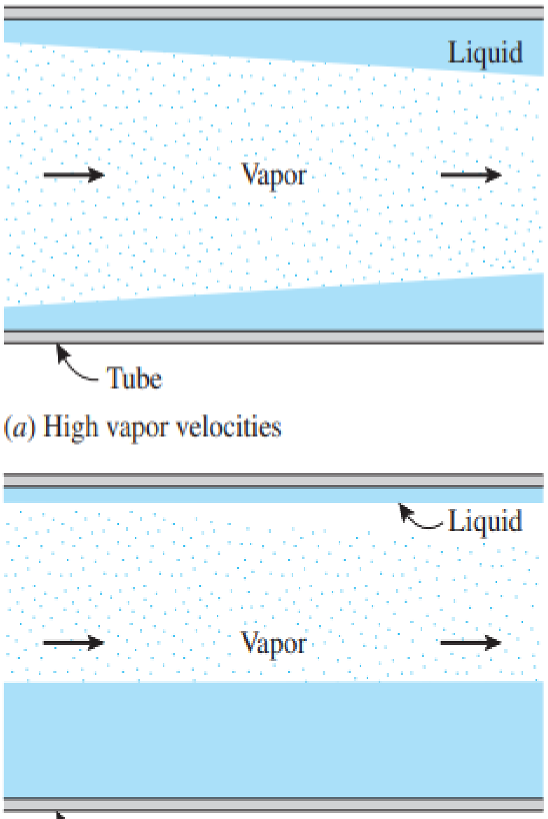
- **FILM CONDENSATION INSIDE HORIZONTAL TUBES**
- **For low vapor velocity**
- $\bar{h}_{int} = 0.555 \left[\frac{g\rho_f(\rho_f-\rho_v)k_f{}^3 h^*_{fg}}{\mu_f(T_{sat}-T_w)D} \right]^{1//4}$
- For $Re_{vapor} = \frac{\rho_v V_v D}{\mu_v} < 3500$



(a) High vapor velocities
(b) Low vapor velocities

- **DROPWISE CONDENSATION**

- Dropwise condensation, characterized by countless droplets of varying diameters on the condensing surface instead of a continuous liquid film, is one of the most effective mechanisms of heat transfer, and extremely large heat transfer coefficients can be achieved with this mechanism.

- $\bar{h}_{dropwise} = 51104 + 204T_{sat}$

  $22^oC < T_{sat} < 100^oC$

- $\bar{h}_{dropwise} = 255510$

  for $T_{sat} > 100^oC$

- **The Condensation Number**
- Because the film Reynolds number is so important in determining condensation behavior, it is convenient t o express the heat-transfer coefficient directly in terms of Re. We include the effect of inclination and write the heat-transfer equations in the form
- $\bar{h} = C\left[\frac{\rho_f(\rho_f-\rho_v)g sin\varphi h_{fg}k_f^3}{\mu_f L(T_g-T_w)}\right]^{1/4}$ (18)
- where the constant is evaluated for a plate or cylindrical geometry. From the equation: $\dot{Q} = \bar{h}A(T_g - T_w) = \dot{m}h_{fg}$
- $(T_g - T_w) = \frac{\dot{m}h_{fg}}{\bar{h}A}$
- We now define a new dimensionless group, the condensation number Co, as
- $Co = \bar{h}\left[\frac{\mu^2}{k^3\rho_f(\rho_f-\rho_v)g}\right]^{1/3}$ (19)

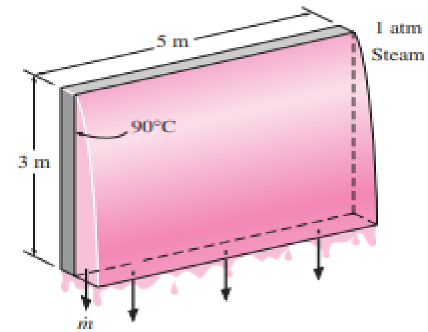
- For a vertical plate A/PL = 1.0, and we obtain, using the constant from Equation (1)
- $$Co = 1.47\left(Re_f\right)^{-1/3} \quad \text{for } Re_f < 1800$$
- For a horizontal cylinder A/PL = π and
- $$Co = 1.514\left(Re_f\right)^{-1/3} \quad \text{for } Re_f < 1800$$
- When turbulence is encountered in the film, an empirical correlation by Kirkbride may be used:
- $$Co = 0.0077\left(Re_f\right)^{0.4} \quad \text{for } Re_f > 1800$$

- Example 1- Saturated steam at 1atm condenses on a 3m-high and 5m-wide vertical plate that is maintained at 90°C by circulating cooling water through the other side. Determine (a) the rate of heat transfer by condensation to the plate, and (b) the rate at which the condensate drips off the plate at the bottom.
- **Solution:** L=3m and w=5m for vertical plate T_w=90^{o}C, T_{sat}=100^{o}C at 1atm.
- $T_f = \frac{(T_{sat}-T_w)}{2} = \frac{100+90}{2} = 95^o C$
- **The properties**: ρ_f=961.5kg/m^3, ρ_v=0.5045kg.m^3, h_{fg}=2270kJ/kg, k_f=0.677W/m.K, Cp_f=4212J/kg.K, μ_f=0.297x10^{-3}kg/m.sec, Pr_f=1.85

- **Requirements:** a) The rate of heat transfer, b) the rate at which the condensate drips off the plate.
- Analysis: at beginning we find modified h_{fg}
- $h^*_{fg} = h_{fg} + 0.68Cp_f(T_{sat} - T_w)$
- $h^*_{fg} = 2270 \times 10^3 + 0.68 \times 4212(100 - 90)$
$= 2312.13 \times 10^3 J/kg$
- Assuming wavy laminar flow then
- $Re = Re_{ver,wavy}$

$$= \left[4.81 + \frac{3.70Lk_f(T_{sat}-T_w)}{\mu_f h^*_{fg}}\left(\frac{g\rho_f^2}{\mu_f^2}\right)^{1/3}\right]^{0.82}$$

- $Re = Re_{ver,wavy} = \left[4.81 + \frac{3.70\times3\times0.677(100-90)}{(0.297\times10^{-3})(2312.13\times10^{3})}\left(\frac{9.81(961.5)^2}{(0.293\times10^{-3})^2}\right)^{1/3}\right]^{0.82} =$
- 1110.73
- It between 30 and 1800 then



- $h = \frac{Re k_f}{1.08Re^{1.22}-5.2}\left(\frac{g\rho_f^2}{\mu_f^2}\right)^{1/3}$
  $= \frac{1110.73\times0.677}{1.08(1110.73)^{1.22}-5.2}\left(\frac{9.81(961.5)^2}{(0.293\times10^{-3})^2}\right)^{1/3} = 6340.8W/\mathrm{m^2K}.$
- $\dot{Q} = hA(T_{sat} - T_w) = 6340.8 \times (3 \times 5)(100 - 90)$
  $= 951119W = 915.12kW$
- Mass of condensate is $\dot{m} = \frac{\dot{Q}}{h_{fg}^*} = \frac{915.12}{2312.13} = 0.411kg/sec$
- To calculate the condensation Number Co
- $Co = 1.47\left(Re_f\right)^{-1/3}$ for $Re_f < 1800$
- $Co = 1.47(1110.73)^{-1/3} = 0.142$

- **Example 2.** Saturated steam at 30°C condenses on the outside of a 4cm-outer diameter, 2m-long vertical tube. The temperature of the tube is maintained at 20°C by the cooling water. Determine (a) the rate of heat transfer from the steam to the cooling water, (b) the rate of condensation of steam, and (c) the approximate thickness of the liquid film at the bottom of the tube.
- **Solution:** Saturated steam at $T_{sat}=30^o$ condenses on tube(its outside) D=4cm L=2m $T_w=20^oC$.

- **Properties:** properties of steam at T_f=25°C are ρ_f=997kg/m^3 h_{fg}=2442kJ/kg, Cp_f=4180J/kg.K, k_f=0.607W/m.K, μ_f=0.891x10^{-3}, Pr_f=6.14.
- **Requirements;** a) rate of heat transfer, b) rate of steam condensation, c) the thickness of liquid film at bottom of the tube
- Analysis: at the beginning, we shall determine the modified h_{fg}^*

$$h_{fg}^* = h_{fg} + 0.68Cp_f(T_{sat} - T_w)$$

- $h_{fg}^* = 2440 \times 10^3 + 0.68 \times 4180(30 - 20)$
  $= 2{,}468.42 \times 10^3 J/kg$

- Assume, wavy-laminar flow then
- $Re = Re_{ver,wavy} = \left[4.81 + \frac{3.70 L k_f (T_{sat} - T_w)}{\mu_f h_{fg}^*} \left(\frac{g \rho_f^2}{\mu_f^2}\right)^{1/3}\right]^{0.82}$
- $Re = Re_{ver,wavy} = \Big[4.81$

- $\dot{Q} = Ah(T_{sat} - T_w) = (\pi DL)4819.2(30$

3- The tube bank of a steam condenser consists of a square array of 400 tubes, each of diameter D= $2r_1$=6mm. If horizontal, tubes are exposed to saturated steam at a temperature of 55^oC and the tube surface is maintained at T_w=25^oC, what is the rate at which steam is condensed per unit length of the tube bank?

Solution: tube bank of steam condenser consists of a square array of 400tubes, D=6mm.

T_{sat}=55^oC, T_w=25^oC

Properties: the properties of saturated water at T_f=40^oC

ρ_f=992.1kg/m^3, ρ_v=0.0512kg/m^3, Cp_f=4179J/kg.K, h_{fg}=2407kJ/kg, k_f=0.631W/m.K μ_f=0.653x10^{-3}kg/m.sec, Pr_f=1.03

- **Requirements**: rate at which steam is condensed per unit length.
- **Analysis:** $h^*_{fg} = h_{fg} + 0.68Cp_f(T_{sat} - T_w) = 2407 + 0.68 \times 4.179(55 - 25) = 2492.25kJ/kg$
- $\bar{h}_h = 0.729\left[\frac{g\rho_f(\rho_f-\rho_v)h^*_{fg}k_f^3}{\mu_f(T_{sat}-T_w)D}\right]^{1/4}$
- $\bar{h}_h = 0.729$
- $\left[\frac{9.81\times992.1(992.1-0.0512)2499\times10^3(0.631)^3}{0.653\times10^{-3}(55-25)0.006}\right]^{1/4} = 8288.4W/m^2.K$

- $\bar{h}_{hb} = \frac{\bar{h}_h}{N^{\frac{1}{4}}} = \frac{8288.4}{20^{1/4}} = 3919.34 W/\text{m}^2\text{K}$
- $\dot{Q} = N \times N\pi DL\bar{h}_{hb}(T_{sat} - T_w) = 20 \times 20\pi \times 0.006 \times 3919.34(55 - 25) = 886.53 kW/\text{m}$
- Mass condensates per unit length is
- $\dot{m} = \frac{\dot{Q}}{h^*_{fg}} = \frac{886.53}{2492.25} = 0.356 kg/\text{sec}=21.34\text{kg/min}$

4- Saturated steam at 120^oC condenses inside a horizontal, 75mm-diameter pipe whose surface is maintained at 100^oC. Assuming low vapor velocities and film condensation, estimate the heat transfer coefficient and the condensation rate per unit length of the pipe.

- **Solution:** T_{sat}=120^oC, T_w=100^oC, D_i=0.075m
- **Properties**: for water at T_f=110^oC, ρ_f=950.6kg/m^3, ρ_v=0.8263kg/m^3, h_{fg}=2230kJ/kg, Cp_f=4.229kJ/kg.K, k_f=0.682W/m.K, μ_f=0.855x10^{-3}kg/m.sec

- Requirement: mass of steam condensate per unit length of the tube
- Analysis: $h_{fg}^{*} = h_{fg} + 0.68Cp_f(T_{sat} - T_w) = 2230 \times 10^3 + 0.68 \times 4229(120 - 100) = 2287.5 \times 10^3 J/kg$
- $\bar{h}_{int} = 0.555\left[\frac{g\rho_f(\rho_f - \rho_v){k_f}^3 h_{fg}^{*}}{\mu_f(T_{sat} - T_w)D}\right]^{1/4}$
- $\bar{h}_{int} = 0.555\left[\frac{9.81 \times 950.6(950.6 - 0.8263)(0.682)^3 \times 2287.5 \times 10^3}{0.855\text{x}10^{-3}(120 - 100)0.075}\right]^{1/4} = 4669.6 W/m^2.\text{K}$
- $\dot{Q} = \pi DL\bar{h}_{in}(T_{sat} - T_w) = \pi \times 0.075 \times 1 \times 4669.6(120$