.00358	0.185
Wall resistance (K m^2/W)	0.00003	
Heat Duty (kW)	16319.460	
Heat transfer Coefficient (W/m^2 K)	736.24	81.27
Material	Stainless steel	Copper

Table 2: Shell and tube Exchanger Design – Physical Properties

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