Department Of Mechanical Engineering

MODULE 8

Condensation and Boiling

Condensation and Boiling

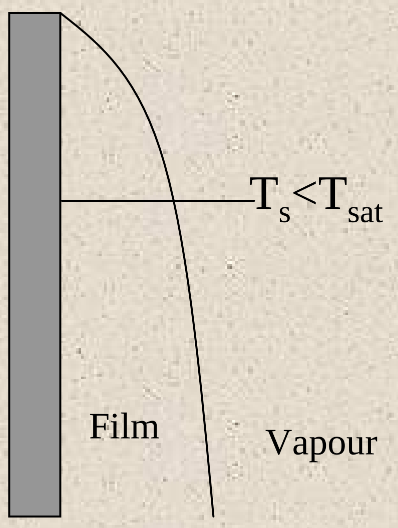
- Until now, we have been considering convection heat transfer in *homogeneous single-phase* (*HSP*) systems
- *Boiling and condensation*, however, provide much higher heat transfer rates than those possible with the *HSP* systems

Condensation

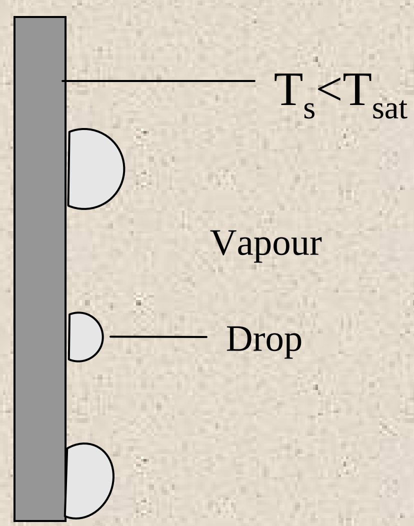
- Condensation occurs when the temperature of a vapor is reduced below its saturation temperature

- Condensation heat transfer

Film condensation

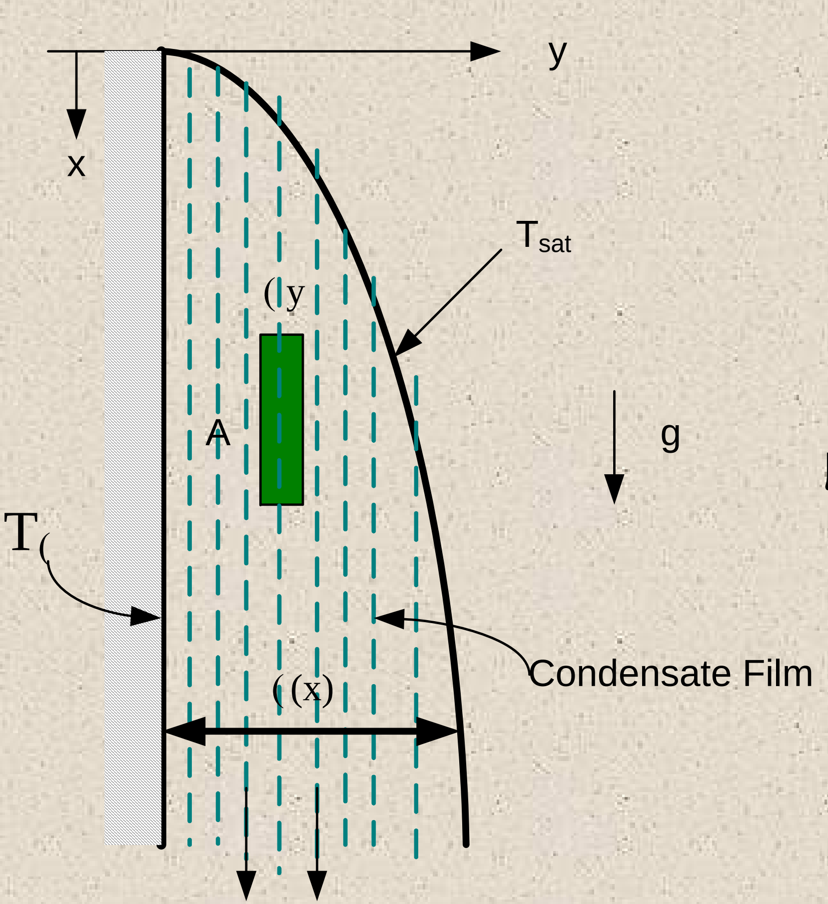


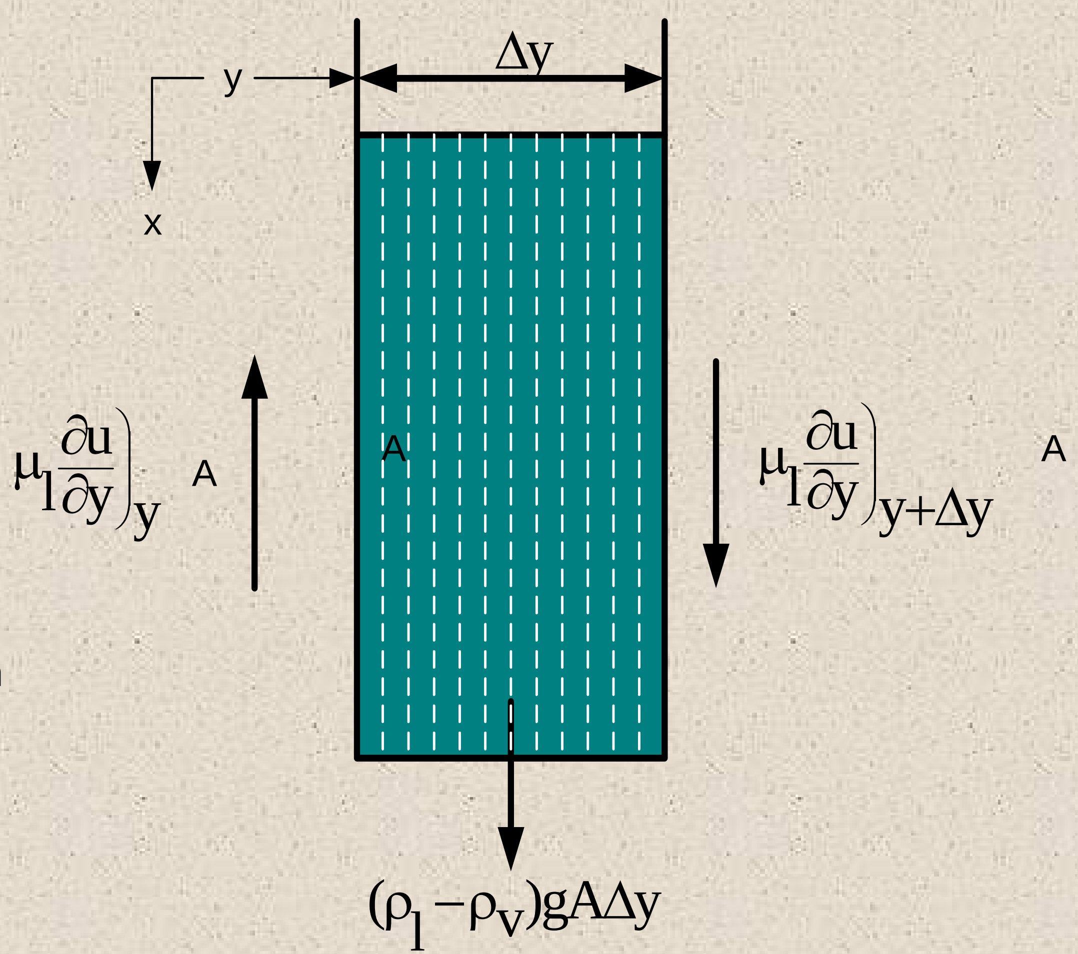
Drop wise condensation



- Heat transfer rates in drop wise condensation *may be as much as 10 times higher* than in film condensation

Laminar Film condensation on a vertical wall (VW)





Laminar Film condensation on a vertical wall (cont..)

$$\delta(x) = \left[\frac{4xk_l(T_{sat} - T_w)\nu_l}{h_{fg}g(\rho_l - \rho_v)}\right]^{1/4} \qquad h(x) = \left[\frac{h_{fg}g(\rho_l - \rho_v)k_l^3}{4x(T_{sat} - T_w)\nu_l}\right]^{1/4}$$

Average coeff. $\bar{h}_L = 0.943\left[\frac{h_{fg}g(\rho_l - \rho_v)k_l^3}{L(T_{sat} - T_w)\nu_l}\right]^{1/4}$

where L is the plate length.

Total heat transfer rate : $q = \bar{h}_L A(T_{sat} - T_w)$

Condensation rate : $\dot{m} = \frac{q}{h_{fg}} = \frac{\bar{h}_L A(T_{sat} - T_w)}{h_{fg}}$

Example

❑Laminar film condensation of steam

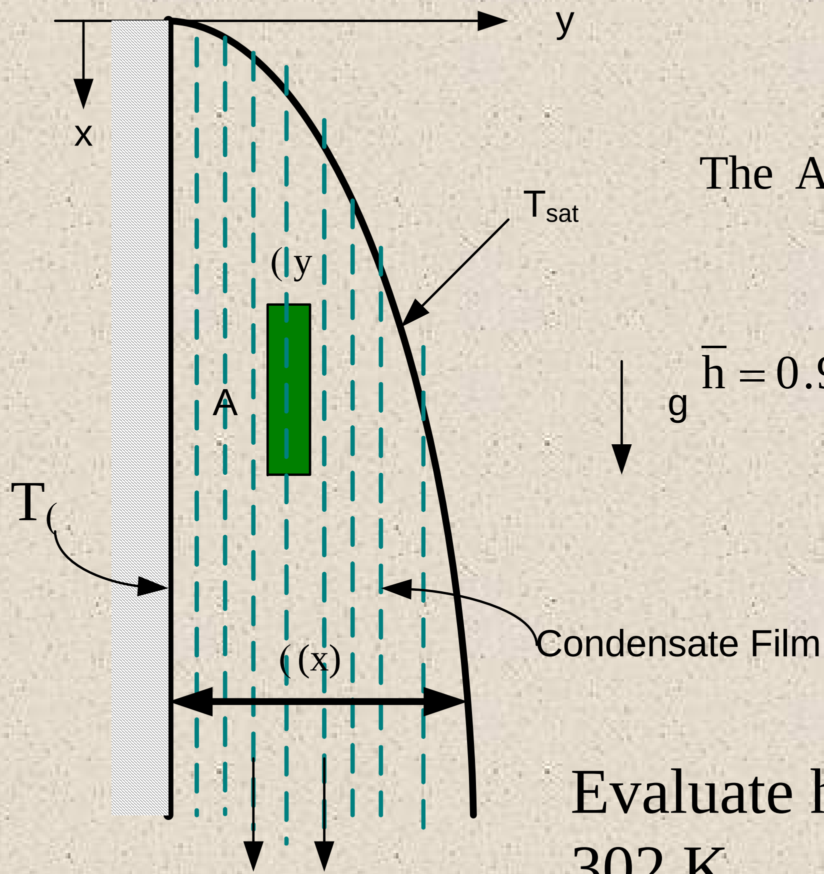
Saturated steam condenses on the outside of a 5 cm-diameter vertical tube, 50 cm high. If the saturation temperature of the steam is 302 K, and cooling water maintains the wall temperature at 299 K, determine: (i) the average heat transfer coefficient, (ii) the total condensation rate, and (iii) the film thickness at the bottom of the tube.

Given: Film condensation of saturated steam

Required: (i) Average heat transfer coefficient, (ii) total condensation rate, (iii) and film thickness

1. Effect of tube curvature negligible
2. Effect of liquid sub cooling negligible
3. Laminar

Example (contd...)



The Average heat trasn sfer coefficent is given by :

$$g \quad \bar{h} = 0.943 \left[\frac{h'_{fg}\, g(\rho_l - \rho_v) k_l^3}{L(T_{sat} - T_w)\nu_l} \right]^{1/4}$$

Evaluate h_{fg} at the saturation temperature of 302 K

From Table of water properties :

$h_{fg} = 2.432 \times 10^6\ J/kg$

$\rho_v = 0.03 kg/m^3$

Example (contd...)

Also, for water

$$k_l = 0.611 \text{ W/mK}$$

$$\rho_l = 996 \text{ kg/m}^3$$

$$\nu_l = 0.87 \times 10^{-6} \text{ m}^2\text{/s}$$

$$\bar{h} = 0.943 \left[\frac{h_{fh} g (\rho_l - \rho_v) k_l^3}{L (T_{sat} - T_w) \nu_l} \right]^{1/4}$$

$$= 0.943 \left[\frac{(2.432 \times 10^{-6})(9.81)(996 - 0.03)(0.611)^3}{(0.5)(3)(0.87 \times 10^{-6})} \right]^{1/4} = 7570 \text{ W/m}^2\text{K}$$

(ii) The total condensation rate is :

$$\dot{m} = \frac{\dot{Q}}{h_{fg}} = \frac{\bar{h} A \Delta T}{h_{fg}} = \frac{(7570)(3)\pi(0.05)(0.5)}{(2.432 \times 10^6)} = 7.33 \times 10^{-4} \text{ kg/s}$$

Example (contd...)

(iii) The film thickness is

$$\delta = \left(\frac{3\nu_l \Gamma}{\rho_l g} \right)^{1/3} \qquad \rho_v << \rho_l$$

The mass flow rate per unit width of film Γ is :

$$\Gamma = \frac{\dot{m}}{\pi D} = \frac{(7.33 \times 10^{-4})}{(\pi)(0.05)} = 4.67 \times 10^{-3} \text{ kg/ms}$$

Hence, $$\delta = \left(\frac{3(0.87 \times 10^{-6})(4.67 \times 10^{-3})}{(996)(9.81)} \right)^{1/3} = 1.08 \times 10^{-4} \text{ m}$$

Boiling

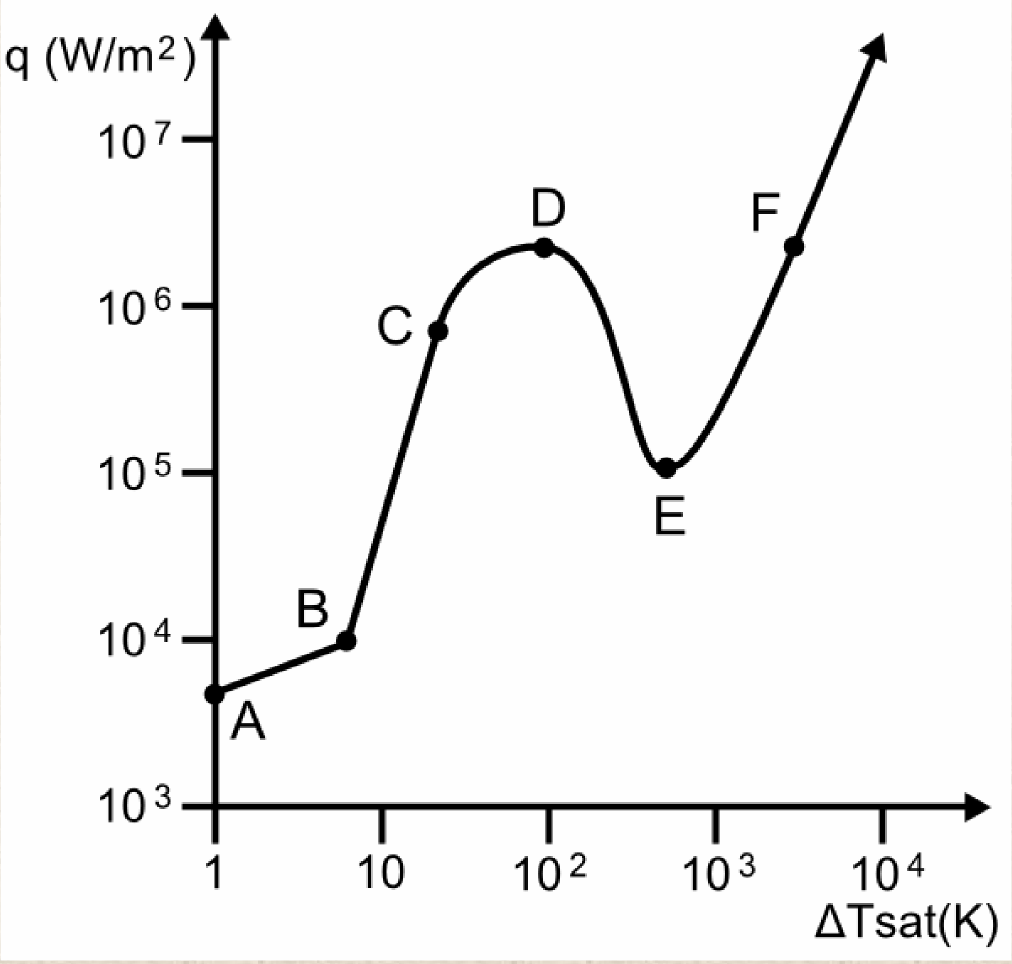
- Boiling occurs when the surface temperature T_w exc the saturation temperature T_{sat} corresponding to the liquid pressure

$$\text{Heat transfer rate}: q_s'' = h(T_w - T_{sat}) = h\Delta T_e$$

$$\text{where} \quad \Delta T_e = T_w - T_{sat} \quad \text{(excess temperature)}$$

- Boiling process is characterized by formation of vapor bubbles, which grow and subsequently detach from the surface
- Bubble growth and dynamics depend on several factors such as excess temp., nature of surface, thermo physical properties of fluid (e.g. surface tension, liquid density, vapor density, etc.). Hence, heat transfer coefficient also depends on those factors.

Pool Boiling Curve



Pool boiling regimes:

A-B: Pure convection with liquid rising to surface for evaporation

B-C: Nucleate boiling with bubbles condensing in liquid

C-D: Nucleate boiling with bubbles rising to surface

D: Peak temperature

D-E: Partial nucleate boiling and unstable film boiling

E: Film boiling is stabilized

E-F: Radiation becomes a dominant mechanism for heat transfer

Modes of Pool Boiling

- Free convection boiling $\Delta T_e \approx 5\,^{o}C$
- Nucleate boiling $5^{o}C \le \Delta T_e \le 30^{o}C$
- Transition boiling $30^{o}C \le \Delta T_e \le 120^{o}C$
- Film boiling $\Delta T_e \ge 120^{o}C$