The required heat transfer area (where, \( n_t = 335 \)):

\[
A_{reqd} = \pi d_o L_t n_t = \pi \times \frac{1}{12} \times 24 \times 335 = 2105 \text{ ft}^2
\]

% Overdesign = 9.8% which is within the acceptable limit.

Refer module # 2 for the mechanical design of shell and tube heat exchanger.

Lecture 5: Shell and Tube Exchanger for Two Phase Heat Transfer

2. PROCESS DESIGN OF SHELL AND TUBE EXCHANGER FOR TWO PHASE HEAT TRANSFER

2.1. Condenser

The change from liquid phase to vapor phase is called vaporization and the reverse phase transfer is condensation. The change from liquid to vapor or vapor to liquid occurs at one temperature (called saturation or equilibrium temperature) for a pure fluid compound at a given pressure. The industrial practice of vaporization and condensation occurs at almost constant pressure; therefore the phase change occurs isothermally.

Condensation occurs by two different physical mechanisms i.e. drop-wise condensation and film condensation.

The nature of the condensation depends upon whether the condensate (liquid formed from vapor) wets or does not wet the solid surface. If the condensate wets the surface and flows on the surface in the form of a film, it is called film condensation. When the condensate does not wet the solid surface and the condensate is accumulated in the form of droplets, is drop-wise condensation. Heat transfer coefficient is about 4 to 8 times higher for drop wise condensation. The condensate forms a liquid film on the bare-surface in case of film condensation. The heat transfer coefficient is lower for film condensation due to the resistance of this liquid film.

Dropwise condensation occurs usually on new, clean and polished surfaces. The heat exchanger used for condensation is called condenser. In industrial condensers, film condensation normally occurs.
2.1.1. Types of condensers

There are two general types of condensers:

i. Vertical condenser

   Downflow vertical condenser: The vapor enters at the top of condenser and flows down inside tubes. The condensate drains from the tubes by gravity and vapor induced shear (Figure 1.7).

   Upflow vertical condenser: In case of upflow condenser, the vapor enters at the bottom and flows upwards inside the tubes. The condensate drains down the tubes by gravity only.

ii. Horizontal condenser: The condensation may occur inside or outside the horizontal tubes (Figure 1.8). Condensation in the tube-side is common in air-cooled condensers. The main disadvantage of this type of condenser is that the liquid tends to build up in the tubes. Therefore the effective heat transfer coefficient is reduced significantly.
Figure 1.7. Downflow vertical condenser with condensation inside tube [5].
2.1.2. Condenser design

The design of condenser is similar to a typical shell and tube exchangers. A condenser must have a vent for removal of non-condensable gas. The non-condensable gas decreases the heat transfer rate. Condenser usually use a wider baffle spacing of \( B = D_s \) (ID of shell) as the allowable pressure drop in shell side vapor is usually less.

Vertical cut-segmental baffles are generally used in condensers for side-to-side vapor flow and not for top to bottom. An opening at the bottom of the baffles is provided to allow draining of condensate.

2.1.2.1. Mean temperature difference

The condensation occurs almost at a fixed temperature (isothermally) at constant pressure for a pure saturated vapor compound. The logarithmic mean temperature difference can be used for condenser design. **No correction factor for multiple pass condensers is required.** The logarithmic mean temperature difference:

\[
LMTD = \frac{(T_{sat} - t_1) - (T_{sat} - t_2)}{\ln \left( \frac{T_{sat} - t_1}{T_{sat} - t_2} \right)} = \frac{(t_2 - t_1)}{\ln \left( \frac{T_{sat} - t_1}{T_{sat} - t_2} \right)}
\]

(1.10)

Where, \( T_{sat} \) = Saturation vapor temperature

\( t_1 = \) Coolant inlet temperature

\( t_2 = \) Coolant outlet temperature
2.1.2.2. Calculation of heat transfer co-efficient during condensation

**Calculation of tube side heat transfer co-efficient** \((h_i)\): The calculation of heat transfer co-efficient for the cold fluid (coolant) can be performed similarly as discussed in design of shell and tube heat exchanger (heat transfer without phase change). Here it is assumed that the coolant flows the in tube side and the condensing saturated vapor flows in the shell side. If the condensation occurs in the tube side, follow the procedure discussed in next section for shell side calculation.

**Calculation of shell-side heat transfer coefficient** (condensing film heat transfer coefficient) \((h_o)\): The Kern method is discussed here to calculate the individual heat transfer co-efficient of the condensing fluid by trial and error calculation.

i. Assume, \(h_o(assum)\) in the range from 100 to 300 BTU.h\(^{-1}\).ft\(^{-2}\).°F\(^{-1}\). The film coefficient of condensing hydrocarbons generally varies in this range. Air-free condensing steam has a coefficient of 1500 BTU.h\(^{-1}\).ft\(^{-2}\).°F\(^{-1}\).

ii. Calculate the tube wall temperature \((T_w)\):

\[
T_w = T_{c(avg)} + \frac{h_o(T_v - T_{c(avg)})}{(h_o + h_o)} \tag{1.11}
\]

or

\[
T_w = T_{cc} + \frac{h_o(T_v - T_{cc})}{(h_o + h_o)} \tag{1.12}
\]

Where, \(h_o = h_i \times \frac{d}{d_o}\) (\(d\) tube ID and \(d_o\) tube OD)

\(T_{c(avg)}\) = Average temperature of the cold fluid

\(T_{cc}\) = Caloric temperature of the cold fluid

iii. Calculate condensate film temperature, \(T_f = \frac{(T_w + T_v)}{2}\) \tag{1.13}

\(T_v\) = Condensation temperature (For pure fluid compound \(T_v\) is the saturation temperature. Average of condensation over a temperature range also can be used for non-isothermal condensation).
iv. Calculate all thermophysical property of the condensing fluid at film temperature ($T_f$).

v. Recalculate, $h_{o(cal)}$ from $j_H$ factor.

Now again set, $h_{o(axm)} = h_{o(cal)}$ and continue the calculation till $h_{o(axm)} \approx h_{o(cal)}$.

vi. Calculate the overall heat transfer-coefficient ($U_d$) including the dirt factors.