Condensers

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ME 307: Heat Transfer Equipment Design
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Condensation Process

When saturated vapour comes in contact with a surface having a temperature below the saturation temperature, condensation occurs. There are two types of condensation:

1. Film-wise condensation: condensed liquid wets the surface and forms a film covering the entire surface.
2. Drop-wise condensation: surface is not totally wetted by the saturated vapour, and the condensate forms liquid droplets that fall from the surface.

▷ Compared to film-wise condensation, drop-wise condensation has a greater surface heat-transfer coefficient as it has a greater area exposed to the saturation vapour.

Stages in Condensation

1. De-superheating of the hot gas
2. Condensing of the gas to liquid state and release of the latent heat.
3. Sub-cooling of the liquid refrigerant.

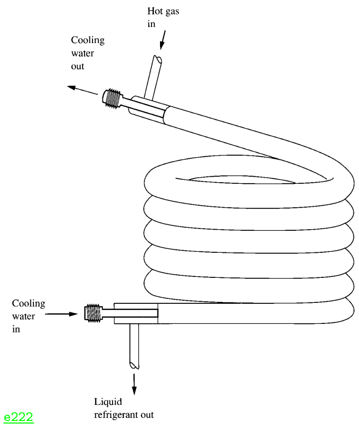
▷ Sub-cooling only occupies a small portion of condenser's surface area. Therefore, an average heat transfer coefficient is used for the whole condenser's surface area, and the condensation is assumed to occur at the condensing temperature.

Types of Condensers

Based on the cooling medium used, condensers used in refrigeration systems can be classified into the following three categories:

1. Water-cooled condensers
   1. Double-tube condenser
   2. Shell-and-tube condenser
2. Air-cooled condensers
3. Evaporative condensers

Double-tube Condenser



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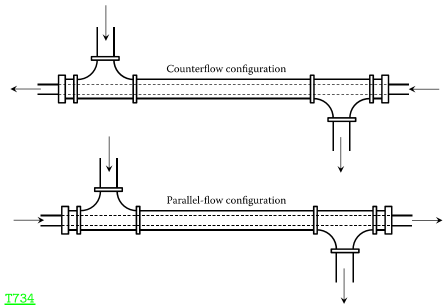

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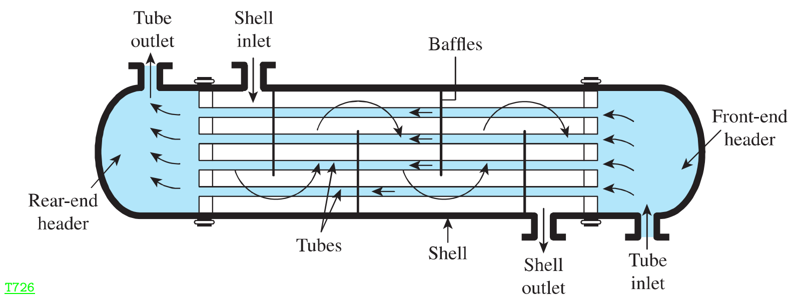
Counterflow and parallel-flow configurations.

Shell-and-tube Condenser



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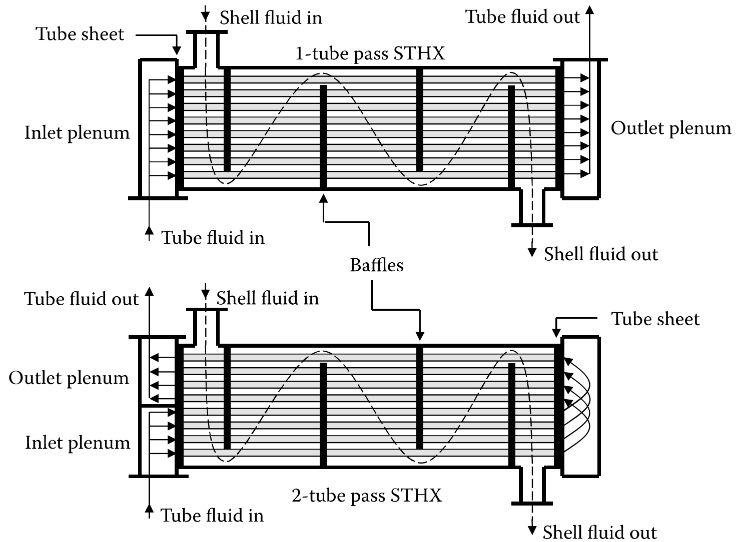
A shell-and-tube heat exchanger (one-shell pass and one-tube pass).



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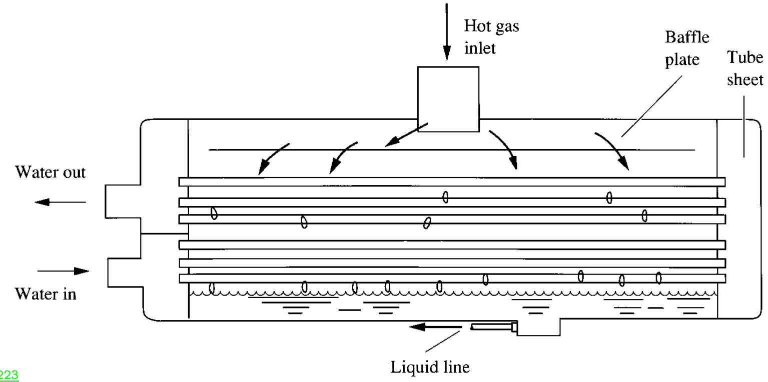
1-tube pass and 2-tube pass STHXs.



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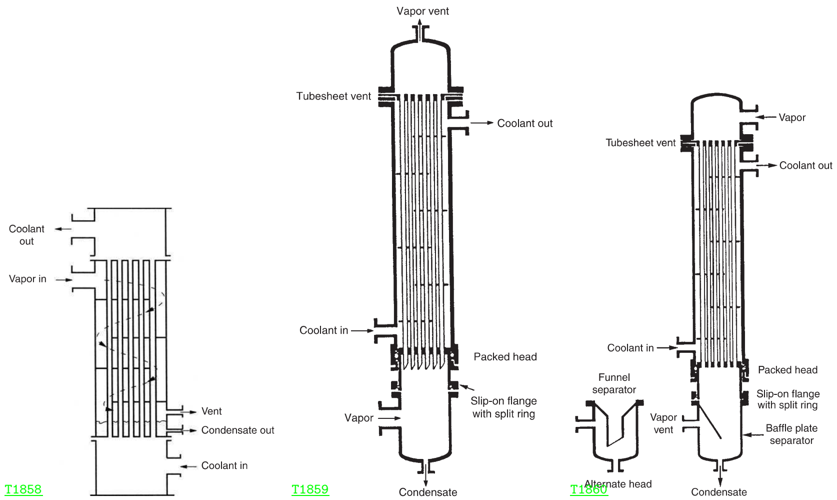
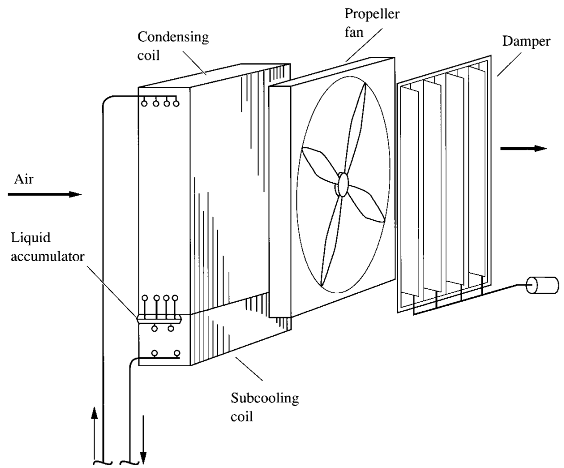


Vertical condensers

- The choice of water-cooled condenser depends on the following factors:
  - Quality and availability of water
  - Space requirements
  - Water treatment costs
  - Noise
- Advantages of water cooled-condensers are:
  - Easy to operate
  - Requires less surface area
  - Low energy requirement for the compressor.

Air-cooled Condenser



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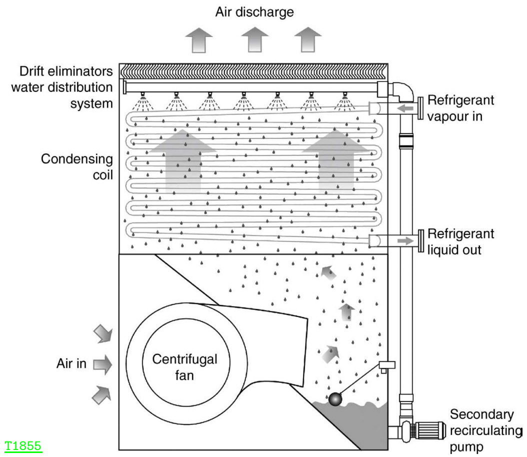
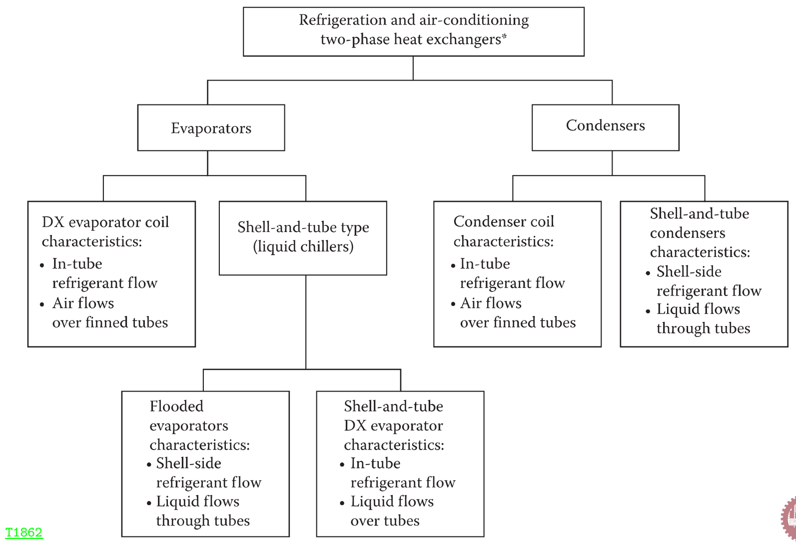
Characteristics of Air-cooled Condenser

- Compact, easy and economical to install.
- Flexibility in changing capacity by varying air flow.
- Hot air may be disposed of easily.
- Easy to clean fin and tube surface by blowing air.
- Required less maintenance.
- Higher power requirement per ton of refrigeration
- On days when maximum cooling is needed, the least is available.

Evaporative Condenser



Evaporation of water spray is used to condense the refrigerant



Condensation Correlations

$$\text{Rate of condensation, } \dot{m} = \frac{A h_m (T_v - T_w)}{h_{fg}}; \qquad Re = \frac{4\dot{m}}{\mu_l P}$$

h_{fg} evaluated at T_v

$$\text{Wetted perimeter, } P = \begin{cases} \pi D & \text{for vertical tube of outside diameter } D \\ 2L & \text{for horizontal tube of length } L \\ w & \text{for vertical or inclined plate of width } w \end{cases}$$

Condensation on vertical surfaces: [Laminar (Re <1800)]

$$h_m = 1.2 \times 0.943 \left[\frac{g \rho_l (\rho_l - \rho_v) h_{fg} k_l^3}{\mu_l (T_v - T_w) L} \right]^{1/4}$$

- Properties are evaluated at film temperature, $T_f = \frac{1}{2}(T_w + T_v)$
- Flow is laminar if $Re < 1800$.

Condensation on inclined surfaces: [Laminar (Re <1800)]

$$h_m = 0.943\left[\frac{g\rho_l(\rho_l-\rho_v)h_{fg}k_l^3}{\mu_l(T_v-T_w)L}\sin\varphi\right]^{1/4}$$

Condensation on horizontal tube: [Laminar (Re <1800)]

$$h_m = 0.725\left[\frac{g\rho_l(\rho_l-\rho_v)h_{fg}k_l^3}{\mu_l(T_v-T_w)D}\right]^{1/4}$$

Comparison of vertical tube of length L and horizontal tube of diameter D:

$$\frac{h_{m,vert}}{h_{m,horz}} = 1.56\left[\frac{D}{L}\right]^{1/4}$$

If $L = 100D \longrightarrow h_{m,horz} \simeq 2.0 h_{m,vert}$. For condensation, horizontal tube arrangements are generally preferred.

Condensation on horizontal tube banks:

$$h_m|_{N\ tubes} = \frac{1}{N^{1/4}} h_m|_{1\ tube}$$

Condensation inside horizontal tube:

$$h_m = 0.555\left[\frac{g\rho_l(\rho_l-\rho_v)h'_{fg}k_l^3}{\mu_l(T_v-T_w)D}\right]^{1/4}$$

$h'_{fg} = h_{fg} + \frac{3}{8}c_{p,l}(T_v - T_w)$; $Re_v = \frac{\rho_v u_v D}{\mu_v} \leqslant 35000$

Turbulent film-wise condensation: vertical tube

$$h_m\left[\frac{\mu_l^2}{k_l^3\rho_l^2 g}\right]^{1/3} = 0.0077 Re^{0.4}$$

Example: ▷ Air free saturated steam at 65°C, P = 25.03 kPa condenses on the outer surface of a 2.5 cm OD, 3-m long vertical tube maintained at constant temperature of 35°C by the flow of the cooling water. Estimate average heat transfer coefficient and the rate of condensate flow at the bottom of the tube.

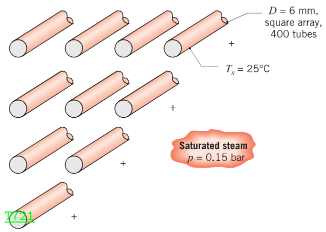
[$\dot{m}_V$ = 0.01124 kg/s]

Example: ▷ Redo Ozisik Ex. 10.1 assuming horizontal tube.

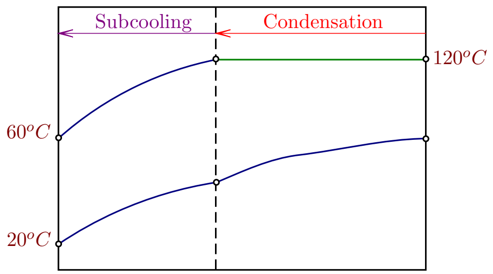
[$\dot{m}_H$ = 0.02386 kg/s]

Example: ▷ The tube bank of a steam condenser consists of a square array of 400 tubes, each 6 mm in diameter. If horizontal, unfinned tubes are exposed to saturated steam at a pressure of 0.15 bar and the tube surface is maintained at 25°C, what is the rate at which steam is condensed per unit length of the tube bank?

[$\dot{m}$ = 0.474 kg/s]



Example: ▷ Saturated water at 120°C with a quality of x_i = 0.2 and a mass flow rate, $\dot{m}_h$ = 10 kg/s is to be cooled to 60°C with a water flow of $\dot{m}_c$ = 40 kg/s at 20°C. If for liquid water, h_w = 8000 W/m^{2}K, and for condensing vapour, h_v = 24000 W/m^{2}K, and C_p = 4200 J/KgK for liquid water, and h_{fg} = 2200 kJ/kg at 120°C, estimate the heat transfer surface area. [21 m^2]



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