University of Al–Mustansiriyah – College of Engineering
Department of Mechanical Engineering

Phase Change and Applications II
Second Semester – Spring 2021

Lecture (3):
Condensation

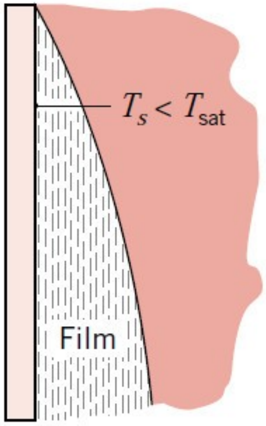
Instructor:
Dr. Aouf A. Al–Tabbakh
aoufaltabbakh72@gmail.com

Definition of Condensation

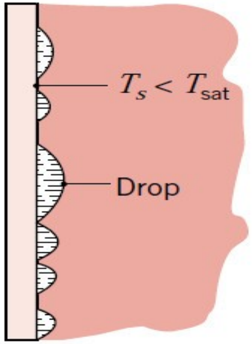
Condensation occurs when the vapor temperature is reduced below the saturation temperature. It is commonly achieved by making the vapor in direct contact with a cold surface. The latent heat of vaporization is released and the **condensate** forms.

Modes of Condensation

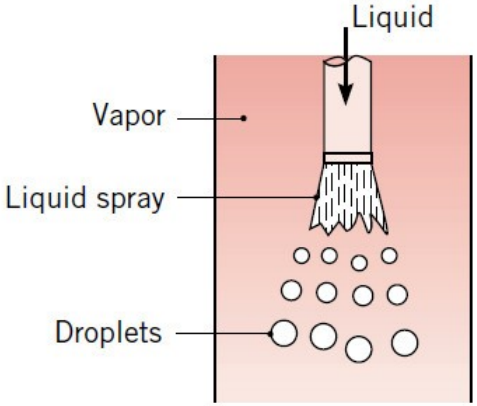
- **Film Condensation**:– Liquid film is formed on a vertical surface.
- **Dropwise Condensation**:– Drops of condensate are formed on the surface.
- **Homogeneous Condensation**:– Tiny droplets of condensate are formed and suspended in the vapor in a fog–like manner.
- **Direct Contact Condensation**:– Condensate is formed by mixing the vapor with cold liquid.



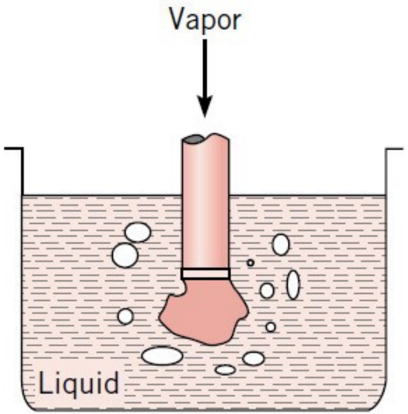
Film Mode



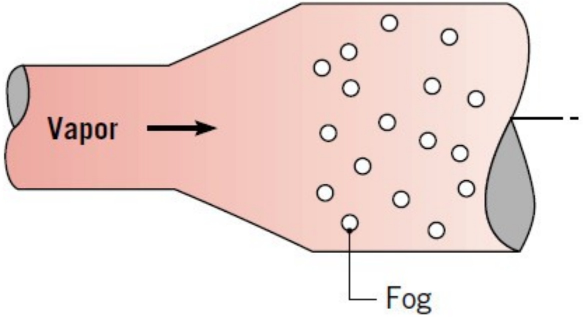
Dropwise Mode



Direct Contact Mode (spray coolant)



Direct Contact Mode (Pool Cooling)



Homogeneous Mode

<u>Laminar Film Condensation over Vertical wall</u>

The following analysis was performed by **Nusselt** in 1916 to predict the overall condensation heat transfer coefficient of the condensate film falling over a vertical wall. The following assumptions were made to simplify the analysis:–

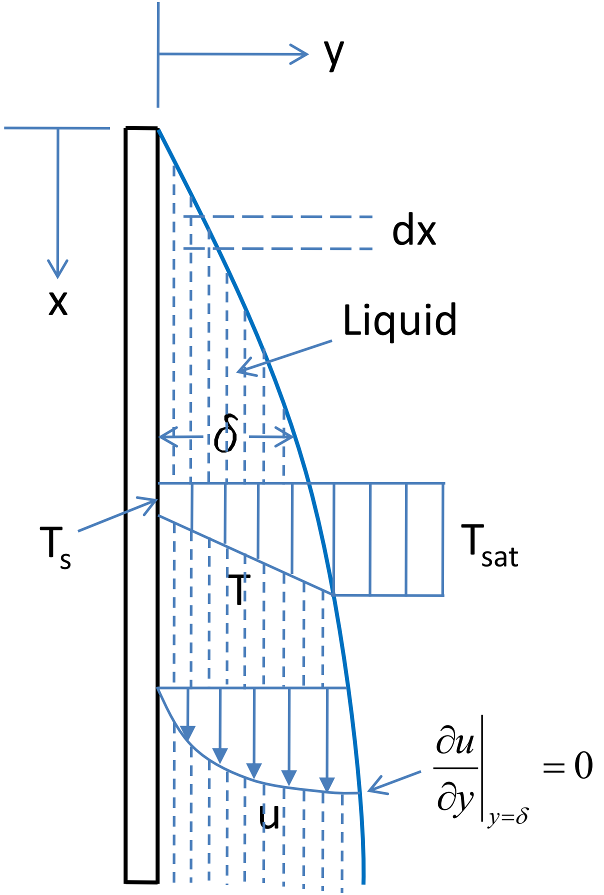
1. **Laminar flow of the condensate film.**
2. **Constant fluid properties across the film.**
3. **The vapor temperature is constant at T_{sat} with no temperature gradient near the film.**
4. **No shear stress in the liquid–vapor interface.**
5. **Heat transfer across the film is only by conduction resulting in a linear liquid temperature distribution across the film.**

From the assumptions mentioned above, the momentum equation for the condensate film can be written as follows:−

$$\frac{\partial^2 u}{\partial y^2} = -\frac{g}{\mu_l}(\rho_l - \rho_v) \quad \textbf{(1)}$$

Integrating twice and applying the boundary conditions; [$u(0)=0$, $(\partial u/\partial y)_{y=\delta} = 0$] we get:−

$$u(y) = \frac{g(\rho_l - \rho_v)\delta^2}{\mu_l}\left[\frac{y}{\delta} - \frac{1}{2}\left(\frac{y}{\delta}\right)^2\right] \quad \textbf{(2)}$$



The condensate mass flow rate per unit width Γ***(x)*** is then defined as:–

$$\frac{\dot{m}(x)}{b} = \int_0^{\delta(x)} \rho_l u(y)\, dy \equiv \Gamma(x) \qquad \textbf{(3)}$$

Substituting eq. (2) and performing the integration, we get:–

$$\Gamma(x) = \frac{g\rho_l(\rho_l - \rho_v)\delta^3}{3\mu_l} \qquad \textbf{(4)}$$

Differentiating eq. (4) with x, we get:–

$$\frac{d\Gamma}{dx} = \frac{g\rho_l(\rho_l - \rho_v)\delta^2}{\mu_l}\frac{d\delta}{dx} \qquad \textbf{(5)}$$

Heat released by condensation (dq) on the incremental length (dx) along the wall is:−

$$dq = h_{fg}\, d\dot{m} \qquad \textbf{(6)}$$

The same amount of heat (dq) is transmitted to the wall, so that:−

$$dq = q''_s(b \cdot dx) \qquad \textbf{(7)}$$

Eliminating (dq) between eqs. (6) and (7), we get:−

$$\frac{d\dot{m}}{dx} = \frac{q_s''b}{h_{fg}} \quad or \quad \frac{d(\dot{m}/b)}{dx} = \frac{d\Gamma}{dx} = \frac{q_s''}{h_{fg}} \qquad \textbf{(8)}$$

Since the liquid temperature distribution is linear, Fourier's law may be used to express surface heat flux (q_s'') as:−

$$q''_s = \frac{k_l(T_{\text{sat}} - T_s)}{\delta} \qquad \textbf{(9)}$$

Therefore eq. (8) becomes:−

$$\frac{d\Gamma}{dx} = \frac{k_l(T_{\mathrm{sat}} - T_s)}{\delta h_{fg}} \qquad \textbf{(10)}$$

Combing eqs. (5) and (10), we get:−

$$\delta^3\, d\delta = \frac{k_l \mu_l (T_{\mathrm{sat}} - T_s)}{g\rho_l(\rho_l - \rho_v) h_{fg}}\, dx \qquad \textbf{(11)}$$

Integrating between x=0, δ=0 to any values of x and δ, we get:−

$$\delta(x) = \left[\frac{4 k_l \mu_l (T_{\mathrm{sat}} - T_s) x}{g\rho_l(\rho_l - \rho_v) h_{fg}}\right]^{1/4} \qquad \textbf{(12)}$$

The condensation heat transfer coefficient h_x can be found by combining convection and conduction heat flux q''_s as follows:−

$$q''_s = h_x(T_{sat} - T_s)$$ (convection) **(13)**

$$q''_s = \frac{k_l(T_{sat} - T_s)}{\delta}$$ (conduction) **(9)**

So that:− $$h_x = \frac{k_l}{\delta}$$ **(14)**

Substituting (δ) from eq. (12) we get:−

$$h_x = \left[\frac{g\rho_l(\rho_l - \rho_v)\,k_l^3 h_{fg}}{4\mu_l(T_{sat} - T_s)x}\right]^{1/4}$$ **(15)**

The latent heat of condensation h_{fg} can be modified to take into account the effect of advection which is the sensible heat transferred between liquid and vapor phases. The modified latent heat h'_{fg} is found as follows:−

$$h'_{fg} = h_{fg} + 0.68 c_{p,l}(T_{sat} - T_s) \quad \textbf{(16)}$$

h_x is the local condensation heat transfer coefficient at any location x along the vertical wall. To find the overall heat transfer coefficient for the entire wall, the following integration is done:−

$$\bar{h}_L = \frac{1}{L}\int_0^L h_x \, dx \quad \textbf{(17)}$$

So, the overall condensation heat transfer coefficient for the entire wall $\overline{h}_L$ is :−

$$\overline{h}_L = 0.943\left[\frac{g\rho_l(\rho_l-\rho_v)k_l^3 h'_{fg}}{\mu_l(T_{\text{sat}}-T_s)L}\right]^{1/4} \qquad \textbf{(18)}$$

All liquid properties in eq. (18) should be evaluated at the film temperature T_f which is the average between saturation and surface temperatures, while vapor density and latent heat are evaluated at the saturation temperature.