DESIGN OF HEAT EXCHANGER TO INCREASE PROCESS EFFICIENCY

Muhammed Fajir V A[1], Ajmal P[2], Aswin K.R[3], Afsal K.A[4], J V C Maliackal[5]

[1] *B-TECH Student, Dept. of Mechanical Engg. KMEA Engineering college, Kerala, India*
[2] *B-TECH Student, Dept. of Mechanical Engg. KMEA Engineering college, Kerala, India*
[3] *B-TECH Student, Dept. of Mechanical Engg. KMEA Engineering college, Kerala, India*
[4] *B-TECH Student, Dept. of Mechanical Engg. KMEA Engineering college, Kerala, India*
[5] *Asst. Professor, Dept. of Mechanical Engg. KMEA Engineering college, Kerala, India*

ABSTRACT

Heat exchanger is a pressure vessel that allows transfer of energy between two media that may or not be separated by a wall. Heat exchangers are used in industries for any process which involve cooling, heating, condensation, boiling or evaporation. This paper discusses an industrial problem to design a heat exchanger for a specific problem. Shell and Tube heat exchangers are widely used in process applications as well as the refrigeration and air conditioning industry. The basic configuration, design and analysis of shell and tube heat exchangers form an indispensable part of mechanical, thermal and chemical engineering scholars. Types of shell and tube heat exchangers are discussed briefly. The process stream is simulated using Design II software to obtain the design parameters and the process datasheet is prepared. The parameters from the datasheet is used to design the heat exchanger. The basic thermal design considerations and design process for a shell and tube heat exchanger is discussed. The mechanical design considerations and design procedure is done. The main objective in any heat exchanger design is to estimate the minimum heat transfer area required to give a specified heat duty. This is important since it governs the overall cost of the heat exchanger. Many configurations with various design variables such as outer diameter, pitch, and length of the tubes; tube passes; baffle spacing; baffle cut, tube thickness etc. are possible. Aspen EDR Software is employed in finding the optimum heat exchanger performance at minimum cost.

Keyword: - *Heat exchanger, heat duty, Aspen EDR Software, Design II Simulation software, heat transfer*

1. INTRODUCTION

Heat exchangers are widely used in industries to transfer thermal energy between two or more media. They are used in process which involve cooling, heating, condensation, boiling or evaporation and applicable to chemical industries, food industries, refrigeration, power engineering and so on. Shell and tube heat exchanger are the most commonly used type of heat exchanger. The robustness, medium weight, compact design of Shell and Tube heat exchangers make them well suited for industrial applications. The basic configuration, design and analysis of shell and tube heat exchangers form an indispensable part of mechanical, thermal and chemical engineering scholars

In this project, a shell and tube heat exchanger is designed for pre-heating Re-gasified LNG. RLNG is used for a certain process heating application and steam is the heating medium. The heat exchanger shall be designed such that the hot process condensate steam flows through the tubes and RLNG through the shell side of the heat exchanger. The shell-and-tube heat exchangers are the most commonly used heat exchangers due to the following advantages. They have larger heat transfer surface area-to volume ratios than the most of common types of heat exchangers, and they can be manufactured relatively easily for a large variety of sizes and flow configurations. They can operate at high pressures, and their construction facilitates disassembly for periodic maintenance and cleaning.

2. SHELL AND TUBE HEAT EXCHANGER

Shell and tube heat exchangers in their various construction modifications are the most commonly used basic heat exchanger configuration in the process industries. Some of the reasons for this wide acceptance are: The shell and tube heat exchanger provides comparatively large heat transfer area to volume ratio. Shell and tube heat exchanger provides a larger surface, which is relatively easy to construct in a wide range of sizes. Also, they are mechanically rugged enough to withstand normal fabrication stresses, shipping stresses, field erection stresses and normal operating conditions. The basic configuration can be modified accordingly so as to solve special problems. It can be easily cleaned. The components which are most subject to failure - gaskets and tubes – can be easily replaced.

2.1 Types of shell and tube heat exchangers

The various types of shell and tube heat exchangers are;

Fixed tube-sheet exchanger (non-removable tube bundle): It is the simplest and cheapest type of shell and tube exchanger. It has a fixed tube sheet design. In this type, the tube sheet is welded to the shell and no relative movement between the shell and tube bundle is possible

Removable tube bundle: In this type, the tube bundle can be removed for ease of cleaning and replacement. They can further be categorized as floating head and U-tube exchanger.

Floating-head exchanger: It consists of a stationery tube sheet clamped with the shell flange. At the opposite end of the bundle, the tubes may expand freely into a floating tube sheet. The floating head cover is bolted to the tube sheet. Also the entire bundle can be removed for cleaning and inspection purposes.
U-tube exchanger: They consists of tubes which are bent in the form of a “U” and rolled back into the tube sheet. This means that it can omit some tubes at the centre of the tube bundle to facilitate the design depending on the tube arrangement. The tubes can freely expand to the U bend end.

Preferably we choose the fixed tube heat exchanger because it provides maximum heat transfer area for a given shell and tube diameter. It can also provide for single and multiple tube passes to assure proper velocity. They are less costly than removable bundle designs.

2.2 Components of fixed tube heat exchanger

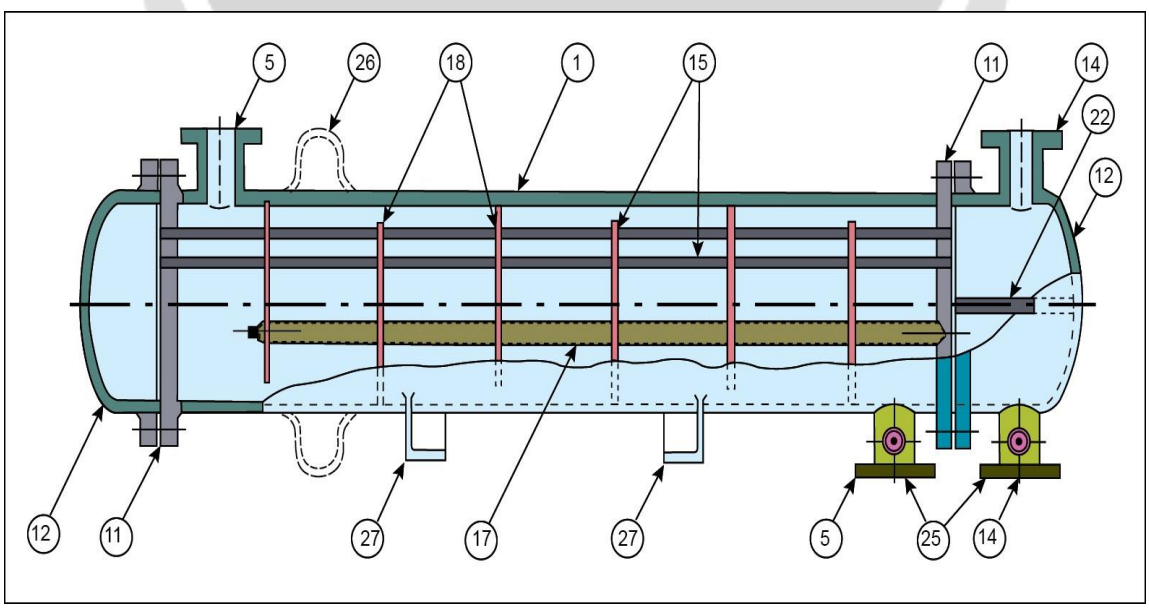

Fig -1: Fixed tube heat exchanger

Table -1: Components of heat exchangers

1. Shell	16. Tubes (U-type)
2. Shell cover	17. Tie rods and spacers
3. Shell flange (channel end)	18. Transverse (or cross) baffles or support plates
4. Shell flange (cover end)	19. Longitudinal baffles
5. Shell nozzle or branch	20. Impingement baffles
6. Floating tube sheet	21. Floating head support
7. Floating head cover	22. Pass partition
8. Floating head flange	23. Vent connection
9. Floating head gland	24. Drain connection
10. Floating head backing ring	25. Instrument connection
11. Stationary tube sheet	26. Expansion bellows
12. Channel or stationary head	27. Support saddles
13. Channel cover	28. Lifting lugs
14. Channel nozzle or branch	29. Weir
15. Tube (straight)	30. Liquid level connection

2.2.1 Tubes: Tubes are the basic component of shell and tube heat exchanger. It provides the heat transfer surface between the fluids flowing through inside and outside of the tube. The tubes are most commonly made of copper or steel alloys and they can be seamless or welded. Alloys of nickel, titanium, or aluminum may also be needed for special applications.

2.2.2 Tube Sheets: The tubes are held in place by being inserted into holes in the tube sheet and are either expanded into grooves cut into the holes or are welded to the tube sheet. The tube sheet is a single round metal plate that is suitably drilled and grooved to take the tubes, gaskets, spacer rods and the bolt circle.

2.2.3 Shell and Shell-side Nozzles: The shell is simply the container for the shell-side fluid, and the nozzles are the inlet and exit ports. The shell has a circular cross section and is made by rolling a metal plate of the necessary dimensions into a cylinder and then welding the longitudinal joint. The roundness of the shell is important in fixing the maximum diameter of the baffles that can be inserted and hence the effect of shell-to-baffle leakage. In order to minimize out-of-roundness, small shells are expanded over a mandrel. In extreme cases, the shell can be cast and then be bored out using a boring mill.

2.2.4 Tube-side Channels and Nozzles: Tube-side channels and nozzles control the flow of the tube-side fluid to and out of the tubes of the exchanger. Since the tube-side generally carries the more corrosive fluid, these channels and nozzles are often made out of alloy materials.

2.2.5 Channel covers: The channel covers are round plates that are bolted to the channel flanges so that they can be removed for inspection without disturbing the tube-side piping. In smaller heat exchangers, bonnets with flanged nozzles are often used instead of channels and channel covers.

2.2.6 Pass divider: A pass divider is needed in one channel for an exchanger having two tube-side passes, and they are needed in both channels for an exchanger having more than two passes. If the channels are cast, the dividers are integrally cast and then faced to give a smooth bearing surface on the gasket. If the channels are rolled from plate, the dividers are welded in place.

2.2.7 Baffles: Baffles mainly has two functions: Primarily, they support the tubes in the proper position and rigidity during assembly and operation. Secondly, they increase the velocity and the heat transfer coefficient by guiding the shell-side flow back and forth across the tube field.

2. DESIGN PROBLEM

The problem is to design a heat exchanger to facilitate the preheating of RLNG using process condensate steam. The input parameters are given and the datasheet is to be created using the Design II simulation software. The simulation results are tabulated in the datasheet given in Table 1.

Table -2: Heat exchanger Datasheet

PROCESS DATA SHEET	**SHELL & TUBE HEAT EXCHANGER**		**PAGE 1 OF 1**	**R1**
Equipment Number	(NEW HEAT EXCHANGER)			
Equipment Name	RLNG Preheating			
No. of Units	One			
PERFORMANCE OF ONE UNIT				
	Unit	Shell Side	Tube Side	
Fluid Name		RLNG	Process Condensate Steam	
Total Fluid	Kg/h /Nm^3/h	26794 / ...	39700 / ...	
Liquid in/out	Kg/h	0	39700	
Vapour in/out	Kg/h / Nm^3/h	26794 / ...	0	
Non condensibles	Kg/h / Nm^3/h	0	0	
Temperature in/out	^{0}C	0 / 90	122 / 86.23	
Pressure in/out	Pa	4412992 / 4372320	3824593 / 3823516	
Latent heat	J/Kg	--	--	

Molecular weight		16.38	
Density in/out	Kg/m^3	35.66 / 24.54	941.19 / 969.05
Specific heat in/out	J/Kg K	2454.22 / 2537.53	4210.93 / 4189.69
Viscosity in/out	Ns/m^2	0.000011 / 0.000014	0.000238 / 0.000329
Thermal conductivity in/out	W/mK	0.0376 / 0.0476	0.6872 / 0.6676
Pressure drop, allow/calc.	Pa	49033.2 / 33911.5	48245.9 / 668
Fouling resistance	m^2K/W	0.00017	0.0006
Heat Exchanged	W	1655984	1655984
Design Pressure	Pa	4900000	4300000
Design Temperature	^0C	125	160

Based on the datasheet the design of the shell and tube heat exchanger is to be done.

3. METHODOLOGY

The method followed for the completion of the project is as given below.

- The analysis of the proposed stream in DESIGN II simulation software to get the stream parameters which is expected in the new heat exchanger.
- Preparation of the required thermo-physical properties of the heat exchanger at mean temperature from the process datasheet.
- Understanding the thermal design of heat exchanger using Kern's method. (LMTD method)
- Understanding various mechanical considerations and calculations of the dimensions of mechanical parts.
- Thermal designing of heat exchanger using Kern's trial and error method to meet the overall heat transfer and pressure drop criteria.
- Mechanical designing of the heat exchanger parts to withstand various thermal and mechanical stresses.

In the previous section we have already got the design parameters in the datasheet and thermos-physical properties are listed in the datasheet. The successive steps of design methodology are continued in the next section.

4. DESIGN PROCEDURE

Table -3: Nomenclature of design factors

A - heat exchanger surface area (m^2)	Nu - Nusselt number (dimensionless)
L - tube length (m)	Pr - Prandtl number (dimensionless)
Q - rate of heat transfer (W)	Re - Reynolds number (dimensionless)

C_p - specific heat at constant pressure (J/kg.K)	ΔT_{lm} - log mean temperature difference (K)
D - tube diameter (m)	N_{tube} - number of tubes
T - Temperature (K)	U_o - overall heat transfer coefficient (W/m2K)
D_{si} - shell inside diameter (m)	K - thermal conductivity (W/mK)
D_b - tube bundle diameter (m)	N_{pass} – no: of tube passes m mass flow rate (kg/s)
V - velocity (m/s)	h_i - internal heat transfer coefficient (W/m2K)
d_o - Outer diameter of tube	h_o - external heat transfer coefficient (W/m2K)
d_i - Inner diameter of tube	f - Permissible stress
t_s - Shell thickness	t_{cc} - Channel cover thickness
t_h - Torispherical head thickness	t - Tube sheet thickness
N - Gasket width	t_n - Nozzle thickness
G - Mean gasket diameter	t_f - Flange thickness

The heat exchanger design process can be mainly grouped as i) Thermal design and ii) Mechanical design

4.1 Thermal Design

Thermal design of a shell and tube heat exchanger typically includes the determination of heat transfer area, type of heat exchanger, number of tubes, tube length and diameter, tube layout, number of shell and tube passes, pitch of tube, baffle number, type and size, shell side pressure drop, tube side pressure drop etc.

Shell and tube heat exchanger is designed by **Kern's method** of trial and error calculations. The main steps of design process are summarized as follows:

Step 1. Obtain the required thermo-physical properties of hot and cold fluids at the arithmetic mean temperature.

Step 2. Find the heat duty (Q) of the exchanger by performing energy balance.

Step 3. Assume a reasonable overall heat transfer coefficient ($U_{o,assm}$).

Step 4. Decide the number of shell and tube passes (n_p). Find the LMTD and the correction factor F_T

Step 5. Calculate the required heat transfer area (A): $A=\frac{Q}{Uo\ assm.LMTD.F_T}$ (1)

Step 6. Select tube material, decide the tube inner and outer diameters (ID=d_i , OD =d_o), tube wall thickness and tube length (L). Calculate the number of tubes (n_t) required to provide the required heat transfer area (A):

$$n_t=\frac{A}{\pi d\ Lo} \quad (2)$$

Calculate tube side fluid velocity, $u=\frac{4m\ (np\ /nt\ )}{\pi \rho di\text{^}2}$ (3)

Step 7. Decide the type of shell and tube heat exchanger (fixed tube sheet or removable tube bundle type) Select the pitch of the tube (P_T), determine the inside shell diameter (D_s) required to accommodate the calculated number of tubes (n_t).

Step 8. Select the type of baffle (segmental, doughnut etc.), baffle percentage cut, (25% baffles are widely used), baffle spacing (B) and baffle number. The baffle spacing is generally chosen within 0.2 D_s to D_s .

Step 9. Determine the tube side heat transfer coefficient (h_i) using Sieder-Tate equation.

Estimate the shell-side heat transfer coefficient (h_o) using:

$$J_H = \frac{hoDe}{k}\left(\frac{c\mu}{k}\right)^{-0.33}\left(\frac{\mu}{\mu w}\right)^{-0.14} \quad (4)$$

Calculate the overall heat transfer coefficient ($U_{o\,cal,}$) based on the outside tube area:

$$Uo\ cal = \left[\frac{1}{ho} + Rdo + \frac{Ao}{Ai}\left(\frac{do-di}{2kw}\right) + \frac{Ao}{Ai}\left(\frac{1}{hi}\right) + \frac{Ao}{Ai}Rdi\right]^{-1} \quad (5)$$

Step 10. If $0 < \frac{Uo\ cal - Uo,assm}{Uo,assm} < 30\%$ go the next **step # 11**. Else go back to **step 5**, and calculate heat transfer area (A) required using $U_{o\,cal,}$ and repeat the calculations from **step 5**.

Step 11. Calculate the pressure drop in tube-side (ΔP_T): This includes: (i) pressure drop in the straight section of the tube (frictional loss) (ΔP_t) and (ii) return loss (ΔP_{rt}) due to change in direction of fluid in a "multi-pass exchange".

Total tube side pressure drop: $\Delta P_T = \Delta P_t + \Delta P_{rt}$ (6)

Step 12. Calculate pressure drop in shell side (ΔP_S): This includes (i) pressure drop in the flow across the tube bundle (frictional loss) (ΔP_s) and (ii) return loss (ΔP_{rs}) due to change of direction of fluid.

Total shell side pressure drop: $\Delta P_S = \Delta P_s + \Delta P_{rs}$ (7)

If the tube-side pressure drop is greater than the allowable pressure drop, then decrease the number of tube passes or increase number of tubes per pass. Go to **step 6** and redo the calculations steps.

If the shell-side pressure drop is greater than the allowable pressure drop, go back to **step #7** and repeat the calculations steps.

4.2 Mechanical Design

Mechanical design of shell and tube heat exchanger includes the design of various pressure and non-pressure parts. The structural rigidity and efficient service of heat exchangers depends on the right mechanical design. Mechanical design is usually done based on certain design standards and codes. Some mechanical design standards used in heat exchanger design are: TEMA (Tubular Exchanger Manufacturers Association) (United States), IS:4503-1967 (India); BS: 3274

4.2.1. Design considerations

Design pressure and temperature: The design pressure of a heat exchanger is the gauge pressure exerted at the top of the vessel. This pressure is the basis to determine the minimum wall thickness of the various pressure parts. The IS: 4503 [8] specifies that the design pressure should be at least 5% more than the maximum allowable pressure. Generally a 10% higher value is used. The design temperature is the basis for determining the minimum wall thickness of various parts of the exchanger for a given design pressure. It is generally taken as 10ºC higher than the maximum allowable temperature.

Materials of construction: All materials used for the construction of heat exchangers for pressure parts must confine with the appropriate specification as given in IS: 4503 [8]. The materials of construction should be compatible with the process fluids and should also be cost effective. High chrome-Mo-Ni alloys (Cr content 12-27%)can be used for high temperature services up to 2100ºC. Use of any carbon or low alloy steel is not recommended for the construction of heat exchangers for the service below 0ºC.

Fouling Considerations: Most of the process fluids in the exchanger foul the heat transfer surface. The material deposited on the heat transfer surfaces reduce the effective heat transfer rate due to their relatively low thermal conductivity. Hence, the net heat transfer with clean surface should be made higher to compensate the reduction in performance during operation. Fouling of the heat transfer surfaces increases the cost of (i) construction due to its oversize, (ii) additional energy due to poor exchanger performance and (iii) occasional cleaning to remove the deposited materials. The effect of fouling is included in heat exchanger design by considering the tube side and shell side fouling resistances.

4.2.2. Mechanical design components

The main mechanical components of shell and tube heat exchangers are: shell thickness, shell cover, gaskets, flanges, nozzles, tube-sheet thickness, stress calculations and design of supports.

i. Shell diameter and thickness

The nominal diameter of the heat exchanger is specified in IS: 2844-1964 [9] for shells manufactured from flat sheet.

$$ts = \frac{pDs}{fJ - 0.6p} + c \quad (8)$$

The shell thickness (t_s) can be calculated from the equation below based on the maximum allowable stress and corrected for joint efficiency

t_s=shell thickness p= design pressure D_s= Shell ID

f=Maximum allowable stress of the material of construction

J=Joint efficiency (usually varies from 0.7 to 0.9)

The minimum shell thicknesses should be decided in compliance with IS: 4503.

ii. Shell cover

There are several types shell covers used in heat exchangers like flat, torispherical, conical, hemispherical and ellipsoidal. The torispherical head is the most widely used type in chemical industries for operating pressures up to 200psi.

The necessary thickness for a torispherical head (t_h) can be calculated using:

$$t_h = \frac{pRWi}{2fJ - 0.2p} + c \quad (9)$$

$$W = \frac{1}{4}\left(3 + \sqrt{\frac{Ri}{ri}}\right) \quad (10)$$

R_i= Crown radius, r_i=Knuckle radius, c=corrosion allowance

iii. Channel cover diameter and thickness

The effective channel cover thickness (t_{cc}) is calculated using

$$t_{cc} = \frac{Dc}{10} * \frac{\sqrt{C1*p}}{f} \quad (11)$$

D_c = diameter of the cover [in mm]

C_1 = a factor which is 0.25 when the cover is bolted with full faced gaskets and 0.3 when bolted with narrow faced or ring type gaskets

p = design press in kgf/cm^2 and f = allowable stress in kgf/mm^2

iv. Tube sheet thickness

Tube sheet is a flat circular plate with pattern drilled holes according to the tube sheet layouts. The open end of the tubes opens into the tube sheet. The tube sheet form the main barrier for shell and tube side fluids. The minimum tube-sheet thickness required to 'resist bending' can be determined using

$$t_{ts} = \frac{FGp}{3}\sqrt{\frac{P}{kf}} \quad (12)$$

Where, F= 1 for fixed tube and floating tube sheet; and F=1.25 for U-tube type sheet

G_p = diameter over which pressure is acting (for fixed tube sheet heat exchanger $G_p = D_s$, shell ID;

G_p is port inside diameter for kettle type,

for floating tube sheet G_p shall be used as that of stationery tube sheet.

f = allowable stress of material of tube sheet

k = Mean ligament efficiency

v. Impingement plates

Impingement plates are fixed on the tube side to deflect the liquid or vapor-liquid mixture to protect the tubes from erosion. Based on the IS:4503, the impingement protection may not be required for the services involving non-corrosive single phase fluids having entrance line values of ρu^2<125, where u is the velocity of the fluid in m/s and ρ is its density in g/cm^3. In all other cases, the tube bundle at the entrance should be protected against impinging fluids. Usually a metal plate of about ¼ inch thickness is used as the impingement plate.

vi. Nozzles and branch pipes

The wall thickness of nozzles and other connections shall not be less than that defined for the applicable loadings, that is, pressure temperature, bending and static loads (according to IS:4503) [8].

Nozzle thickness, $t_n = \frac{pDn}{2fJ-p} + c$ (12)

vii. Gaskets

Gaskets are used to make metal to metal contact surfaces leak-proof. Gaskets are made of elasto-plastic materials and are relatively softer than the flange materials. Deformation of gaskets under load helps to seal the surface irregularities between metal-metal surfaces and prevents leakage of the fluid. For design pressures lesser than 16 kgf/cm^2 and when there is no direct contact with oil, the compressed asbestos fiber, natural or synthetic rubber or other suitable gasket and packing materials having the appropriate mechanical and corrosion resisting properties can be used (IS:4503) [8].

The preliminary calculation of gaskets is done using following expression:

Residual gasket force = Gasket seating force – Hydrostatic pressure

The residual gasket force should be greater than that required to prevent the leak of internal fluid. The final expression for this condition is:

$$\frac{Do}{Di} = \sqrt{\frac{Y-pm}{Y-p(m+1)}} \quad (13)$$

D_o = outside gasket diameter

D_i = inside gasket diameter

p = design pressure

Y = minimum design seating stress

m = gasket factor

Calculate the width of the gasket width, $N = 0.5*(D_o - D_i)$ (14)

viii. Design of flange

Flange bolt load for seating condition, $W = \frac{(Am+Ab)fa}{2}$ (15)

Flange thickness, $t_f = \sqrt{\frac{Mf*Y}{fg*B}}$ (16)

5. RESULTS AND OBSERVATIONS

5.1. Thermal design

Heat duty (Q) of the exchanger Q = 1643959.26W
($U_{O,assm}$) = 400 W/m^{2}K
LMTD = 54.7^{o}C
Correction factor (F_T) = 0.8
Heat transfer area (A) = 96.32m^2
The number of tubes (n_t) required to provide the heat transfer area = 308 tubes
Tube side flow velocity (u) = 0.379m/s
Baffle diameter D_b = 503.71mm
Shell diameter D_s =520mm
Tube side film heat transfer coefficient (h_i) = 3032.74W/m^{2}K
Shell side heat transfer coefficient (h_s) = 928.74 W/m^{2}K
Overall heat transfer coefficient (U_o) =408.25 W/m^{2}K
Tube side pressure drop ΔP_t = 1588.52N/m^2
Shell side pressure drop ΔPs = 46614.37N/m^2 (which is modified)

5.2. Mechanical design

Shell side pass = 1
Tube side pass = 2
Outer diameter of tube, do =20mm
Inner diameter of tube, di = 16mm
Layout of tubes = Triangular
Tube pitch = 23.7mm
Design temperature = 10% higher value of inlet temperature = 134.2 ^{o}C
Design pressure = 10% higher value of larger pressure among inlet pressure of shell and tube side = 53936.5Pa
Permissible stress, f =100.6N/mm^2
Shell thickness, t_s = 3.347mm
Torispherical head thickness, (t_h) =3.245mm
Channel cover thickness, t_{cc} = 2.077mm

Tube sheet thickness, t_{ts} = 6.72mm
Nozzle thickness, t_n = 3.034mm
Gasket width, N = 2mm
Mean gasket diameter, G = 520mm
Basic gasket seating width, b_o = 5mm
Effective gasket seating width, b = 1.118mm
Bolt load due to gasket reaction under atmospheric pressure and temperature, W_{m1} = 428500N
Bolt load under light pressure, W_{m2} = 13106.56N
The minimum bolt cross section area A_{min} = 4259.44mm^2
Actual bolt circle area, A_b = 5089.4mm^2
Flange thickness, t_f = 56.6mm

6. CONCLUSIONS

Based on the above study it is clear that shell and tube heat exchanger is a versatile type of heat transfer apparatus, and for this reason it is the most commonly used type of heat exchanger in a variety of applications. It is given a great respect among all the classes of heat exchangers. Moreover very well-designed and well-described methods are available for its designing and analysis (such as the Kern's LMTD method). It has great advantages of pressures and pressure drops can be varied over a wide range, thermal stresses can be accommodated at relatively low cost. Cleaning and repair are relatively easy.

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