Design and Analysis of Filter Tube Sheet of Pressure Vessel Against Fatigue and Fouling

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Abstract - Many Petroleum industries use Filter sheet vessel for various applications. It generally deals with filtering the Natural gas immediately after it is mined. During these operations, natural gas contains common but serious contaminant e.g. sulphur in the form of H2S, SO2, CH4S, OCS and CS2. Of these sulphur combines with sand to create a rough particulate impurity like slogging, clogging, fouling etc. Filter tubes in pressure vessels provides a large surface for filtration. These tubes are made up of ceramics, steel etc and provide filtration up to 0.1 micro mm. But due to continuous use, these filter tubes gets layer of clog on surface which raises the overall pressure in the vessel. This pressure rise has some limits which cant exceeds beyond certain limits because of stability issues. Due to this reason the filter tubes are cleaned once a month/ week. This causes shut down of whole plant during cleaning which affects the economic costs due to loss of production. This problem can be reduced by designing a self cleaning filter unit which is divided into two sections and after every 4 to 5 seconds one of the compartments receives a reverse pressure of 1 sec and washes out the filter tubes. This system of cleaning of tubes without stopping the plant gives good results without reduction in production and since it is a regular cycle so its needs to be shut down the plant once a year for full clean-up. However, due to reverse pressure, the stress profile in the filter changes from tensile to compressive, creating possibility of fatigue. The main aim of this project work is to design of filter tube sheet on basis of working parameters, analyze the fatigue variation with modified concept using finite element analysis method to avoid fouling, slog and fatigue.

Key Words: FEA, tube sheet, fatigue, cyclic loads, de-clogging, Fouling.

1. INTRODUCTION

The present work predicting the fatigue life of the tube sheets (used as main supporting element in large filter vessels), by design modification using proposed working cycle and transient analysis of the same. The application of the filters which is considered in this project is of petro chemical industries. This analysis finds application in natural gas filtering when it is immediately mined from the ores.

A tube sheet can be defined as perforated circular sheet or a plate with a pattern of holes (triangular / rectangular) specially designed to accept pipes or tubes. These tubesheet facilitate the smooth flow of fluid inside the tubes and also support and isolate the boilers, heat exchangers and other types of filter elements. The variety of material use to make tube sheet ranges from different types of metal, resin composites, ceramics or plastic. Cladding / insulating material / sacrificial /galvanic anode method is used as a corrosion barrier and insulator and may also be fitted with a galvanic anode which covers the tubesheet during its manufacturing.

Figure 1: Assembly of Pressure Vessel & tube sheet

Generally tubesheet are used in bundles in filters, boilers and heat exchangers with thin walled dense arrangements. These Tubes are supported on either end or in between according to specified design by sheets which drilled in specific pattern, generally triangular or rectangular to allow the tube ends to pass through the sheet. The ends of the tubes which are fixed in the tube sheet are expanded by means of flowing fluid and getting fixed in closed chamber to form a seal and makes a complete unit between the tube sheets. Flanges and tubesheet are bolted to make rigid unit to avoid any further design issues. The shell of heat exchanger extends beyond the end of tube sheet and is sealed, to form two closed chambers on the non-tube ends. An arrangement is formed where the heat exchanger / boiler consists of different chambers joined by tubes. Heated fluid generally in gaseous or liquid forms including other foreign materials from ore i.e. minerals etc. is then passed from one end to the other end of chamber through the tubes using various metallurgical processes like hydrometallurgy, pyrometallurgy or electrometallurgy. Generally these flowing fluid are high in temperature which creates to increase in temperature of tubesheet. Attempt can be made...
to increase the velocities of these fluids which otherwise can create fouling and creating cloggy surface on the tubesheet or on the surface of tubes. Also this fouling can be reduced by analysing the fatigue life behaviour of the tubesheet by transient analysis. Design calculation of tubesheet and its pattern to fixe tubes is somewhat complex process. These patterns include triangular or rectangular holes to have maximum tubes on the tubesheet with reduction in fouling and fatigue. Many computer aided technologies like CAD, CAM, and FEA are used now a day for safer design and analysis of the tubes and tubesheet. Tube sheets have pattern of holes with designed diameter and pitch. The portion between these holes is called ligament and the cross sectional area of the ligament w.r.to the area in a normal unpercieved cross section of width is called ligament efficiency. The Stress Concentration Factor (SCF) is defined as the ratio of maximum principal stress in the stressed model to the nominal stress applied at the boundary of the plate. As tubesheet plays a vital role in design and analysis of the pressure vessel it should be carefully studied for various loads and working conditions. The thickness of the tubesheet varies directly to the costing and procurement of various component of pressure vessel. Thicker tubesheet results in longer tube length inside the tubesheet that do not take part during working operations. The primary aim of this project is to evaluate the fatigue life design of tubesheet by determining and analysing the effects of instant back pressure for cyclic loadings using Finite Element Analysis. The diameter, thickness and other design parameters are studied for given mechanical and working parameters for efficient and safe performance of the pressure vessel. Also various possible causes of fouling and clogging are theoretically analysed to find out suitable solution to avoid risk of fluing in tubesheet. This Research paper includes various design calculations using standard ASME codes for pressure vessel tubesheet. A mathematical modelling has been prepared by considering tubesheet as a flat plate with center hole, for verifying the designed and FEA solution. Further dynamic and transient analysis has been done with FEA software ANSYS for evaluating the fatigue life of the tube sheet.

1.1 Problem Definition

Tube Sheet filters is cleaned by applying back pressure, and the pollutants are then collected at the opposite end of the vessel. Industrial filters do this operation once a month. However in a Coal gas plant, the level of impurities is high, and this results in dense clogging of the filters within 5 days, and severe damage is caused to the filter and assembly due to the heavy built up of pressure as the tube get clogged. To tackle this problem, an instantaneous back pressure mechanism has been developed, which delivers 5 seconds of back pressure after 14 seconds of front pressure. This de-clogs the filters and reduces chances of pressure built up. However, due to back pressure, the stress profile in the filter changes from tensile to compressive, creating possibility of fatigue.

1.2 Objectives

1) To analyse the filter sheet for the load cycle specified.
2) To Study the possible causes and remedial measure of fouling on tube sheet surface.
3) To Study the effect of variation of parameters on the performance of the system. Since Flammable gases are involved in the process, safety is of prime importance.
4) To perform an ideal case analysis to benchmark the normal stresses during operation.
5) To conduct Transient analysis to check performance under a single cycle operation.
6) To perform Fatigue analysis to be undertaken to check the life of the component.
7) To modify the design if the fatigue life is not up to requirements.
8) To perform Tests will be to benchmark the modifications.

1.3 Scope

1) Three dimensional modeling of the tube sheet using any suitable CAD modeler, Viz. CATIA /ANSYS Workbench.
2) Finite element analysis (dynamic and transient) using suitable solver viz. ANSYS14.0.
3) Load cycle analysis by graphical methods using MS Office Excel and word.
4) Determination of fatigue and the stress profile on the filter due to pressure variation from tensile to compressive.
5) Comparative analysis with existing results of similar products.
6) Cost estimation for optimized solution.

1.4 Methodology

During normal operation, air flows inward through the intake duct and passes through the filter elements. Duct is collected on the outside surfaces of the elements. Clean air flows through the center of the elements into the clean air storage elements.

Figure 2: Basic operation of filter tube sheet
Creating pressure rises. Once the allowable value is reached it need to shut down the plant and apply back pressure to clean the filter tubes. However when the filter tubes are being cleaned, the entire plant line has to be shut down. This comes with economic costs as the production of the pant reduces. Furthermore after restarting the system takes 30 mins to reach full capacity which further augments the production losses. Furthermore this cleaning is needed every month creating schedule losses.

To reduce the production losses and scheduled losses in the system a new system has been incorporated which reduces the compulsion of shut down of entire plant line for cleaning of filter tubes and also increases the overall productivity of the plant. The newly designed compartments are divided into two compartments as shown in figure after every 5 seconds one of the compartments receives a back pressure of 1 second, and cleans the filter tubes. This ensures cleaning without stopping the plant, plus since this is in regular cycles, plant shutdowns for full clean up are needed only once a year. During filtration process the compressed gas is passed through the gas inlet chamber to the Filter elements. This gas is collected at the top of the filter compartment. Blow pipes with nozzles are provided for providing the back pressure and clean the filter elements. A compressed air supply is provided for creating a high intensity back pressure. The process of creating back pressure is divided into number of cycles for cleaning number of chambers.

**Conventional and Proposed Filtration Process**

When natural gas is mined it contains contaminants. The most common and serious contaminants is sulphur, usually in the form of oxides, these sulphur at times combines with sand to create a rough particulate impurity. The gas is usually considered sour if the hydrogen sulphide content exceeds 5.7 milligrams of H2S per cubic meter of natural gas. Filter tubes are the most commonly used filter options as they provide a large surface for filtration. They are typically made of ceramic and provide filtration up to 0.1 micro m.m. However these filters do get clogged over a period of time. Once they get clogged they obstruct the flow of offflow of gases.

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**Table 2: LITERATURE REVIEW**

<table>
<thead>
<tr>
<th>Title of Publication</th>
<th>Author and Publisher</th>
<th>Findings / Concluding remarks</th>
<th>Work to be completed / scope</th>
</tr>
</thead>
<tbody>
<tr>
<td>A finite element Benchmark for the Dynamic Analysis of Perforated Plates with a Square Penetration Pattern</td>
<td>D.L. Kaap, M.A. Sprague, R.L.Engelstad (2018)</td>
<td>for the dynamic of perforated plates with a square penetration pattern</td>
<td>Effect of reduction in thickness of the tubesheet and its result on tubesheet stresses and design modification considering this changes.</td>
</tr>
<tr>
<td>Gas-side fouling, erosion and corrosion of heat exchangers for middle/low temperature waste heat utilization: A review on simulation and experiment</td>
<td>Ming-jia Li, Song-Zhen Tang, et.al. in ELSEVIER (2017)</td>
<td>The simulations and experimental studies for the fouling, erosion and corrosion of heat exchangers.</td>
<td>Fatigue and transient analysis with effect to reduce the fouling. Design modifications to reduce the stresses due to variation in thickness of tubesheet.</td>
</tr>
<tr>
<td>Strength Analysis of Tube to Tubesheet joint in Shell and Tube Heat Exchanger*</td>
<td>Kotcherla Sriharsha, Venkata Ramesh Mamilla and M.V. Mallikarjun in IISET indifference</td>
<td>The strength analysis of a typical tube to tube sheet joint in shell and tube heat exchanger.</td>
<td>Fatigue and fouling behavior with design modifications and FEA analysis through transient and dynamic approach.</td>
</tr>
<tr>
<td>Analysis of the Tubesheet Cracking in Slurry Oil Steam Generators.</td>
<td>L.K. Zhu, L.J. Qiao, X.Y. Li, B.Z. Xu, W. Pan, L. Wang, Alex A. Volinsky in ELSEVIER.</td>
<td>Analysis of the tube sheet cracking in slurry oil steam generators. Tubesheet to increase the service life.</td>
<td>Same as above with further work related to tubesheet in pressure vessel.</td>
</tr>
</tbody>
</table>

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**Figure 3: The proposed filtration process**

The process repeats itself over and over again. However one of the crucial components is the filter sheet itself. This sheet stress reversals from positive to negative and is susceptible to fatigue.
3. DESIGN AND MATERIAL SELECTION

3.1 Material Selection

Materials are selected according to the following criteria.
1) Corrosive or noncorrosive service
2) Contents and its special chemical/physical effects
3) Design condition (temperature)
4) Design life and fatigue affected during the plant life
5) Referenced codes and standards
6) Low temperature service
7) Wear and abrasion resistance
8) Welding and other fabrication processes

During analysis and testing of tubesheet of pressure vessel in this case the material used is SA 516 GR70 having following properties,

Table 1: Properties of the tubesheet material

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Grade 55</th>
<th>Grade 60</th>
<th>Grade 65</th>
<th>Grade 70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon, max and under</td>
<td>0.18%</td>
<td>0.21%</td>
<td>0.24%</td>
<td>0.27%</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.60-0.90%</td>
<td>0.60-0.90%</td>
<td>0.85-1.20%</td>
<td>0.85-1.20%</td>
</tr>
<tr>
<td>Tensile strength in ksi</td>
<td>55-75</td>
<td>60-80</td>
<td>65-85</td>
<td>70-90</td>
</tr>
<tr>
<td>Yield strength in ksi</td>
<td>30</td>
<td>32</td>
<td>35</td>
<td>38</td>
</tr>
</tbody>
</table>

Careful examination reveals that a material with maximum carbon content of 0.18%, manganese content of 0.90%, 70 ksi tensile strength and yield strength of 38 ksi will satisfy the requirements for all grades of SA-516. If the material also meets all other requirements of the specification, then it may be marked for all four grades of SA-516. The material taken for tubesheet is SGR 590, as per the specifications of ASME codes.

3.2 Design Calculation

For design calculations, ASMEVIII, Div 1, TEMA codes and UHX of ASME BPVC part VIII-1 is used.

All necessary design values for the calculation are listed.

Table 2: Tubesheet Parameters for Design Calculations (Instant Back Pressure)

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Parameter Description</th>
<th>Notations</th>
<th>Given Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Internal Pressure</td>
<td>P</td>
<td>0.14 MPa</td>
</tr>
<tr>
<td>2</td>
<td>External Pressure</td>
<td>P0</td>
<td>Atmospheric</td>
</tr>
<tr>
<td>3</td>
<td>Process Volume</td>
<td>Vp</td>
<td>126 cu m</td>
</tr>
<tr>
<td>4</td>
<td>Expected Stagnant Volume</td>
<td>Vs</td>
<td>Not Specified</td>
</tr>
<tr>
<td>5</td>
<td>Buffer Volume Requirement</td>
<td>Vb</td>
<td>Not Specified</td>
</tr>
<tr>
<td>6</td>
<td>Tube Porosity Volume</td>
<td>Tp</td>
<td>70</td>
</tr>
<tr>
<td>7</td>
<td>Tube Length</td>
<td>Tt</td>
<td>5.5m</td>
</tr>
<tr>
<td>8</td>
<td>Radius of tube sheet</td>
<td>r</td>
<td>2m</td>
</tr>
<tr>
<td>9</td>
<td>Tube Diameter</td>
<td>d</td>
<td>0.15m</td>
</tr>
</tbody>
</table>

A 5% Gap will be maintained on the Tube Sheet radius to allow for welding. Tubes shall be spaced in a manner such that they form a 60 deg Equilateral Triangle.

Calculations for unknown parameters:

Total volume = Pressure Volume + Expected Stagnant Volume + Buffer Volume

\[ V = V_p + V_s + V_b \] 

\[ V = V_p + 0.1V + 0.01V \] 

\[ V(1 - 0.1 - 0.01) = V_p \]

\[ V(0.89) = 126 \times 109 \]

\[ V = 1.415730 \times 1011 \text{mm}^3 \]

Buffer Volume = \[ V_b = 0.01V = 1.415730 \times 109 \text{mm}^3 \]

Stagnant Volume = \[ V_s = 0.1V = 1.415730 \times 1010 \text{mm}^3 \]

Here, \[ V_s > 0.1V_p \]

Hence, the vessel is characterized as a full process reactionary vessel.

Referring A2209, for full process reactionary vessel, \[ V_p = (0.90NTD) \times (\pi r^2) \] (NTD is nozzle to nozzle distance in meters).

\[ 126 \times 109 = 0.90 \times NTD \times \pi \times r^2 \]

\[ NTD = 11146.4968 \text{mm} \]

i.e. NTD = 11.146 metres

Now, \[ Vs + V_b = (0.82L1) \times (\pi r^2) \]

Here, \[ Vs > V_b \]

Calculations for Tube sheet volume (\( T_s \)):

\[ T_s = \frac{\pi}{4} (3800)^2 \times T_t \]

Assuming \[ T_t = 1 \text{mm} \]

\[ T_s = 11341.1494 \times 103 \]

The above volume is reduced value of actual tube sheet volume by 5% for welding space.

Calculation for tube volume:

Total volume = \[ \frac{\pi}{4} T_d^2 \times T_L \] \[ \text{.....} T_L = T_t \]

\[ T_v = 17671.458 \text{mm}^3 \]

Calculations for ‘n’ no of holes,

\[ T_v / T_s = 0.3 \]

\[ 0.3 = 1 - \frac{\text{Tube volume}}{\text{Tube sheet volume}} = 0.7 \]

\[ 0.7 = \frac{\text{Tube volume}}{\text{Tube sheet volume}} \]

\[ 11341.1494 \times 103 \times 0.7 = 17671.458 \times n \]

\[ n = 449.244 \text{ nos} \]

Calculations for ligament efficiency,

\[ \frac{\text{Area remaining after drilling holes}}{\text{area before drilling the holes}} = \frac{D - nd}{D} \]

\[ = \frac{4000 - (22 \times 150)}{4000} = 0.175. \]

Calculations for Tubesheet thickness,

Referring ASME section VIII, div-I, page no. 34.

\[ t = d \sqrt{C.P \over S.E} \]
For, 1000°C i.e. SA516 GR70
S = 20.0KSi
S = 137.895 N/mm²

\[ t = \frac{4000 \times 0.2 \times 0.14}{137.895 \times 0.175} = 136.253 \text{m} = 137 \text{mm} \]

Recalculating volumes considering tube sheet thickness,
\[ V_p = 1.1 \left( V_p' + Tr \right) + 1.2 \left( P_t \times T_d \times T_d \right) \times \left( Tp / 400 \right)N \]
But \( Tr / Tp = 0.3 \)
\[ Tr = 5301.43 \text{mm} \]
\[ Td = 150 \text{mm (Tube Diameter)} \]
\[ Tp = 70 \text{ (Tube Porosity Volume)} \]
\[ N = 450 \text{ nos. (No of tubes)} \]
\[ V_p = 1.14191781 \times 1011 \text{ mm}^3 \]
For full process reactionary vessel,
\[ V_p = (0.90 \text{ NTD}) \times (\pi \times 2) \]
\[ 1.41 \times 1011 = (0.90 \times NTD) \times \left( \pi \times 20002 \right) \]
\[ \text{NDT} = 12548.290 \text{mm} \]
i.e. \( \text{NTD} = 12.54 \text{m} \).

Now Total volume, \( V = V_p + V_b + V_s \)
Where, \( V_b = 0.01 \text{ and } V_s = 0.1 \text{V} \)
\[ V = 1.41 \times 1011 + 0.01 \times 0.1 + 0.1 \]
\[ V = 15944943 \times 109 \text{mm}^3 \]
\[ V_b = 0.01 \times 15944943 = 106 \text{mm}^3 \]
\[ V_s = 0.1 \times 15944943 = 106 \text{mm}^3 \]
Now, \( V_s + V_b = (0.82 \times L1) \times (\pi \times 2) \)
Here, \( V_s > V_b \),
Hence considering \( V_b = V_s \)
\[ 2V_s = (0.82 \times L1) \times (\pi \times 20002) \]
\[ L1 = 3094.776 \text{ mm} = L1 = 3.094776 \text{ m} \]

**Design of Shell:**

According to ASME Section-VIII, Division-I, UG27,

Thickness of Shell (tshell) = \( \frac{P_R}{SE - 0.6P} \)

\[ tshell = \frac{0.14 \times 2000}{137.895 \times (0.6 \times 0.14)} = 2 \text{mm} \]

According to ASME Section-VIII, Division-I, UG32,

Thickness of ellipsoidal head (thead) = \( \frac{P_D}{2SE - 0.2P} \)

\[ thead = \frac{0.14 \times 4000}{2 \times 137.895 \times (0.2 \times 0.14)} = 2.029 \text{mm} \]

But according to According to ASME Section-VIII, Division-I, the thickness of shell as well as ellipsoidal head should be taken minimum 6mm.

**Design of Nozzle:**

According to ASME Section-VIII, Division-I, UG36,

\[ t_m = \frac{P_d}{2a_f - P_t} = 0.14 \times 300 = \frac{0.14 \times 4000}{(2 \times 137.85 \times 0.6) - 0.14} \]

\[ t_m = 0.1544 \text{mm} \]

Similarly,

\[ t_r = \frac{P_{d,shell}}{2a_f - P_t} = \frac{0.14 \times 2000}{(2 \times 137.85 \times 0.6) - 0.14} \]

\[ t_r = 3.388 \text{mm} \]

But as per ASME codes minimum thickness should be taken as 6mm.

\[ h = 2.5(\text{tr} - \text{CA}) = 2.5(6 - 3) = 7.5 \text{mm} \]

\[ d = \text{di} + 2\text{CA} = 300 + (2 \times 3) = 306 \text{mm} \]

\[ x = d \text{ or whichever is maximum} \]

\[ x = 306 \text{mm} \]

OR

\[ x = \frac{d}{2} \]

\[ x = 153 \text{mm} \]

Therefore, taking maximum value as, 306mm

**Area calculation:**

Area pertaining to material removed
\[ i.e. A = d.tr = 306 \times 3.388 = 1036 \text{mm}² \]

Excess area in the shell,
\[ A_1 = (2x - d) (t - tr - CA) \]
\[ = [(2 \times 153) - 306] [6 - 3.388 - 3] = 0 \]

Excess area in the nozzle,
\[ A_2 = 2h(tn - tr - CA) = 2(3.1)6(0.154 - 3) \]
\[ A_2 = 42.69 \text{mm}² \]

Excess area in the nozzle inside the shell,
\[ A_3 = 2h(2t - CA) = 2(3.1)6 - (2 \times 3)] = 0 \]

Therefore required area,
\[ Ar = A - (A_1 + A_2 + A_3) = 1036 - (0 + 42.69 + 0) \]
\[ Ar = 993.31 \text{mm}² \]

**Design of Reinforcement pad,**

\( d_{ip} = \text{internal diameter of RF pad} \)
\( d_{op} = \text{external diameter of RF pad} \)
\( t = \text{thickness of RF pad} \)
\( d_{op} = d_i + 2t = 300 + (2 \times 6) = 312 \text{mm} \)
\[ \text{load} = \frac{A_t}{t_p} = \frac{993.31}{312} = 477.55 \text{mm}² 478.44 \text{mm}² \]

**Design of flange,**

(Referring PV Engineering design calculation as per ASME standards)

Load on projected area = pressure x projected area.
\[ P = (0.14 \times 4000) \text{ i.e. } P = 560 \text{N} \]

Nomenclature,
\[ A = \text{Flange overall diameter} = 162'' \]
\[ Bn = \text{Flange internal diameter} = 157.5'' \]
\[ TFlange = \text{Flange thickness} = 0.5'' \]
\[ Rf = \text{Hub corner radius} = TFlange/2 = 0.25'' \]
\[ Gof = \text{Hub thickness} = 6mm = 0.25'' \]
\[ GI = \text{Hub base thickness} = 6mm = 0.25'' \]
\[ m = \text{gasket factor} \]

Referring PV Engineering Data sheet,
\[ B = Bn + 2CA = 157.5 + (2 \times 0) = 157.5'' \]
\[ VarR = [(VarC - VarB)/2] - g1 \]
\[ VarC = \text{Bolt circle diameter} = (PCD) bolt = 162 - 2 = 160'' \]
\[ VarB = 157.5'' \]
\[ VarR = [(160 - 157.5)/2] - 0.25 = 1'' \]
\[ GID = 157.5 + (G0/2) = 157.5 + (0.25/2) = 157.625'' \]
\[ GOD = 159'' \]
\[ VarN = \frac{G_{OD} - G_{ID}}{2} = \frac{159 - 157.625}{2} = 0.687'' \]
\[ G0 = N/2 = 0.687/2 = 0.3437'' \]
\[ b = \text{if } (b0 > 0.25 \text{ then } , b0) \]

Here, \( b0 > 0.25 \)
Design of bolt

H = 0.785 (VarG)2 Pr
= 0.785 (158.414)2 20.305
H = 399.99 103 Pounds.................end load
He to be considered wind pressure here,
He = [0.785 (VarG) 2 0.0265] < H
Hp = 2 VarB 3.14 VarG m P
= 2 0.293 3.14 158.414 3 20.305
= 17755.9974 Pounds.................contact load
Wm1 = H + Hp = (399.99 103) + 17755.9974
Wm1 = 417745.99 Pounds.................bolt load.

Bolt area required,
Am = \( \frac{W_{m1}}{159.15^2} \) = 20.887 \text{m}^2.................bolt area.
Now, \( Am = 0.87 \) ".............for bolt area.
No. of bolts = \( \frac{Am}{0.87} = 24 \text{nos.} \)

Total length of the shell,
L0 = NTD + (RF Pad)OD = 12.54 + 0.3556 = 12895.6 mm.
Reinforcement pad diameter = 14" = 355.6 mm.

Approved Design Modification after Testing,

- Bottom nozzle size will be increase to 700 mm and there will be 2 nozzles at 180 degree orientation.
- Nozzle on the dish end will also be upgraded to 500 mm dia; this is because SGR 590 has tendency of coagulating impurities into larger blocks.

Pressure Cycle
For SGR 590 the following pressure cycle is present for one chamber of the sheet.
0 - 5 sec 0.14 MPa (Up) A
5 - 6 sec 0 MPa
6 - 10 sec 0.145 MPa (Back) B
10 - 11 sec 0 MPa
When chamber 1 is at cycle A, chamber 2 will be at cycle B. Both will be shut off at the same time.
During Shutoff, the accumulation of gas will increase the upward pressure up to 0.143 MPa.
Since the entire process is working at differential of 0.005 MPa, Max upward pressure will be 0.145 MPa.
Design Pressure is hence considered to be \( 1.2 \times 0.145 = 0.174 \text{ MPa} \), which will be the test pressure.
Corrosion allowance is considered to be 3 mm.

Modified design calculations:
Calculation for tubesheet thickness, Referring ASME codes section VIII, division-I, UG 34, \( t = \frac{d}{2} \frac{C}{6} \)
Where, \( C = \text{factor considering the method of attachment} \) (0.20 for fillet welding).
\( d = \text{diameter of vessel} \)
\( P = \text{internal pressure} \)
\( S = \text{Allowable stress} \)
\( E = \text{efficiency (summation of ligament and joint efficiency)} \).
For given material, i.e., SA516 GR70, allowable stress = \( S = 20.0 \text{ksi} = 137.895 \text{ N/mm}^2 \).

Volume of tubesheet (Tv),
Tv = \( \frac{\pi}{4} \times d^2 \times T \)
Where, \( T \times t = \text{tubesheet thickness} \)
Tv = total volume of the tubesheet
\( TL = \text{tube length} \).
Tv = \( \frac{\pi}{4} (4000)^2 \times 1 \)
Considering, \( T = 1 \text{mm} \)
Tv = 125663.71 \text{103mm}^3.
Reducing 2.5% space for welding, i.e., taking diameter = 3900 mm.
Tv = \( \frac{\pi}{4} (3900)^2 \times 1 \)

Volume of tube (Tv),
Now tube diameter = 0.14 m = 140 mm
Considering length of the tube = length of tube sheet,
Tubesheet volume = \( \frac{\pi}{4} \times T^2 \times T_L \)..............(TL = T)
Tube volume = \( \frac{\pi}{4} (140)^2 \times 1 \)
Tube volume = 15393.804 \text{mm}^3.

Calculation for no. of holes on tubesheet,
Volume of holes = 15393.804 n
Residual volume = tubesheet volume – tube volume
\( TR = TV - TT \)
But \( TR/TV = 0.3 \)
i.e. $0.3 = 1 - \frac{\text{Tube volume}}{\text{Tube sheet volume}} = \frac{15393.804 \times n}{11945.906 \times 10^3}$

$n = 543.214 \times 544$ holes.

Total pitch = total diameter - (2.5%diameter) - diameter of hole = Total pitch = $3900 - 140 = 3760$mm.

for locating the holes,
Considering pitch as 1.1d, we get,
Pitch = $1.1 \times 140 = 154$mm.

i.e. $2b = 154$mm

$b = 77$mm

$a = b (\tan 60)$

$a = 77 (\tan 60)$

$a = 133.3679$mm.

Number of holes arranged = 509

Ligament efficiency, $\eta = \frac{D - 2a}{D} = \frac{4000 - (24 \times 140)}{4000}$

$\eta = 0.16$

Now, thickness of tubesheet, $t = \frac{0.2 \times 0.14}{137.895 \times 0.16}$

$t = 142.49$ 150mm (minimum to be taken for tubesheet design as per ASME code).

4. EXPERIMENTAL ANALYSIS

4.1 FEA Analysis

Filter sheet bending failure usually follows a path from the center of filter holes pattern to outside surface of filter sheet. Fractures are usually asymmetric and it is often possible to decide whether the bending loads leading to fracture are the results of gas loads. High gas loads induce tensile stresses in the filter sheets.

In the project four different cases of loadings on tubesheet has been considered, to analyze the effects of cyclic loadings on tubesheet as follows, CAD Model of Tubesheet using CAD Modeler. Import this model in ANSYS workbench for Meshing. Mesh generation has been done using HEX and TET element of ANSYS 14.5. Results has been tabulated for both elements considering different load conditions to evaluate the convergence factor and nature of curve between number of nodes vs deformation & stress value. Thus Fatigue life has been evaluated using transient analysis in ANSYS 14.5 solver. Various testing results have been compared with FEA solution to determine infinite fatigue life behavior.

Case I: Self Weight and Gravity Load (TET element)

<table>
<thead>
<tr>
<th>No. of Nodes</th>
<th>Element Size</th>
<th>Max Deformation (mm)</th>
<th>Max Stress (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>110814</td>
<td>95</td>
<td>0.67284</td>
<td>34.065</td>
</tr>
<tr>
<td>150019</td>
<td>64</td>
<td>0.70022</td>
<td>34.037</td>
</tr>
<tr>
<td>220253</td>
<td>54.5</td>
<td>0.71235</td>
<td>35.264</td>
</tr>
<tr>
<td>250225</td>
<td>50</td>
<td>0.71512</td>
<td>35.013</td>
</tr>
<tr>
<td>297126</td>
<td>37.5</td>
<td>0.71817</td>
<td>35.944</td>
</tr>
<tr>
<td>355759</td>
<td>35</td>
<td>0.71837</td>
<td>35.148</td>
</tr>
</tbody>
</table>

Case II: Gravity with Design Loads in opposite direction of gravity (TET element)

<table>
<thead>
<tr>
<th>No. of Nodes</th>
<th>Element Size</th>
<th>Max Deformation (mm)</th>
<th>Max Stress (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>110814</td>
<td>95</td>
<td>0.72728</td>
<td>38.015</td>
</tr>
<tr>
<td>14974</td>
<td>64</td>
<td>0.80331</td>
<td>38.231</td>
</tr>
<tr>
<td>222416</td>
<td>54.5</td>
<td>0.81815</td>
<td>38.352</td>
</tr>
<tr>
<td>250544</td>
<td>50</td>
<td>0.82115</td>
<td>38.361</td>
</tr>
<tr>
<td>298837</td>
<td>37.5</td>
<td>0.82449</td>
<td>38.36</td>
</tr>
</tbody>
</table>
Case III: Gravity with Back Pressure in the direction of gravity (TET element)

<table>
<thead>
<tr>
<th>No. of Nodes</th>
<th>Element Size</th>
<th>Max Deformation (mm)</th>
<th>Max Stress (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>110814</td>
<td>95</td>
<td>1.9762</td>
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<td>150019</td>
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<td>222053</td>
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<tr>
<td>250225</td>
<td>50</td>
<td>2.1</td>
<td>99.829</td>
</tr>
<tr>
<td>297126</td>
<td>37.5</td>
<td>2.1083</td>
<td>98.742</td>
</tr>
<tr>
<td>355759</td>
<td>35</td>
<td>2.1091</td>
<td>98.327</td>
</tr>
</tbody>
</table>

Case IV: Positive and Negative Pressure both at a Time (TET element)

<table>
<thead>
<tr>
<th>No. of Nodes</th>
<th>Element Size</th>
<th>Max Deformation (mm)</th>
<th>Max Stress (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>110853</td>
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<tr>
<td>149744</td>
<td>64</td>
<td>0.99743</td>
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<tr>
<td>222416</td>
<td>54.5</td>
<td>1.0172</td>
<td>61.575</td>
</tr>
<tr>
<td>250544</td>
<td>50</td>
<td>1.0212</td>
<td>62.146</td>
</tr>
<tr>
<td>298837</td>
<td>37.5</td>
<td>1.0255</td>
<td>62.056</td>
</tr>
<tr>
<td>355381</td>
<td>35</td>
<td>1.0256</td>
<td>62.101</td>
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</tbody>
</table>

Transient Analysis

**CASE I: (Without gravity)**

<table>
<thead>
<tr>
<th>Time</th>
<th>Wmax</th>
<th>Max Stress</th>
<th>Time</th>
<th>Wmax</th>
<th>Max Stress</th>
</tr>
</thead>
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<td>1.1286</td>
<td>6.2</td>
<td>1.32E-02</td>
<td>1.2333</td>
</tr>
<tr>
<td>0.4</td>
<td>2.31E-02</td>
<td>2.2638</td>
<td>6.4</td>
<td>2.17E-02</td>
<td>2.0087</td>
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<tr>
<td>0.6</td>
<td>3.34E-02</td>
<td>3.2746</td>
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<td>0.8</td>
<td>4.50E-02</td>
<td>4.4112</td>
<td>6.8</td>
<td>4.44E-02</td>
<td>4.13</td>
</tr>
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<td>1</td>
<td>5.64E-02</td>
<td>5.5351</td>
<td>7</td>
<td>5.84E-02</td>
<td>5.4384</td>
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<tr>
<td>1.2</td>
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<td>6.6711</td>
<td>7.2</td>
<td>6.80E-02</td>
<td>6.3314</td>
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<td>7.95E-02</td>
<td>7.7958</td>
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<tr>
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<td>8.9308</td>
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<td>8.5312</td>
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<td>9.7498</td>
</tr>
<tr>
<td>2</td>
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<td>11.19</td>
<td>8</td>
<td>0.11524</td>
<td>10.728</td>
</tr>
<tr>
<td>2.2</td>
<td>0.12559</td>
<td>12.317</td>
<td>8.2</td>
<td>0.12793</td>
<td>11.911</td>
</tr>
<tr>
<td>2.4</td>
<td>0.13715</td>
<td>13.45</td>
<td>8.4</td>
<td>0.13878</td>
<td>12.92</td>
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<tr>
<td>2.6</td>
<td>0.14864</td>
<td>14.577</td>
<td>8.6</td>
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<td>2.8</td>
<td>0.16019</td>
<td>15.709</td>
<td>8.8</td>
<td>0.16228</td>
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</tr>
<tr>
<td>3</td>
<td>0.17169</td>
<td>16.837</td>
<td>9</td>
<td>0.17447</td>
<td>16.244</td>
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<tr>
<td>3.2</td>
<td>0.18323</td>
<td>17.968</td>
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<td>3.4</td>
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<td>18.416</td>
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<td>0.20628</td>
<td>20.228</td>
<td>9.6</td>
<td>0.20921</td>
<td>19.48</td>
</tr>
</tbody>
</table>

Similar results were obtained for the same case (1 to 4) with "Hex" element for comparative analysis.

4.2 Transient Analysis

**CASE I: (Without gravity)**

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<td>0.20921</td>
<td>19.48</td>
</tr>
</tbody>
</table>

Similar results were obtained for the same case (1 to 4) with "Hex" element for comparative analysis.
4.3 Experimental validation

1) All new product equipments were be tested at 2.5 times the operating pressure using Hydro test.
2) The Hydro test has slow built up of pressure, from base pressure to test pressure over a period of 120 min.
3) The equipment is maintained at test pressure of 30 min.
4) The pressure gradually reduced to base pressure within a period of 45 min.
5) After test, all components subjected to NDT as below,
   a) No surface irregularities must be present.
   b) Pre Dyed components should have no loss of dye due to leakage.
   c) Ultra Sonic Testing – Post Test, internal damage shall get amplified if any, and shall be recorded in an Ultra Sonic Test.
6) The test performance of the assembly should be completely elastic; this shall be verified by checking the dimensions of product for any permanent yield.

Hydro Test Condition

- **Working fluid**: Water with Anti Scaling Additives
- **Test Pressure**: 2.5 x 0.07 MPa
- **Leak Inspection**: Sensors (LDR) on the top side of Filter assembly.
- **Method**: Visual Inspection on top side after completion of test.
- **Remark**: Simultaneous testing of all 7 chambers was done. Filter holes were plugged with caps of SA 204.

Test Execution Details

- **Begin Time**: 09.00 hrs
- **Base Pressure**: 0 MPa (Empty vessel)
- **Peak Pressure Time**: 11.00 hrs
- **Peak Pressure**: 0.175 MPa
- **Pressure relief begins Time**: 11.30 hrs

Visual Inspection Details

- No leak observed on Top Side of Assembly
- No visible damage observed after test.
- Plug Adhesion intact after test.

Auditors Remarks:

- Code requirements have been met by the analysis.
- The Mesh is satisfactorily fine enough to generate accurate results with considering boundary conditions.
• The maximum Stress in Filter sheet is 32 MPa, however nominal value if calculated is much lower, it satisfy FOS is 5.
• Gasket plate shows peak pressure of 34 MPa. However it is observed to significant stress raiser due to vicinity of contact and relatively less thickness of the plate compared to the other components.
• Material Non Linearity may not be modeled in future analysis as it will have negligible effect on accuracy and unnecessary increases solution time.
• FEA processing has been done in line with requirements of SA 516 GR70, FEA and the component maintains a FOS greater than 5 for the current boundary conditions.

5. CONCLUSION AND FUTURE SCOPE

5.1 Conclusions
• The filter tube sheet is analyzed for proposed load cycle of four stages compared to conventional and found satisfactory results with FEA and transient analysis to reduce fatigue.
• Theoretical approach of studying possible causes and remedial measure of fouling on tube sheet surface conclude that fouling can be reducing by design modification and implementing the mechanism by increasing the velocity of flue gases.
• Modified design calculations shows acceptable effect of variation of parameters on the performance of the system.
• Analysis results are reliable as seen in Mesh Sensitivity convergence and actual Testing.
• Concerned with FEA analysis more accurate results are achieved using HEX element compared to TET element with fine meshing but increased time.
• FEA Validation shows we can increase efficiency of Filter sheet by increasing number of tubes and maintaining Factor of Safety 5, to benchmark the normal stresses during operation.
• Transient analysis done for predicating the fatigue life shows satisfactory results.
• Transient analysis illustrates the scope for enhancement of infinite fatigue life of the tubesheet which will increase the overall efficiency.

5.2 Future Scope
• Further analysis can be done for different components of the pressure vessel such as shell, flange, support etc for evaluating the results to improve efficiency and life of the pressure vessel.
• Similar transient and dynamic analysis can be performed for thickness optimization of tubes as well as tubesheet.
• Design modification and its FEA analysis can be performed for different patterns of tubesheet hole and insertion in between the tube pathways to support the tubes with different materials, distances and thickness.
• Further Transient analysis can be performed for velocity and pressure calculations of flowing fluid effect on pressure vessel components using CFD analysis, so as to reduce time for fouling by the suit particles and other fouling materials.

ACKNOWLEDGEMENT

It is indeed a great pleasure and moment of immense satisfaction for me to present a seminar report on "Design and Analysis of Pressure Vessel Filter Tube Sheet against Fouling and Fatigue" amongst a wide panorama that provided us inspiring guidance and encouragement, I take the opportunity to thanks to those who gave us their indebted assistance. I wish to extend my cordial gratitude with profound thanks to our internal guide Prof. R. K. Nanwatkar and Prof. S. M. Jadhav. It was their inspiration and encouragement which helped me in completing my work. My sincere thanks and deep gratitude to Head of Department, Prof. D. H. Burande and other faculty member; but also to all those individuals involved both directly and indirectly for their help in all aspect of the project.

At last but not least I express my sincere thanks to the Institute's Principal Dr. S. D. Markande, for providing us infrastructure and technical environment.

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BIOGRAPHIES

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