CONDENSATION

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- Condensation: The liquid film starts forming at the top of the plate and flows downward under the influence of gravity.
- . The thickness of the film

δ increases in the flow direction x because of continued condensation at the liquid–vapor interface Heat released in condensation Is equal to latent heat of Evaporation h_{fg}(kJ/kg)

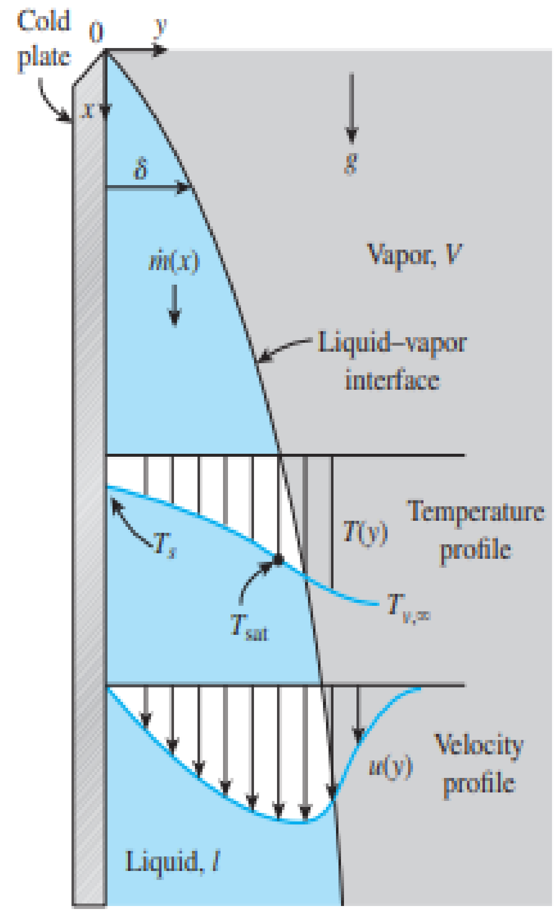


Fig.1

- The heat is transferred through the film to the plate surface at temperature T_w. Note that T_w must be below the saturation temperature T_{sat} of the vapor for condensation to occur.
- Typical velocity and temperature profiles of the condensate are also given in Fig.1. Note that the velocity of the condensate at the wall is zero because of the “no-slip” condition and reaches a maximum at the liquid–vapor interface. The temperature of the condensate is T_{sat} at the interface and decreases gradually to T_s at the wall.

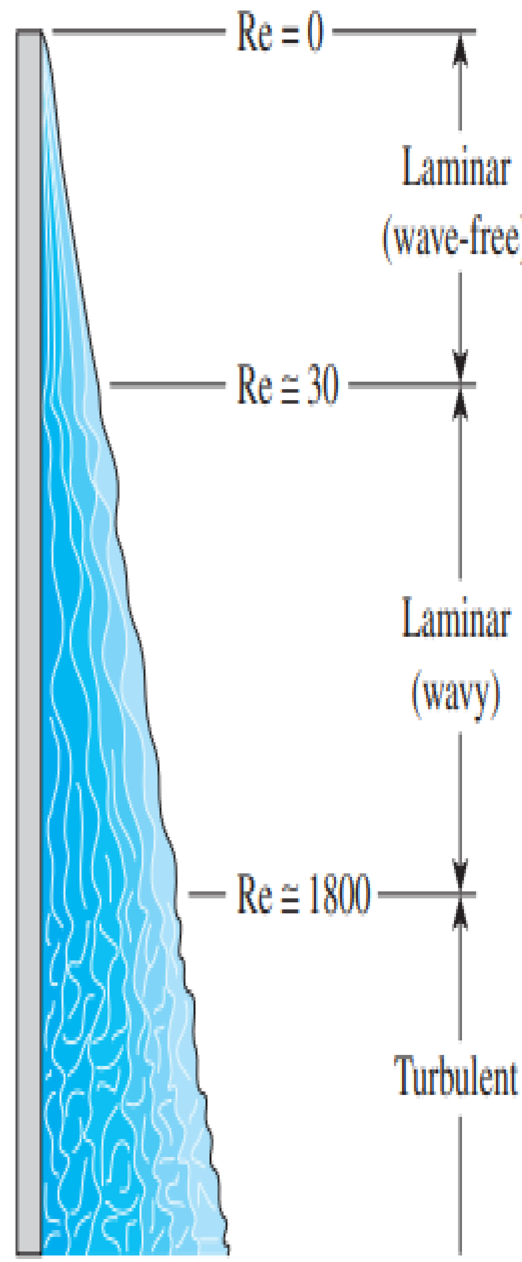
- heat transfer in condensation also depends on whether the condensate flow is laminar or turbulent. Again the criterion for the flow regime is provided by the Reynolds number, which is defined as
- $Re = \frac{D_h \rho_f V_f}{\mu_f} = \frac{4A_c \rho_f V_f}{p\mu_f} = \frac{4\rho_f V_f \delta}{\mu_f} = \frac{4\dot{m}}{p\mu_f}$ (1)
- $A_c = p\delta$ = wetted perimeter x film thickness, m^2, cross-section area of the condensate flow at the lowest part of the flow
- $\rho_f =$ density of the liquid kg/m
- μ_f = viscosity of the liquid, kg/m.sec
- V_f=average velocity of the condensate at the lowest part of the flow, m/sec
- $\dot{m} = \rho_f V_f A_c$ =mass flow rate of the condensate at the lowest part, kg/sec. $D_h = 4\delta$

- Rohsenow showed in 1956 that the cooling of the liquid below the saturation temperature can be accounted for by replacing h_{fg} by the modified latent heat of vaporization $h^*{}_{fg}$, defined as
- $h^*{}_{fg} = h_{fg} + 0.68cp_f(T_{sat} - T_w)$ (2)
- The rate of heat transfer is expressed by
- $\dot{Q} = \dot{m}h^*{}_{fg} = \bar{h}A(T_{sat} - T_w)$ (3)
- where A is the heat transfer area (the surface area on which condensation occurs). Solving for $\dot{m}$ from the equation above and substituting it into Eq.(1) gives yet another relation for the Reynolds number
- $Re = \frac{4\dot{Q}}{p\mu_f h^*{}_{fg}} = \frac{4\bar{h}A(T_{sat}-T_w)}{p\mu_f h^*{}_{fg}}$ (4)

- Flow Regimes

It is observed that the outer surface of the liquid film remains smooth and wave-free for about Re $\leq$ 30. he flow is clearly laminar.

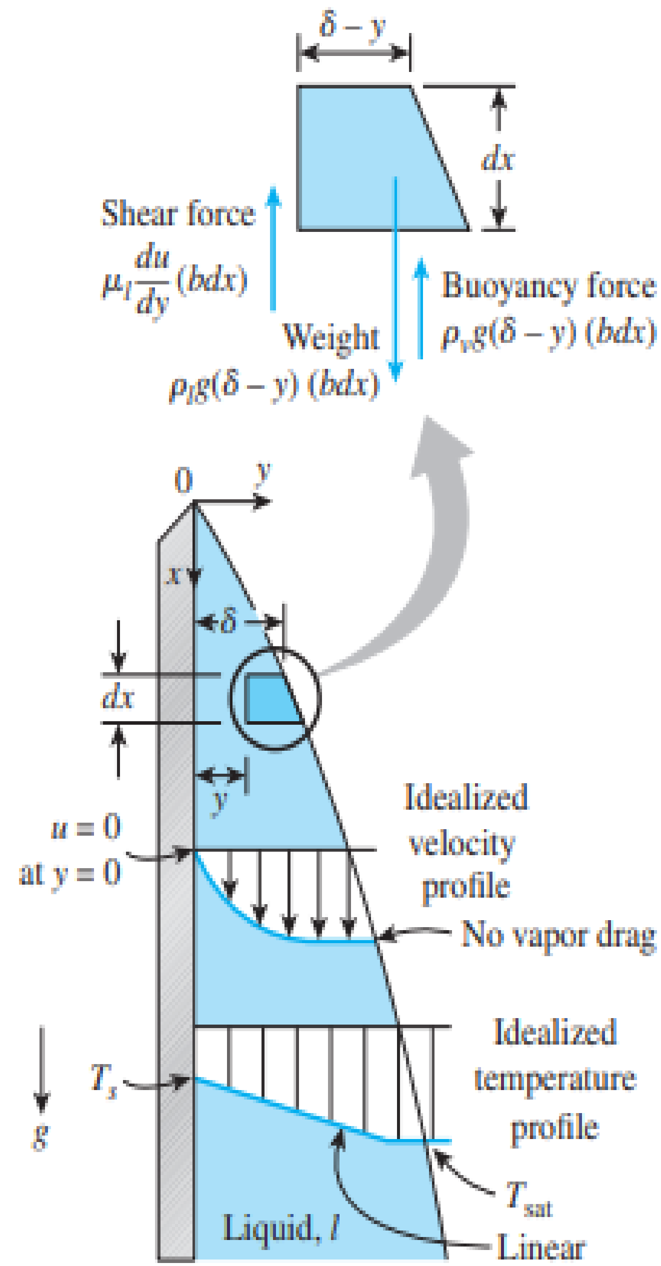
- the condensate flow becomes fully turbulent at about Re $\approx$ 1800
- The condensate flow is called wavy-laminar in the range of 30< Re< 1800
- turbulent for Re> 1800.



- **Heat Transfer Correlations for Film Condensation**
- **1- Vertical Plates**

The analytical relation for the heat transfer coefficient in film condensation on a vertical plate described above was first developed by Nusselt in 1916 under the following simplifying assumptions:

1. Both the plate and the vapor are maintained at constant temperatures of T_w and T_{sat}, respectively, and the temperature across the liquid film varies respectively.



2. Heat transfer across the liquid film is by pure conduction (no convection currents in the liquid film).

3. The velocity of the vapor is low (or zero) so that it exerts no drag on the condensate (no viscous shear on the liquid–vapor interface).

4. The flow of the condensate is laminar and the properties of the liquid are constant.

5. The acceleration of the condensate layer is negligible.

The velocity in the film of condensate at any (y) vertical distance from the plate is

$$u(y) = \frac{g(\rho_f - \rho_v)g}{\mu_f}\left(y\delta - \frac{y^2}{2}\right) \qquad (5)$$

- The Mass flow rate at any distance x from the leading edge of the plate is

$$\dot{m}(x) = \frac{gb\rho_f(\rho_f - \rho_v)\delta^3}{3\mu_f} \qquad (6)$$

Where b is width of the plate

The derivative with respect to x is

$$\frac{d\dot{m}}{dx} = \frac{gb\rho_f(\rho_f - \rho_v)\delta^2}{\mu_f}\frac{d\delta}{dx} \qquad (7)$$

And $d\dot{Q} = h_{fg}d\dot{m} = \frac{k_f}{\delta}(bdx)(T_{sat} - T_w) \rightarrow$

$$\frac{d\dot{m}}{dx} = \frac{k_f b}{\delta h_{fg}}(T_{sat} - T_w) \qquad (8)$$

- From Eq.(7) and Eq.(8) we get:
- $\delta^3 d\delta = \frac{\mu_f k_f (T_{sat} - T_w)}{g\rho_f(\rho_f - \rho_v)h_{fg}} dx$
- Integrating from x=0 where δ =0 (the top of the plate) to x=x where δ=δ(x), the liquid film thickness at any location x is determined to be
- $\delta(x) = \left[\frac{4\mu_f k_f (T_{sat} - T_w) x}{g\rho_f (T_{sat} - T_w) h_{fg}}\right]^{1/4}$ (9)
- The heat transfer rate from the vapor to the plate at a location x can be expressed as

- $\dot{q}_x = h_x(T_{sat} - T_w) = \frac{k_f}{\delta}(T_{sat} - T_w) \rightarrow h_x = \frac{k_f}{\delta(x)}$
- Substituting this in Eq.(9) we get that
- $$h_x = \left[\frac{g\rho_f(\rho_f - \rho_v)k_{fg}k^3{}_f}{4\mu_f(T_{sat} - T_w)x}\right]^{1/4} \quad (10)$$
- The average heat transfer coefficient $\bar{h}$
- $$\bar{h} = 0.943\left[\frac{g\rho_f(\rho_f - \rho_v)h_{fg}k^3{}_f}{\mu_f(T_{sat} - T_w)L}\right]^{1/4} \quad (11)$$
- the average heat transfer coefficient for laminar film condensation over a vertical flat plate of height L is determined to be

- $\bar{h} = 0.943\left[\frac{g\rho_f(\rho_f - \rho_v)h^*{}_{fg}k^3{}_f}{\mu_f(T_{sat} - T_w)L}\right]^{1/4}$ 0<Re<30
- And Reynolds number can be
- $Re = \frac{4g\rho_f(\rho_f - \rho_v)\delta^3}{3(\mu_f)^2} = \frac{4g(\rho_f)^2}{3(\mu_f)^2}\left(\frac{k_f}{h_{x=L}}\right)^3 = \frac{4g}{3(h_L)^2}\left(\frac{k_f}{3\bar{h}/4}\right)^3$
- Then the heat transfer coefficient in terms of Re becomes
- $\bar{h} = 1.47k_f Re^{2/3}\left(\frac{(\rho_f)^2 g}{(\mu_f)^2}\right)^{1/3} = 1.47k_f Re^{2/3}\left(\frac{g}{(\nu_f)^2}\right)^{1/3}$ (12)
- For 0<Re<30 and $\rho_v \ll \rho_f$

- For Wavy Laminar Flow ong Vertical Plates
- $\bar{h} = \frac{Rek_f}{1.08Re^{1.22}-5.2}\left(\frac{g}{(\nu_f)^2}\right)^{1/3} = \frac{Rek_f}{1.08Re^{1.22}-5.2}\left(g\left(\frac{\rho_f}{\mu_f}\right)^2\right)^{1/3}$

(13) For 30<Re<1800 and $\rho_v \ll \rho_f$

- where $\nu = \frac{\mu}{\rho}$
- Reynolds number for wavy laminar region
- $Re_w = \left[4.81 + \frac{3.70Lk_f(T_{sat}-T_w)}{\mu_f h^*{}_{fg}}\left(g\left(\frac{\rho_f}{\mu_f}\right)^2\right)^{1/3}\right]^{0.82}$ (14)
- Turbulent Flow on Vertical Plates
- $\bar{h} = \frac{Rek_f}{8750+58Pr^{-0.5}(Re^{0.75}-253)}\left(g\left(\frac{\rho_f}{\mu_f}\right)^2\right)^{1/3}$ (15)
- Re>1800 $\rho_v \ll \rho_f$

- The physical properties of the condensate in all regions are evaluated at the film temperature T_f= $(T_{sat} - T_w)/2$.
- $Re = \left[\frac{0.0690 L k_f Pr^{0.5}}{\mu_f h^*_{fg}} \left(\frac{g}{(\nu_f)^2}\right)^{1/3} - 151 Pr^{\frac{1}{3}} + 253\right]^{4/3}$
- For inclined surface with horizontal with angle Ø
- $\bar{h}_{inc} = \bar{h}[sin\emptyset]^{1/4}$
- **The relations of the vertical plate are also used for vertical tube of d>>δ**

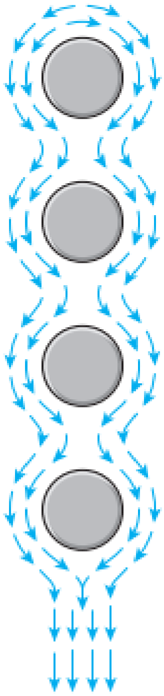
- **Horizontal Tubes and Spheres**

- $\bar{h}_h = 0.729\left[\frac{g\rho_f(\rho_f-\rho_v)h_{fg}{}^{*}k_f{}^3}{\mu_f(T_{sat}-T_w)D}\right]^{1/4}$ (16)

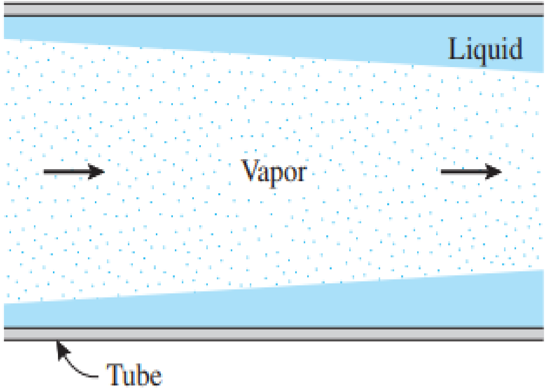
- **Horizontal Tube Banks**

- $\bar{h}_{hb} = 0.729\left[\frac{g\rho_f(\rho_f-\rho_v)h_{fg}{}^{*}k_f{}^3}{\mu_f(T_{sat}-T_w)ND}\right]^{1/4}$

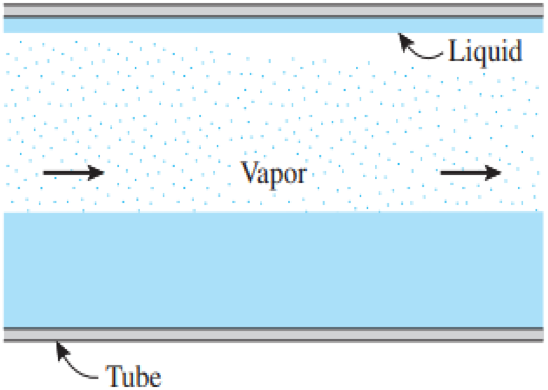
  $= \bar{h}_h/N^{1/4}$ (17)



- **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

- <u>**DROPWISE CONDENSATION**</u>

- 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)

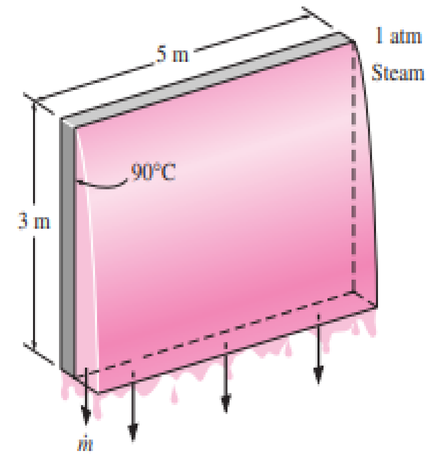
- For a vertical plate A/PL = 1.0, and we obtain, using the constant from Equation (1)
- $$Co = 1.47\left(Re_f\right)^{-1/3} \quad \text{for } Re_f < 1800$$
- For a horizontal cylinder A/PL = π and
- $$Co = 1.514\left(Re_f\right)^{-1/3} \quad \text{for } Re_f < 1800$$
- When turbulence is encountered 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 $T_w=90^oC$, $T_{sat}=100^oC$ at 1atm.
- **The properties**: $\rho_f=957.9kg/m^3$, $\rho_v=0.5978kg.m^3$, $h_{fg}=2257kJ/kg$, $k_f=0.679W/m.K$, $Cp_f=4217J/kg.K$, $\mu_f=0.282x10^{-3}kg/m.sec$, $Pr_f=175$

- **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}
- $h^*_{fg} = h_{fg} + 0.68Cp_f(T_{sat} - T_w)$
- $h^*_{fg} = 2257 \times 10^3 + 0.68 \times 4217(100 - 90)$
$= 2285.68 \times 10^3 J/kg$
- Assuming wavy laminar flow then
- $Re = Re_{ver,wavy}$

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

- $Re = Re_{ver,wavy} = \Big[4.81$



- **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 $T_w=20^{o}C$.

- **Properties:** properties of steam at $T_{sat}=30^oC$ are $\rho_f=996 kg/m^3$ $h_{fg}=2431 kJ/kg$, $Cp_f=4178 J/kg.K$, $k_f=0.615 W/m.K$, $\mu_f=0.798 x 10^{-3}$, $Pr_f=5.42$.
- **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}^*

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

- $h_{fg}^* = 2431 \times 10^3 + 0.68 \times 4178(30 - 20) = 2{,}459.41 \times 10^3 J/kg$

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

- $\dot{Q} = Ah(T_{sat} - T_w) = (\pi DL)4520.8(30$