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

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.

Types of condensers

There 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 co-efficient is reduced significantly.

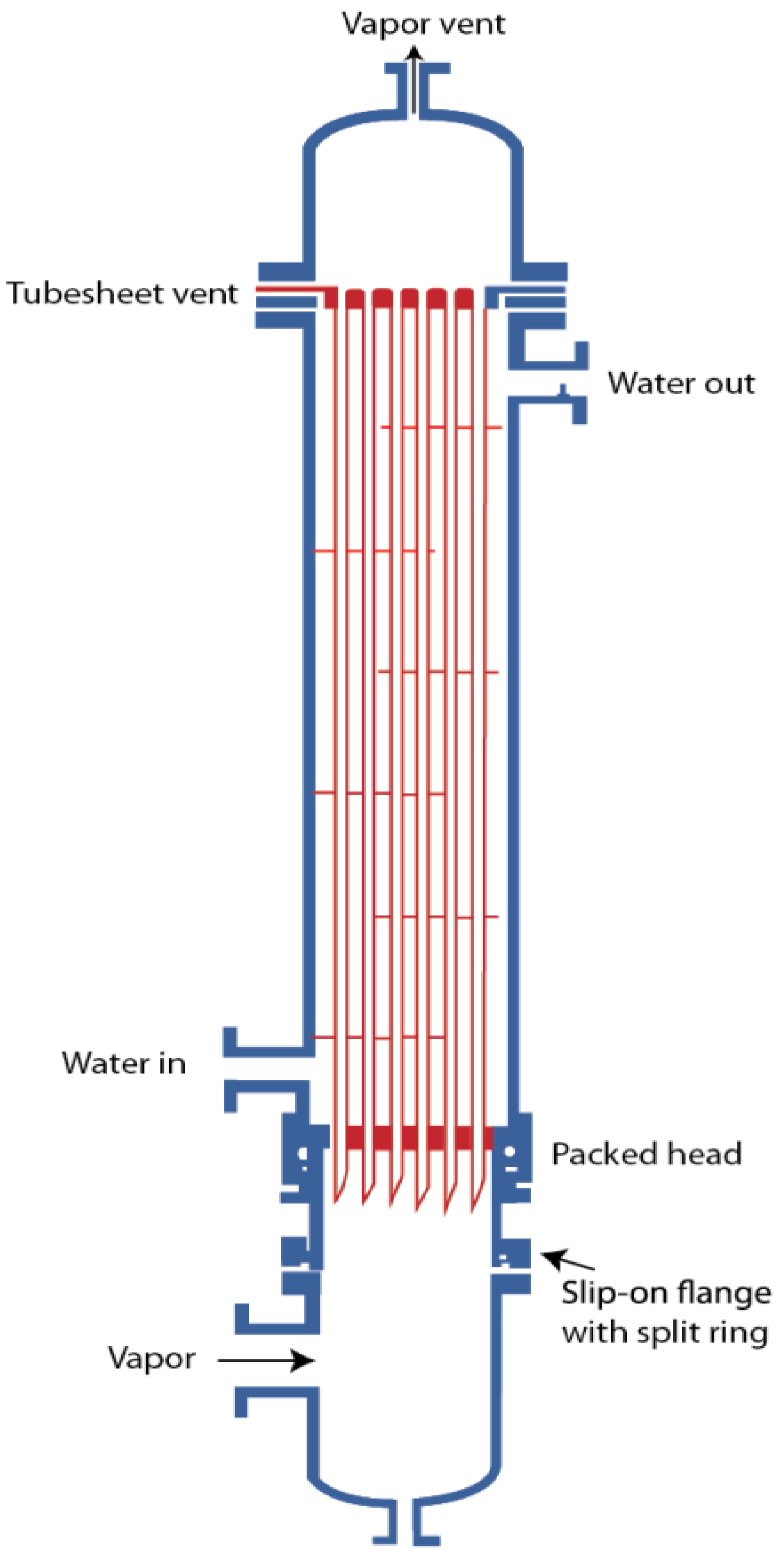

Figure 1.7. Downflow vertical condenser with condensation inside tube

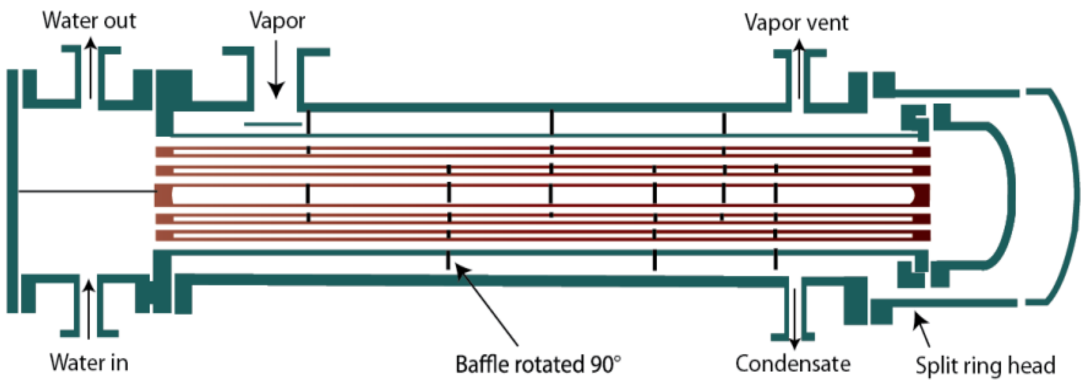

Figure 1.8. Horizontal condenser with condensation outside horizontal tubes

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.

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:

$$LMTD = \frac{(T_{sat} - t_1) - (T_{sat} - t_2)}{\ln \frac{(T_{sat} - t_1)}{(T_{sat} - t_2)}} = \frac{(t_2 - t_1)}{\ln \frac{(T_{sat} - t_1)}{(T_{sat} - t_2)}} \tag{1.10}$$

Where, T_{sat}= Saturation vapor temperature

t_1 = Coolant inlet temperature

t_2 = Coolant outlet temperature

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, $h_{o(assm)}$ 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):

$$T_w = T_{C(avg)} + \frac{h_o(T_v - T_{C(avg)})}{(h_{io} + h_o)} \tag{1.11}$$

or

$$T_w = T_{cc} + \frac{h_o(T_v - T_{cc})}{(h_{io} + h_o)} \tag{1.12}$$

Where, $h_{io} = h_i \times \frac{d_i}{d_{io}}$ (d_i 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, $T_f = \frac{(T_w + T_v)}{2}$ (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, $h_{o(assm)} = h_{o(cal)}$ and continue the calculation till $h_{o(assm)} \approx h_{o(cal)}$.

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

Condenser and Reboiler Design

Pressure drop calculation

i. Tube side pressure drop

<u>In case of tube side condensation:</u>

For condensation in the tube side by taking one-half of the conventional pressure drop relation can be used.

$$\Delta P_t = \frac{1}{2}\left(\frac{f G_t^2 L_t n_p}{7.5\times10^{12}\times d_i S_t \phi_t}\right), \text{ psi} \tag{1.14}$$

Where,

f = friction factor

G_t =mass velocity [lb. h^{-1}.ft^{-2}]

L_t =Tube length [ft]

n_p =Number of tube passes

d_i =Tube ID [ft]

S_t =Specific gravity of the tube side fluid

ϕ_t =Viscosity correction factor

($\phi_t = \dfrac{\mu}{\mu_w} = 1$, μ = viscosity of the tube side fluid; μ_w = viscosity of water)

ii. Shell side pressure drop

<u>In case of shell side condensation</u>: Similarly for condensation in the shell side:

$$\Delta P_s = \frac{1}{2}\left(\frac{fG_s^2 D_S(n_b+1)}{7.5\times10^{12}\times D_e S_s \phi_s}\right), \text{psi} \tag{1.15}$$

Subscript '*s*' indicates shell side fluid.

n_b = number of baffles

D_e = Equivalent diameter for the shell [ft]

Calculate all fluid property at film temperature T_f. No return loss calculation is required for the condensing fluid.

In case of non-condensing fluid (single phase flow), use the conventional pressure drop relation.

De-superheating and sub-cooling

De-superheating is different from condensation of a saturated vapor. The sensible heat should be removed first to de-superheat the vapor to obtain the saturated vapor. Similarly, the saturated liquid is to be further cooled down (sub-cooled) by extracting sensible heat below the boiling point. The temperature profile is shown in **Figure 1.9** for the condensation of superheated vapor to obtain the sub-cooled liquid from the same exchanger. The mean temperature difference and heat transfer coefficient should be calculated individually for each section if the degree of superheat/ sub-cool is large. The weighted mean temperature difference and overall transfer co-efficient can be used to design the condensers if heat load due to sensible heat transfer in each unit about 25% of latent heat transfer. Otherwise, it is convenient to design separate de-superheater and sub-cooling exchangers.

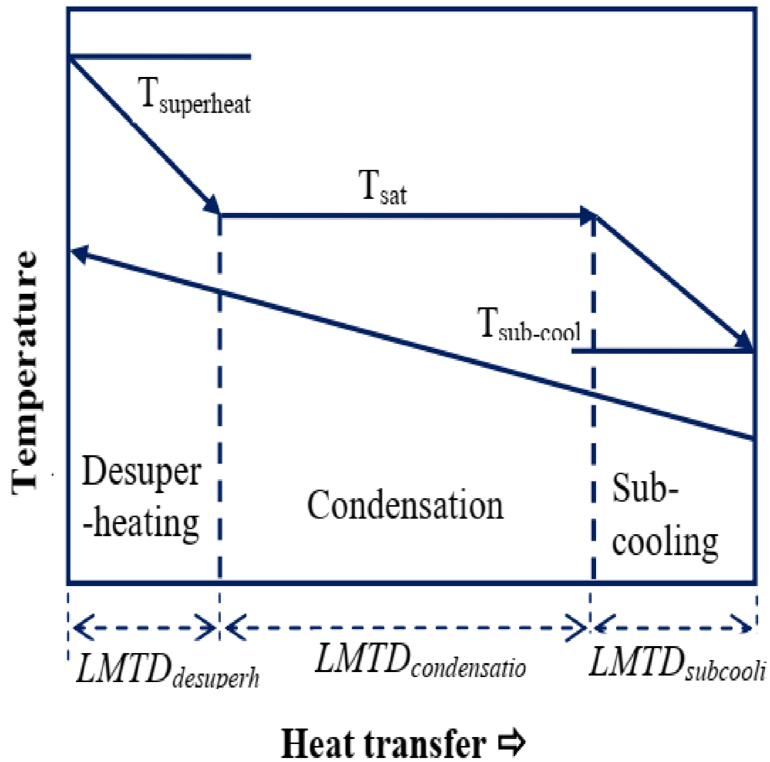

Figure 1.9. Condensation with de-superheating and sub-cooling

Practice problem:

Design a horizontal condenser for the condensation of 45,000 lb/h of almost pure normal propyl alcohol available at 15 psig. At this pressure, the boiling point of n-propyl alcohol is 244°F. Water available in the temperature range of 95 to 120°F can be as the coolant. The maximum pressure drop of 2 psi and 10 psi is permissible for the vapor phase and water respectively.

Reboilers

Classification of reboilers

There are three major types of reboilers:

i. **Thermosyphon natural circulation reboiler:** The boiling occurs inside the tubes in vertical thermosyphon reboiler and inside shell in horizontal thermosyphon reboiler (**Figure 1.10**). In vertical thermosyphon reboiler, the liquid circulation occurs due to density difference between vapor-liquid mixture (two phase) in the exchanger from the reboiler and the liquid through the downcomer to the reboiler.

Advantages: most economical because no pump is required.

Limitations: not suitable for heavily viscous fluid; high construction cost for the installation of the column base at suitable elevation to get thermosyphon effect; not suitable for low temperature difference processes due to boiling point elevation imposed by static head.

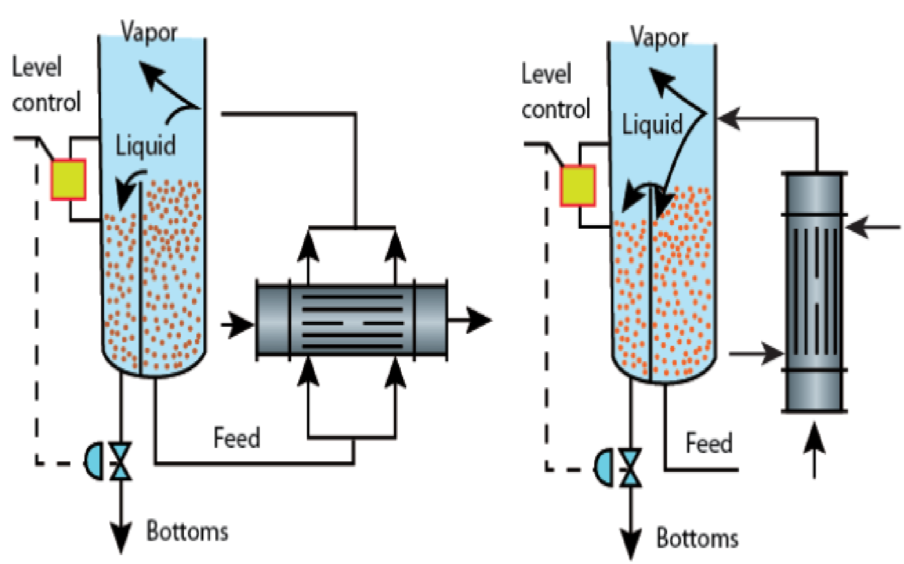

Figure 1.10. Thermosyphon reboiler [5]. (a) Horizontal thermosyphon reboiler. (b) Vertical thermosyphon reboiler

ii. **Forced circulation reboiler**: The liquid is fed by means of a pump. Forced circulation reboilers with vertical or horizontal tubes boiling may be designed. Forced circulation reboilers are similar to vertical thermosiphon reboilers, except the pump is used for the circulation of the liquid and the hot liquid flows inside column. To calculate the heat transfer coefficient it is generally assumed that, heat is transferred only by forced convection. The usual method of shell and tube exchanger design can be used.

Advantage: suitable for viscous and highly fouling fluids.

Disadvantage: high pumping and maintenance cost; pump is required to circulate the boiling liquid through the tubes and back into the column.

iii. **Kettle reboiler**: The tube bundle is immerged in a pool of liquid at the base of the column in an oversize shell (**Figure 1.11**). Kettle reboiler is also called a "submerged bundle reboiler". The height of the tube bundle is usually 40-60% of the shell ID. The submergence of the tube bundle is assured by an overflow weir at height of typically 5-15 cm from the upper surface of topmost tubes.

Advantage: suitable for vacuum operation and high vaporization rate up to about 80% of the feed.

Limitations: low heat transfer rate than other types as there is no liquid circulation (low velocity); not appropriate for fouling fluids; kettle reboiler is not suitable for heat sensitive materials as it has higher residence time.

The bundle diameter D_b, can be obtained from the empirical equation

$$D_b = d_o \left(\frac{n_t}{K_1} \right)^{1/n_1} \qquad (1.16)$$

where, D_b = bundle diameter [mm], n_t = number of tubes, d_o = tube outside diameter [mm]. The values of the constants K_1 and n_1 are in **Table 1.5.**

Table 1.5. Constants used to calculate the tube bundle diameter.

Pitch type	Constants	Number of tube passes (n_t)				
		1	**2**	**4**	**6**	**8**
Triangular ($P_T = 1.25d_o$)	K_1	0.319	0.249	0.175	0.0743	0.0365
	n_1	2.142	2.207	2.285	2.499	2.675
Square ($P_T = 1.25d_o$)	K_1	0.215	0.156	0.158	0.0402	0.0331
	n_1	2.207	2.291	2.263	2.617	2.643

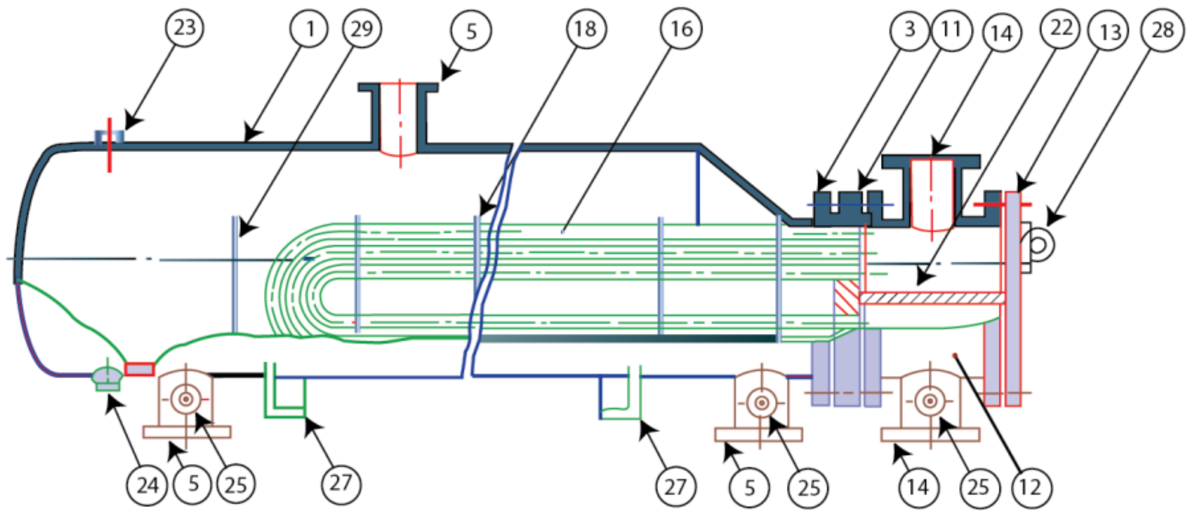

Figure 1.11. Kettle type reboiler

Design of kettle reboiler

The Kern method for designing of Kettle reboiler for isothermal boiling is summarized below. It is assumed that the degree of sub-cooling and super-heating of the cold fluid is negligible i.e. vaporization of close boiling compounds with negligible super-heating of vapors formed.

i. Make energy balance and determine the heat duty.

ii. Calculate of fluid property at the caloric temperature (or at arithmetic mean temperature) as already shown.

iii. Follow the same guideline and design requirements for shell containing the vaporing liquid.

iv. Calculation of heat transfer co-efficient

Calculation of individual heat transfer co-efficient hot fluid: The calculation of heat transfer co-efficient of the hot fluid can be performed similarly as in case of design of shell and tube heat exchanger for single phase.

Calculation of individual heat transfer coefficient of the boiling liquid: The Kern method is discussed here to calculate the individual heat transfer co-efficient of the boiling liquid by trial and error procedure.

Kern [2] recommends that the maximum allowable vaporizing film coefficients:

- 300 Btu/h.ft^2 °F for natural or forced circulation vaporizing organics.
- 1000 Btu/h.ft^2 °F for natural or forced circulation vaporizing aqueous solution of low concentration.

The maximum allowable heat flux:

- 20000 Btu/(h)ft^2) for forced circulation reboilers and 12000 Btu/(h)ft^2) for natural circulation reboilers vaporizing organics.

- 30000 Btu/(h)ft^2) for both forced or natural circulation reboilers vaporizing aqueous solution.

Assume that $h_{(assm)}$ = 300 Btu/h.ft^2 °F for organics or 1000 Btu/h.ft^2 °F for water.

With this assumed value, calculate the tube wall temperature (T_w):

$$T_w = T_{h(avg)} + \frac{h_{io}(T_{hc} - T_{h(avg)})}{(h_{io} + h_o)} \qquad (1.17)$$

Where, $h_{io} = h_i \times \dfrac{d_i}{d_{io}}$ (d_i tube ID and d_o tube OD)

$T_{h(avg)}$ = Average temperature of the hot fluid

T_{hc} =Caloric temperature of the hot fluid

Now, re-determine h_{cal} (latent heat transfer) from the **Figure 1.12** corresponding to $(T_w - t)$. (t is the cold fluid boiling temperature).

Continue the calculation till, $h_{cal} \approx h_{(assm)}$.

If the calculated h_{cal} is greater than the maximum heat transfer co-efficient of 300 Btu/h.ft^2 °F for organics and 1000 Btu/h.ft^2 °F for water, take h_{cal} = 300 Btu/h.ft^2 °F for organics and h_{cal} =1000 Btu/h.ft^2 °F for water.

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

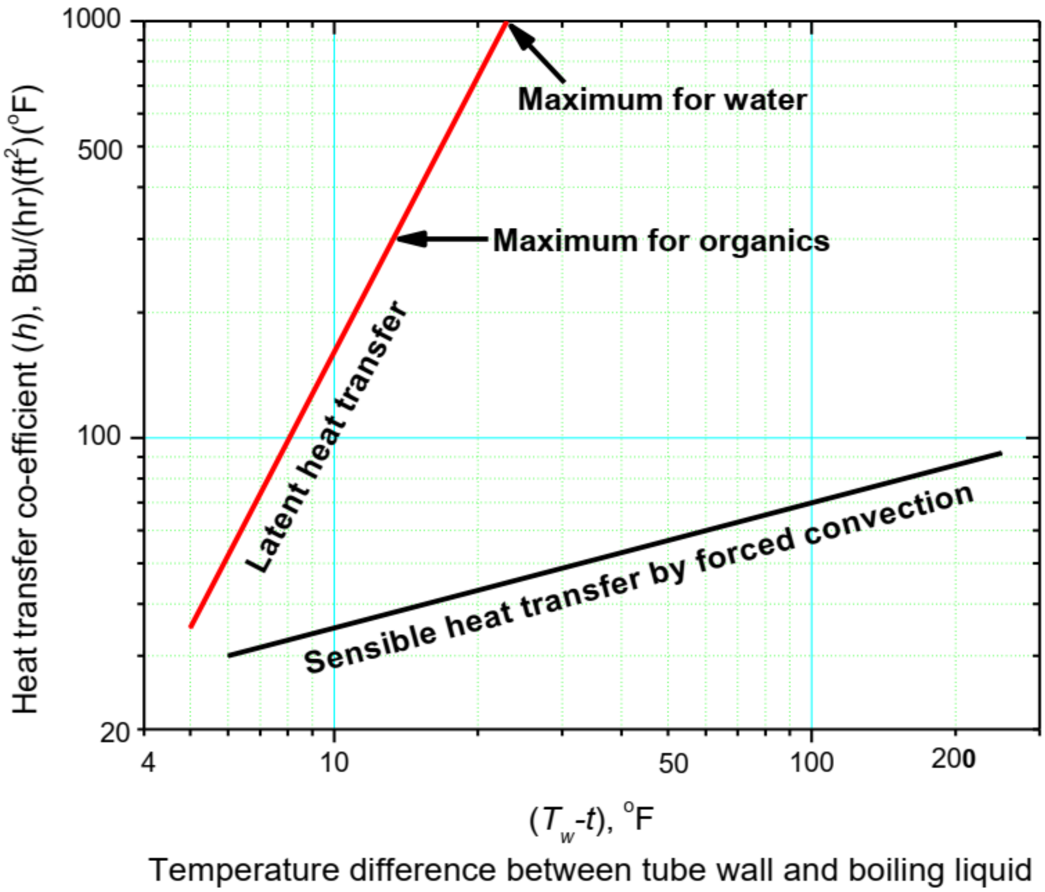

Figure 1.12. Natural circulation boiling and sensible heat transfer

v. Decide type of exchanger i.e. fixed tube sheet or U- shell (use U-tube reboiler for large temperature difference), tube size (diameter, length, tube pitch), layout, effective tube length. A tube pitch of between 1.5 to 2 times the tubes OD should be used to avoid vapor blanketing.

vi. Calculate exchanger area ($A = \dfrac{Q}{U_d(LMTD)}$) and number of tubes ($n_t = \dfrac{A}{\pi d_o L_t}$).

The number of tubes should be calculated based on the effective tube length for U-tube reboilers. The effective tube length is less than physical tube length due to U-bend.

vii. Calculate the heat flux= $\dfrac{Q}{A}$ [Btu/(h.ft^2)]. This value should be less than the maximum heat flux of 20000 Btu/(h)ft^2) for forced circulation reboilers vaporizing organics and 30000 Btu/(h)ft^2) for both forced or natural circulation reboilers vaporizing aqueous solution. Otherwise, go to **step # v**, repeat the calculation until within the allowable limits.

viii. Check for allowable vapor velocity (u_v)

The maximum vapor velocity u_v (m/s) at the liquid surface should be less than that given by the expression below to avoid too much entrainment.

$$u_v < 0.2\left(\frac{\rho_l - \rho_v}{\rho_v}\right)^{1/2} \tag{1.18}$$

where, ρ_l = liquid density and, ρ_l = vapor density

If this criterion is not satisfied, go to **step # v** and revise the calculation.

ix. Pressure drop calculation

Tube side pressure drop (hot fluid): The pressure drop calculation of the hot fluid can be carried out as already presented.

Shell side pressure drop (vaporizing liquid): There will be negligible hydrostatic head for the flow of liquid from the column to reboilers (low circulation velocity) if the liquid level above the tube bundle is not too high. Therefore, shell side pressure drop may be considered negligible.

x. Calculate over surface and over design

xi. Go for mechanical design

Design problem:

Gasoline (65°API gravity) flow rate of 60,000 lb/h with a small boiling range at 400°F is to be vaporized to form 37,050 lb/h vapor at an operating pressure of 200 psig. Use gas oil (30°API gravity) in the temperature range from 600 to 500°F at 120 psig operating pressure as the heating medium. A tube side pressure drop of 10 psi is allowable. Design a suitable Kettle reboiler to serve the purpose.