Material selection and design of shell and tube heat exchanger for thermos-syphon steam generator

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Abstract. Pure steam generated by conventional boiler is not devoid of chemical additives, rust or other undesirable materials and fails to meet essential quality of steam needed for pharmaceutical and health care process industries for WFI (Water for Injection), sterilization of medical equipment and clean room humidification on account of the limitations in achieving desired standards needed by the qualities of ideal pure steam such as pH value, conductivity, bacteria count etc. as prescribed by the International Society of Pharmaceutical Engineers (ISPE). Dry and pure steam is produced by ‘pure steam generators’ using purification process of the plant steam and doesn’t contain any liquid droplets, any anti scaling additives and corrosion inhibitors. - Thermo siphon type Pure Steam Generator has been chosen in the present project for its extremely good heat transfer performance at low temperature differences, less sensitivity to large changes in process condition and more stable operation. In this paper design of the heat exchanger for generation of pure steam has been discussed. Here shell and tube type heat exchanger has been selected due to its flexibility of design, which allows wide range of pressures and temperatures. Standards laid out in ASME BPE for selection of material, CGMP and TEMA for design and manufacturing methods are followed for efficient and safe steam generation. Parameters given by the industry to meet customers’ requirements have been considered while designing the HE, its accessories, piping, valves and instruments. Thermal design of the two phase shell and tube heat exchanger has been done manually and validated using HTRI suite. The mean % error between HTRI results and manual results is 12.05%.

Keywords: Thermo siphon, shell and tube heat exchanger design, pure steam generator.

1. Introduction

Pharmaceutical and health care process industries where the steam comes in contact with a pharmaceutical or medical product, use pure steam to avoid contamination [1]. Steam from conventional
boiler (Plant steam), if utilized in such cases, does not meet requisite specifications because of the undesirable dissolved materials, chemical additives, or rust [2]. Pure Steam Generator produces pure steam known as Pyrogen, which is a free dry steam and in the condensed state meet the requirements of water for injection (WFI) [3]. Pharmaceutical industries use pure steam for the sterilization purposes. Steam Sterilization is mainly required in the manufacture of water used for injectable and use of pure steam for creating a sterile environment, or into autoclaves where vials and stoppers are sterilized [4]. Pure steam is also used for some other function like Clean Room Humidification.

The following tables illustrate the purity required of pure steam and the purity of water used in pharmaceutical industries as per published standards.

Table 1. Purified Water/ Feed Water Specification [5].

| Heading level      | Example                      |
|--------------------|------------------------------|
| P.H Value          | 5 to 7 at 25°C               |
| Conductivity       | ≤ 5 µs/cm at 25°C            |
| Chlorides          | Absent                       |
| Sulphates          | Absent                       |
| Metals             | Absent                       |
| Nitrates           | Absent                       |
| Micro Organisms    | < 1000 cfu/ml                |
| Total Organic Carbon| < 500 ppb                  |
| Bacterial endotoxin| < 25 EU/ml                  |
| Silica             | < 1ppm                       |

Table 2. Pure steam specification [6].

| Heading level         | Example                      |
|-----------------------|------------------------------|
| P.H Value             | 5 to 7 at 25°C               |
| Conductivity          | ≤ 1.3 µs at 25°C             |
| Total Bacteria count  | ≤ 10 cfu / 100 ml           |
| Total organic carbon  | < 500 ppb                   |
| Bacterial Endotoxin   | < 0.25 EU/ml                |
| Non-Condensable Gases | < 3.5%                      |
| Moisture Content      | < 5%                         |
| Pressure              | 2.5 kg/cm² to 3 kg/cm²      |
| Temperature           | 121°C to 136 °C             |

Pure steam should meet all the qualities mentioned above. Above Properties are collected after condensing the pure steam.

2. Overview of Pure Steam Generator

It is possible to purify the plant steam to some extent by using filters to remove undesired particles such as rust particles; however, it is not practically possible to remove vaporized condensable contaminants from steam [7]. Therefore, it becomes desirable to generate pure steam in a pure form, rather than purifying the plant steam. For producing dry steam it is ensured that feed water does not contain any corrosion inhibitors and anti-scaling
additives[8]. Advantages and disadvantages of different types of pure steam generators which are available in industries has been discussed in table 3[9].

| Generator type                      | Advantages                                                      | Disadvantages                           |
|-------------------------------------|-----------------------------------------------------------------|----------------------------------------|
| (1) Kettle Re-boiler type Pure Steam generator. | Low investment cost. Simple design like a boiler. All safety and controls. Already established as in case of commercial boiler. | Higher water holds up capacity. May lead to high down rates (High running cost). |
| (2) Thermo – Syphon type Pure Steam Generator | - Reduction in stress fatigue of tubes due to Short evaporator column - Easy maintenance. - Short external evaporator. | Recirculation rates and pressure drops (For two phase flow) are critical. Special design care is to be taken. |
| (3) Falling film evaporator         | Good steam quality. Least water hold up capacity.               | Long evaporator columns resulting in (a) Stress fatigue of tubes (b) Difficult maintenance. (c) Large space required for disassembly. |

Based on above comparison we decided to design Thermo-siphon type Pure Steam Generator. Thermosiphon type re-boiler gives extremely good heat transfer performances at low temperature differences, less sensitive large changes in process condition and therefore its operation is more stable[10]. As per market survey, approximately 107 new pharmaceutical plants are expected to come up in the country, in which number of pure steam generators required will be about 285[11]. Total market potential for steam generators in next three years is about Rs 45 crores. Fig 1 shows details of thermosyphon pure steam generator.

Like most pure steam generators, thermos-syphon pure steam generator is fitted with feed water heaters and makes use of generator’s blow down as the heating media [12]. This naturally results into added obvious advantage of cooling the blow down avoiding discharge of very hot and flashing water. If the feed water supply pressure is inadequate there may be a need of a feed pump. Pressure of feed water should be above the maximum steam pressure by 0.5 bar to 0.75 bar. This will overcome the pressure drop in pipes and valves[13].

Quality of condensate of pure steam is monitored by a sample cooler fitted with a conductivity meter. Conductivity of pure steam measured by conductivity meter is used for checking the final quality of steam [14]. It is necessary to supply the plant steam to the generator at higher pressure than the required pure steam pressure (7 - 8.5 bar).
Higher pressure difference between the plant and the pure steam pressure increases rate of pure steam generation. Plant steam pressure should be maintained higher than the pure steam pressure by 2 to 3 bar for maximum pure steam production. Plant steam consumption will be greater than the 10% to 20% of pure steam production [15].

Fig. 1. Schematic Diagram of Thermosyphon Pure Steam Generator

Conventional boilers has tendency to corrode fire tube sheets materials, so clean and pure steam generator boilers do not use gas or oil as the primary heat source. Therefore, in clean and pure steam generator boilers, plant steam or pressurized hot water or thermal oil is most commonly used as a heating source.

Even though steam generators use treated water as feed water, there is tendency to have concentrated contaminants in the low levels of hold up volume as the water is evaporated. Blow down process is often used to discharge these contaminants. The frequency of blow down is determined by the quality of the feed water. For the high quality feed water intermittent blow down may be adequate. However, for lower quality feed water, 15% continuous blow down of the feed water is required. Automatic control of the process use conductivity measurement of the holdup liquid. Blowdown often leads to flashing after release from the generator pressure and need to be cooled down. Blowdown water is used in larger generators to enhance energy efficiency by preheating the feed water through heat exchanger. Design of this heat exchanger has been discussed in this paper.
3. Heat Exchanger Design

Shell and Tube Heat Exchangers offers the flexibility of design allowing its use in wide range of pressures and temperatures making it one of the most popular types of heat exchanger. Two main categories of Shell and Tube exchanger are used in industries [16-17]. One used in the petrochemical industry and pharmaceutical industry and the second type are used in power industry such as power plant condenser and feed water heater. Heat exchangers used in the petrochemical and pharmaceutical industry should follow TEMA (Tubular Exchanger Manufacturers Association) guidelines. So here we have followed TEMA guidelines for heat exchanger design.

Shell and tube heat exchanger consist of shell, containing bunch of tubes, front header and rear header. Through the front header fluid enters the tube side. Sometime front header is also called stationary header. The tube side fluid leaves the exchanger from rear header after passing through multiple passes and is returned to the front header. Tube bundle comprises of the tube sheets, baffles and tie rod for holding the bundle together.

A double tube sheet design is adopted for welded shell and tube heat exchangers to prevent product contamination in the case of a tube joint failure. It’s imperative that the product contact surface must not be scored during fabrication when the tubes are to be expanded into the inner and outer tube sheets. It is to be ensured that tubes shall be seal welded to the outer tube sheet. And the distance between inner and outer tube sheets should be sufficient to allow leak detection and examination. Moreover, tube sheets and channels should be drainable [18].

For designing following standards are to be compulsorily taken into consideration while designing any product for pharmaceutical industry. The International Society of Pharmaceutical Engineers (ISPE) states the qualities of ideal pure steam required for pharmaceutical industry for pH value, conductivity, bacteria count etc. As per ASME BPE rules the material of construction is selected, its design methodology is finalized, fabrication techniques inspection etc. are finalized. As per CGMP general equipment requirements are considered so as to have highly efficient as well as best quality product. TEMA guidelines are compulsory to follow so as to design heat exchanger. TEMA standards provide most current, efficient design and manufacturing methods. [19-20].

4. Material Selection

Material selection is of utmost importance in the design of pure steam generator and heat exchanger due to tendency of corrosion of best of the steel materials and possibility of unacceptable impurity levels. Feed water use for producing pure steam tends to corrode carbon steel used in boiler and heat exchanger of the steam generation plant. This causes damage to components and pipe work besides contamination of steam. Corrosion of components tend to rapidly proliferate leading to the formation of ‘rouge’.

Corrosion resistant grades of stainless steel is used for manufacturing components of high purity steam system to avoid any possibility of corrosion as there is high possibility that the corrosion products may reach the point of use. Materials of construction are so selected that they are capable of withstanding the temperature, pressure, and chemical corrosiveness ensuring the purity and integrity of the product. Normally, stainless steel materials of 316, 316L grades and higher alloys have proven to be acceptable [16]. When nonmetallic materials are used (elastomers, adhesives plastics), the manufacturer shall specify the materials shall carry a compliance certificate.

| Material       | Weight% AISI304 | Weight% AISI316L | Weight% AISI316 |
|----------------|----------------|------------------|----------------|
| Iron (Fe)      | 66.4-74        | 65               | 65             |
| Nickel (Ni)    | 8-10.5         | 12               | 10-14          |
| Chromium (Cr)  | 18-20          | 17               | 16-18          |

Table 4. Stainless steel standards for pure steam generation.
As per requirement given by the industry following parameters have been used for heat exchanger design. Following equations have been used for design of heat exchanger.

### 4.1 Energy balances

Total heat carried by water has been calculated by equation 1

\[ Q_w = (m_w \times c_{Pw} \times \Delta T_w) \text{ pure water} + (m_w \times \lambda_w) \text{ pure water} + (m_s \times c_{Ps} \times \Delta T_s) \tag{1} \]

In the above equation,
- \( Q_w \) = Heat carried by water (kcal/hr)
- \( m_w \) = mass of water (kg/hr)
- \( c_{Pw} \) = Specific heat of water (kcal/kg\(^\circ\)C)
- \( \Delta T_w \) = Temperature difference between inlet and outlet of temperature (\(^\circ\)C)
- \( \lambda_w \) = Latent heat of water (kcal/kg)
- \( m_s \) = mass of steam = \( m_w \) (kg/hr)
- \( c_{Ps} \) = Specific heat of steam (kcal/kg\(^\circ\)C)
- \( \Delta T_s \) = Temperature difference of superheated steam (\(^\circ\)C)

Log mean temperature of the heat exchanger is calculated by equation 2

\[ \text{LMTD} = \frac{(T_2 - T_a) - (T_1 - T_b)}{\ln \left(\frac{T_2 - T_a}{T_1 - T_b}\right)} \tag{2} \]

Here,
- Inlet Temp of pure water 30\(^\circ\)C (\( T_a \))
- Outlet Temp of pure water 140\(^\circ\)C (\( T_b \))
- Inlet Temp of Plant Steam 164\(^\circ\)C (\( T_1 \))
- Outlet temperature of plant steam 160\(^\circ\)C (\( T_2 \))

### 4.2 Overall heat transfer coefficient (UD)

Value of overall heat transfer coefficient is assumed for estimating the size of the heat exchanger and after calculation the value has been validated.

\[ U_D = 950 \text{ kcal / m}^2 \text{ \( ^\circ\)C} \tag{3} \]

Area of the heat exchanger and tubes no inside the heat exchangers are calculated using equation 4 and 5.

\[ A = \frac{Q_w}{U_D \times \text{LMTD}} \tag{4} \]

Here
- \( A \) = Heat transfer area \( m^2 \)
- \( N_T \) = no of tubes in heat exchanger
- \( N_T \) = A / \( \pi \) Do L
- \( D_o \) = Outer dia of tube (m)
L = length of the tube (m) = 0.400m

4.3 Number of passes

Here flow inside the heat exchanger tubes considered as turbulent flow and accordingly no of passes are chosen. From heat transfer data book Reynolds no. (Re) has been chosen Re = 4000

\[
R_e = 4 \times m_w \times \frac{(N_p)}{(\pi \times \mu \times D_i)}
\]  

(5)

Here,

N_p = number of pass,

D_i = inner diameter of pipe (m)

\( \mu \) = kinematic viscosity of water (kg/ m-s)

Tube size and actual tube count have been calculated using equation 6 and 7. The initial design of the heat exchanger is completed here.

4.4 Adequacy of the initial design

Fluid properties dependent on temperature are assumed constant since these are not available. The viscosity correction factors is assumed as one. Overall coefficient is calculated using equation 6.

\[
U_{req} = \frac{Q_w}{\frac{N_f \times \pi \times D_o \times L \times (LMTD)}{}}
\]  

(6)

Convective heat transfer coefficient inside the tube wall (hi) is calculated using equation 7. We use k = Thermal conductivity of SS 316 L

\[
hi = \left(\frac{K}{D_i}\right) \times 0.023 \times Re \times 0.8Pr \times \frac{1}{3} \times \left(\frac{\mu}{\mu_w}\right) \times 0.14
\]  

(7)

Convective heat transfer coefficient for outer surface of tube (h_o) is calculated using equations 8 to 13 as follows.

Diameter of Shell D_S = 0.300 m

Baffle Spacing B = 0.2 x D_S

Area of Shell is calculated using equation 9.

\[
A_s = \frac{D_s \times C \times B}{\left(\frac{144 \times \pi^{1.44}}{144}\right)}
\]  

(9)

In above equation, \( \zeta \) = 0.00635 \quad B=0.06 \quad P_T = 0.03175 [24]

\[
Re = De \times \frac{G}{\mu}
\]  

(10)

In above equation D_e = 0.0185 m

\[
G = \frac{m_w}{A_s}
\]  

(11)

\[
j_H = 0.5 \times \left(1 + \frac{g}{D_S}\right) \times \left(0.08 \times Re^{0.6821} + 0.7 \times Re^{0.1772}\right)
\]  

(12)

\[
h_o = j_H \times \left(\frac{K}{D_S}\right) \times Pr^{1/3} \times \left(\frac{\mu}{\mu_w}\right) \times 0.14
\]  

(13)

Clean overall coefficient of heat exchanger has been calculated using equation 14.
\[ U_C = \left( \frac{D_O}{h_l \times D_l} \right) + \left( \frac{D_O \ln \frac{D_O}{D_l}}{2 \times k} \right) + \left( \frac{1}{h_0} - 1 \right) \]  

(14)

\( U_C \) should be greater than \( U_{req} \) then only next process will continue.

The fouling factor for the tube side is considered as 0.000102 \( \text{m}^2 \cdot \text{K} / \text{kcal} \)

\[ R_D = R_{Di} \times \left( \frac{D_O}{D_l} \right) + R_{Do} \]  

(15)

4.5 Design overall heat transfer coefficient is calculated from equation

\[ U_D = \frac{1}{U_C} + R_D - 1 \]  

(16)

As per heat exchanger design data hand book if \( UD > U_{req} \), heat exchanger design should be thermally stable. Over-surface and over-design of heat exchanger is monitored by equation 17 and 18.

For finding over-surface and over-design, overall heat transfer coefficient of heat exchanger is used here for convenience of calculation rather than surface areas.

Over-surface = \( \left( \frac{U_C}{U_{req}} \right) - 1 \)  

(17)

Over-design = \( \left( \frac{U_D}{U_{req}} \right) - 1 \)  

(18)

For shell and tube heat exchanger pressure drop is very important factor for calculating rate of heat transfer. Pressure drop inside the shell and tube have been calculated using following equations. The friction factor is calculated using equation 19.

\[ f = 0.4137 \left( \text{Re}^{-0.2585} \right) \]  

(19)

\[ G = \frac{m_w \times \left( \frac{N_p}{N_T} \right)}{\pi \times \frac{D_i^2}{4}} \]  

(20)

The friction loss is calculated using following formula. Frictional pressure loss due to flow inside the tube is calculated as

\[ \Delta P_t = 1.644 \times f \times N_p \times L \times G^2 / 7.50 \times 10^{12} \times D_i \times S \times \Phi \]  

(21)

The tube entrance, exit, and return losses are estimated using \( \alpha_r = (2 N_p - 1.5) \)

\[ \Delta P_r = 1.664 \times 1.334 \times 10^{-13} \times (2 N_p - 1.5) \times G^2 / S \]  

(22)

Nozzle Diameter = 0.0254 m

\[ \text{Re}_{nozzle} = \frac{(4 \times m_w)}{\pi \times D_n \times \mu} \]  

(23)

\[ G_n = \frac{m_w}{\pi \times \left( \frac{D_n^2}{4} \right)} \]  

(24)

After calculation it has been found that Reynolds no is more than 2000 i.e. it is turbulent flow. So we opt following pressure formula for finding pressure drop inside the nozzle.

\[ \Delta P_n = 1.644 \times 4 \times 10^{-13} \times N_s \times G_n^2 / S \]  

(25)

So total Pressure Drop in tube side is calculated as
\[ \Delta P = P_f + P_r + P_n \]  

(26)

Pressure drop on the shell side of heat exchanger is calculated using following formulae. Following two equations are used for calculating the friction factor:

\[ f_1 = (0.0076 + 0.000166 D_S) \times Re^{-0.125} \]  

(27)

\[ f_2 = (0.0016 + 5.8 \times 10^{-5} D_S) \times Re^{-0.157} \]  

(28)

It is assumed that \( B / D_S = 0.06 \), therefore the friction factor (f) is calculated by:

\[ f = 144 \times f_2 \]  

(29)

\[ Re_{nozzle} = 4m / (\pi \times D_n \times \mu) \]  

(30)

\[ G_n = m / (\pi \times D_n^2 / 4) \]  

(31)

\[ \Delta P_n = 1.644 \times 4 \times 10^{-13} \times N_s \times G_n^{2/3} \]  

(32)

\[ \Delta P_f = 1.644 \times f \times G^2 \times D_S \times (N_b + 1) \times 7.50 \times 10^{12} \times \phi \times \Phi \]  

(33)

The total shell-side pressure drop is:

\[ \Delta P_o = \Delta P_f + \Delta P_n \]  

(34)

5. Result and discussion

Process industries mostly use shell and tube heat exchangers. These heat exchangers consist of a shell and number of tubes. Hot fluid flows through tube and cold fluid put into shell side. As per industries requirement, shell size and tube size are taken as constant. Following parameters are used for heat exchanger analysis. Heat transfer takes place between the tubes and the fluid through the surface of tube walls. Heat exchangers of shell and tube type can be manufactured easily in different sizes and flow configurations [24-36]. Several parameters which decide the heat transfer rate are temperature and pressure of feed water, geometry of tube, spacing between the baffles, and diameter of shell. In this paper heat exchanger has been designed by using different parameters for studying the effect of mass flow rate of water and diameter of tube on convective heat transfer coefficient and pressure drop inside the tube. The above formulae are used for analysis. EES simulation program has been used for analysis. The input and output temperature and pressure of water and steam, shell diameter, nozzle diameter, tube length are provided by industry as working conditions. These are displayed in table 5.

| Parameters                              | Values       |
|-----------------------------------------|--------------|
| Inlet Temp of pure water (Ta)           | 30°C         |
| Outlet temp of pure water (Tb)          | 140°C        |
| Inlet Pressure of water (P_{iw})        | 3 bar        |
| Mass flow rate of Plant Steam (m_a)     | 130 kg/hr    |
| Inlet Temp of Plant Steam (T_1)         | 164°C        |
| Outlet temperature of plant steam (T_2) | 160°C        |
| Inlet pressure of steam (P_{is})        | 6 bar        |
| Length of the tube (L)                  | 0.400m       |
Thickness of tube ($\Delta t$) 1.5mm
Diameter of Shell ($D_S$) 0.300 m

Fig. 2. Variation of heat capacity with mass flow rate of water

Fig. 3. Variation of Reynolds no in Tube and Nozzle with mass flow rate of water

Fig 2 shows variation of heat capacity for different mass flow rate of water. Curve shows that heat capacity increases with positive change in mass flow rate. Fig 3 shows how Reynolds no in tubes and in nozzle is varies positively with increase in mass flow rate. It shows that increasing value of Reynolds no’s in Nozzle increase abruptly after mass flow rate crosses 100kg/hr. That’s mean more turbulence is generated inside the nozzle. So in design mass flow rate kept 100kg/hr.

Fig 4. Variation of pressure drop and convective heat transfer coefficient inside the tube with mass flow rate

Fig 5. Variation of convective heat transfer coefficient and Reynold’s no inside the tube with variation tube numbers.

Fig 2 shows variation of heat capacity for different mass flow rate of water. Curve shows that heat capacity increases with positive change in mass flow rate. Fig 3 shows how Reynolds no in tubes and in nozzle is varies positively with increase in mass flow rate. It shows that increasing value of Reynolds no’s in Nozzle increase abruptly after mass flow rate crosses 100kg/hr. That’s mean more turbulence is generated inside the nozzle. So in design mass flow rate kept 100kg/hr.
It’s observed in Fig 5 and 6 that there is decrease in convective heat transfer coefficient, Reynolds number and pressure drop inside the tube with increase in number of tubes. Fig 7 and 8 shows variation of convective heat transfer coefficient, pressure drop and Reynolds no inside the tube with variation of diameter of tube. It shows increase of inner diameter of tube decreases convective heat transfer coefficient, Reynolds no and pressure drop. Same process we have done for shell side analysis.

6. Conclusion

Shell and tube heat exchanger for Pure Steam Generator of Thermo-siphon Type of capacity 100 kg/hr has been designed here. A Piping and Instrumentation Diagram has been made with all necessary required components of the entire setup. Two phase heat exchanger has been design by manual calculations based on parameters provided by industries and validated using HTRI suite. The mean % error between HTRI results and manual results is 12.05%. Mechanical design of heat exchanger has been done manually in accordance with TEMA guidelines, in which 15 % design error is allowable. So our design is in compliance with the industries standards. The scope of our project included preparation of process and instrumentation diagram, thermal and mechanical design of heat exchanger and its validation, mechanical design of heat exchanger and its validation, part modeling of heat exchanger components and their 2-D drawings. Everything mentioned in scope of our project has been completed on time and is submitted to the industry. The company has appreciated our effort and hard work for completing our project well in time. The Designs and Drawings submitted to the company has been
reviewed by their technical team for any discrepancies in design, and further decision on fabrication and testing of the product have been taken.

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