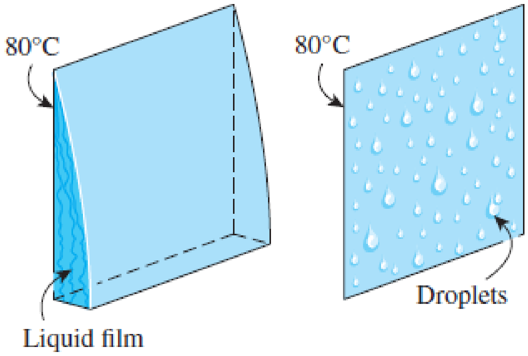
Lecture Seven

Condensation Heat Transfer

1- Introduction.

Condensation occurs when the temperature of a vapor is reduced *below* its saturation temperature T_{sat}. This is usually done by bringing the vapor into contact with a solid surface whose temperature T_s is below the saturation temperature T_{sat} of the vapor. But condensation can also occur on the free surface of a liquid or even in a gas when the temperature of the liquid or the gas to which the vapor is exposed is below T_{sat}. In the latter case, the liquid droplets suspended in the gas form a fog. In this chapter, we consider condensation on solid surfaces only. Two distinct forms of condensation are observed: *film condensation* and *dropwise condensation.* In **film condensation**, the condensate wets the surface and forms a liquid film on the surface that slides down under the influence of gravity. The thickness of the liquid film increases in the flow direction as more vapor condenses on the film. This is how condensation normally occurs in practice. In **dropwise condensation**, the condensed vapor forms droplets on the surface instead of a continuous film, and the surface is covered by countless droplets of varying diameters, Fig.1 shows the two forms of condensation.



(*a*) Film condensation

(*b*) Dropwise condensation

Figure (1)

2- Laminar Film condensation on a vertical wall (VW).

We now consider film condensation on a vertical plate, as shown in Fig. 2. 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 in the amount h_{fg} (the latent heat of vaporization) is released during condensation and is *transferred* through the film to the plate surface at temperature T_s. Note that T_s 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.2. 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.

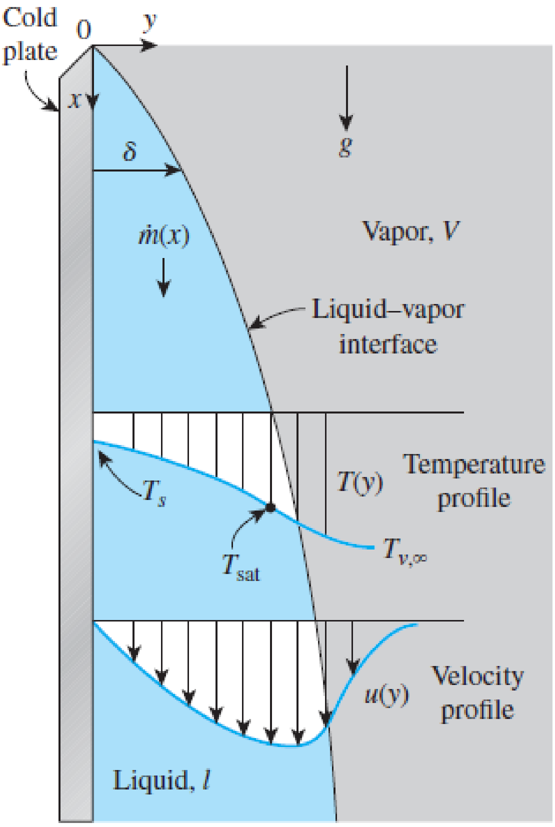


Figure 2: Film condensation on a vertical plate.

3- Flow Regime.

The Reynolds number for condensation on the outer surfaces of vertical tubes or plates increases in the flow direction due to the increase of the liquid film thickness δ. The flow of liquid film exhibits *different regimes,* depending on the value of the Reynolds number. It is observed that the outer surface of the liquid film remains *smooth* and *wave-free* for about Re $\leq$ 30, as shown in Fig. 3, and thus the flow is clearly *laminar*. Ripples or waves appear on the free surface of the condensate flow as the Reynolds number increases, and the condensate flow becomes fully *turbulent* at about Re < 1800. The condensate flow is called *wavy-laminar* in the range of 30 < Re < 1800 and *turbulent* for Re >1800. However, some disagreement exists about the value of Re at which the flow becomes wavy-laminar or turbulent.

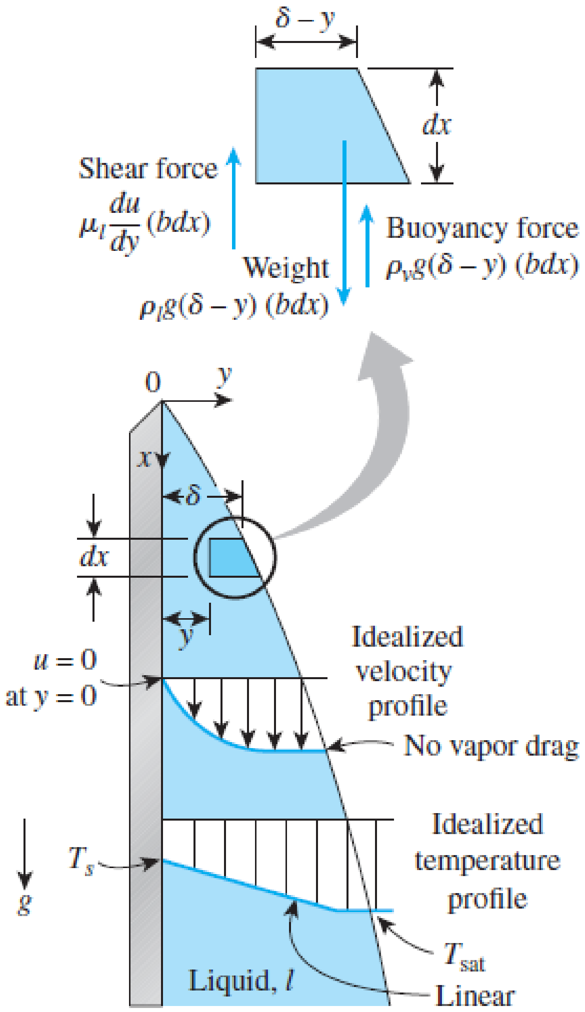


Figure 3 The volume element of condensate on a vertical

4- Heat Transfer Correlations for Film Condensation.

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_s and T_{sat}, respectively, and the temperature across the liquid film varies *linearly*.
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 liquid film thickness at any location *x* is determined to be

$$\delta(x) = \left[\frac{4\mu_l k_l (T_{\text{sat}} - T_s)x}{g\rho_l(\rho_l - \rho_v)h_{fg}}\right]^{1/4}$$

The local heat transfer coefficient h_x is determined to be

$$h_x = \left[\frac{g\rho_l(\rho_l - \rho_v)h_{fg}k_l^3}{4\mu_l(T_{\text{sat}} - T_s)x}\right]^{1/4}$$

The average heat transfer coefficient over the entire plate is determined from its definition by substituting the h_x relation and performing the integration. It gives

$$h = h_{\text{vert}} = \frac{1}{L}\int_0^L h_x\,dx = \frac{4}{3}h_{x=L} = 0.943\left[\frac{g\rho_l(\rho_l - \rho_v)h_{fg}k_l^3}{\mu_l(T_{\text{sat}} - T_s)L}\right]^{1/4}$$

where

g = gravitational acceleration, m/s^2
ρ_l, ρ_v = densities of the liquid and vapor, respectively, kg/m^3
μ_l = viscosity of the liquid, kg/m·s
k_l = thermal conductivity of the liquid, W/m·K

L = height of the vertical plate, m
T_s = surface temperature of the plate, °C
T_{sat} = saturation temperature of the condensing fluid, °C

Total heat transfer rate:

$$q = \bar{h}_L A(T_{sat} - T_s)$$

Condensation rate:

$$\dot{m} = \frac{q}{h_{fg}} = \frac{\bar{h}\,A(T_{sat} - T_s)}{h_{fg}}$$

While using above equation, it may be noted that, all liquid properties are to be evaluated at the temperature $\left(\frac{t_{sat} + t_s}{2}\right)$ and h_{fg} should be evaluated at t_{sat}.

For inclined flat surfaces, the gravitational acceleration (g) in above equation is replaced by (g*sinθ) where (θ) is the angle between the surface and horizontal as in Fig.4, now the equation of heat transfer coefficient is modified as

$$h_{inclined} = h_{vertical} \times (\sin \theta)^{1/4}$$