Condensation

Chapter 10

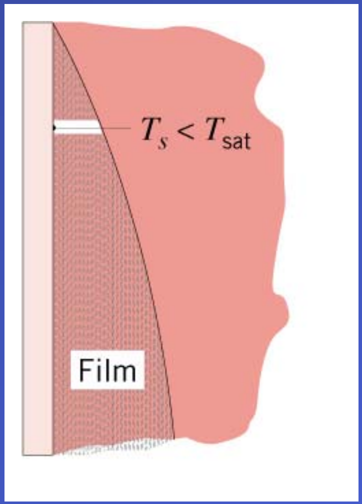
Sections 10.6 through 10.11

General Considerations

- Heat transfer to a surface occurs by condensation when the surface temperature is less than the saturation temperature of an adjoining vapor.

- Film Condensation

  - Entire surface is covered by the condensate, which flows continuously from the surface and provides a resistance to heat transfer between the vapor and the surface.

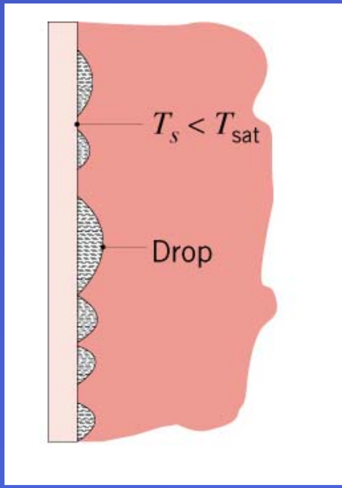


  - Thermal resistance is reduced through use of short vertical surfaces and horizontal cylinders.

  - Characteristic of clean, uncontaminated surfaces.

- Dropwise Condensation

  - Surface is covered by drops ranging from a few micrometers to agglomerations visible to the naked eye.

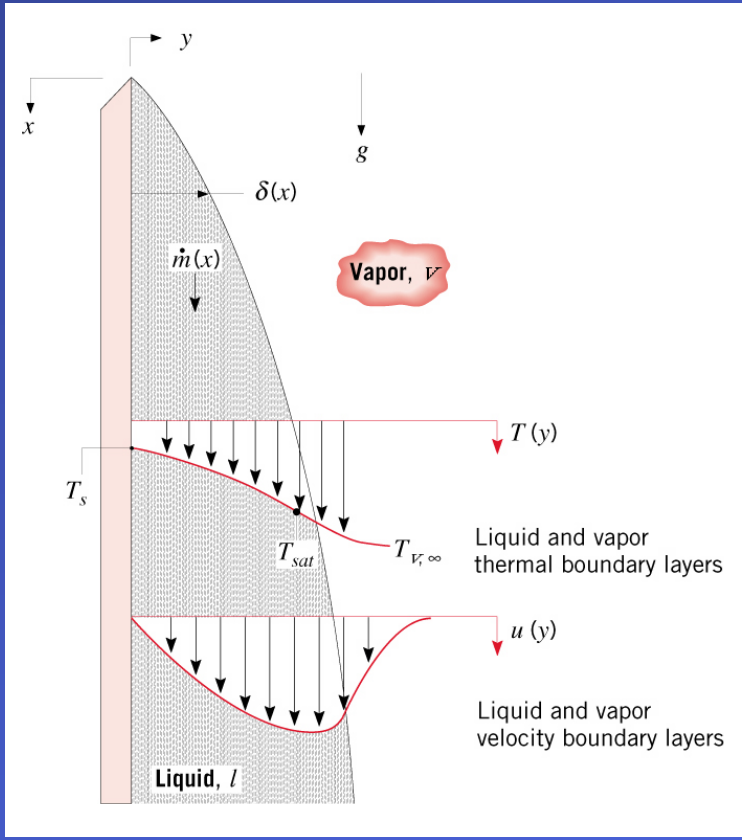


General Considerations (cont).

- Thermal resistance is greatly reduced due to absence of a continuous film.
- Surface coatings may be applied to inhibit *wetting* and stimulate dropwise condensation.

Film Condensation on a Vertical Plate

- Distinguishing Features
  - Thickness (δ) and flow rate $(\dot{m})$ of condensate increase with increasing x
  - Generally, the vapor is superheated $(T_{v,\infty} > T_{sat})$ and may be part of a mixture that includes noncondensibles.
  - A shear stress at the liquid/vapor interface induces a velocity gradient in the vapor, as well as the liquid.



- Nusselt Analysis for Laminar Flow

  Assumptions:
  - A pure vapor at T_{sat}.
  - Negligible shear stress at liquid/vapor interface.

$$\rightarrow \left.\frac{\partial u}{\partial y}\right|_{y=\delta} = 0$$

- Negligible advection in the film. Hence, the steady-state x-momentum and energy equations for the film are

$$\frac{\partial^2 u}{\partial y^2} = \frac{1}{\mu_l}\frac{dp_\infty}{dx} - \frac{\rho_l g}{\mu_l}$$

$$\frac{\partial^2 T}{\partial y^2} = 0$$

- The boundary layer approximation, $\partial p / \partial y = 0$, may be applied to the film. Hence,

$$\frac{dp_\infty}{dx} = \rho_v g$$

- Solutions to momentum and energy equations ⟶

Film thickness:

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

Flow rate per unit width:

$$\Gamma \equiv \frac{\dot{m}}{b} = \frac{g\rho_l(\rho_l - \rho_v)\delta^3}{3\mu_l}$$

Average Nusselt Number:

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

$$h'_{fg} = h_{fg}(1 + 0.68\ Ja)$$

$$Ja \equiv \frac{c_{p,l}(T_{sat} - T_s)}{h_{fg}} \rightarrow \text{ Jakob number}$$

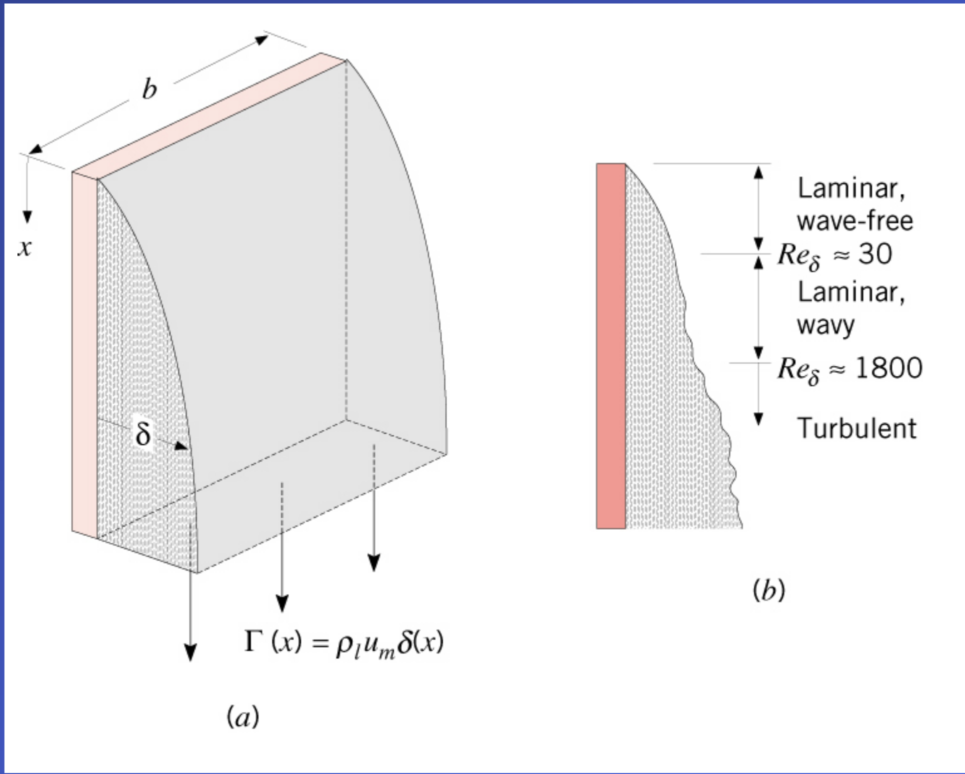
Total heat transfer and condensation rates:

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

$$\dot{m} = \frac{q}{h'_{fg}}$$

- Effects of Turbulence:
  - Transition may occur in the film and three flow regimes may be identified and delineated in terms of a Reynolds number defined as

$$\mathrm{Re}_\delta \equiv \frac{4\Gamma}{\mu_l} = \frac{4\dot{m}}{\mu_l b} = \frac{4\rho_l u_m \delta}{\mu_l}$$



Re_δ can be determined by calculating the three values below and selecting the one that lies within the range of applicability for that equation.

- Wave-free laminar region $\left(\mathrm{Re}_\delta < 30\right)$:

$$Re_\delta = 3.78\left[\frac{k_l L\left(T_{sat}-T_s\right)}{\mu_l h'_{fg}\left(v_l^2/g\right)^{1/3}}\right]^{3/4} \quad (10.42)$$

- Wavy laminar region $\left(30 < \mathrm{Re}_\delta < 1800\right)$:

$$Re_\delta = \left[\frac{3.70 k_l L\left(T_{sat}-T_s\right)}{\mu_l h'_{fg}\left(v_l^2/g\right)^{1/3}} + 4.8\right]^{0.82} \quad (10.43)$$

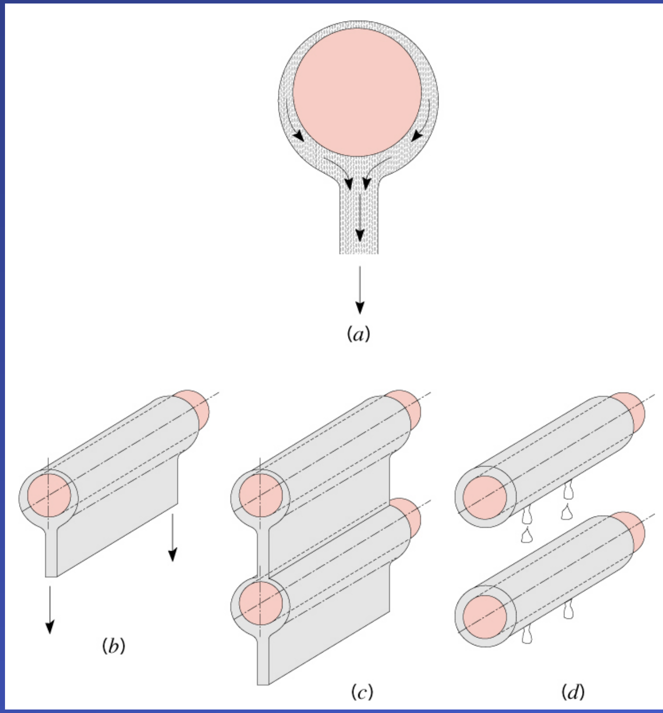
- Turbulent region $\left(\mathrm{Re}_\delta > 1800\right)$:

$$Re_\delta = \left[\frac{0.069 k_l L\left(T_{sat}-T_s\right)}{\mu_l h'_{fg}\left(v_l^2/g\right)^{1/3}} Pr_l^{0.5} - 151 Pr_l^{0.5} + 253\right]^{4/3} \quad (10.44)$$

- $\bar{h}_L$ can then be found from

$$\bar{h}_L = \frac{Re_\delta\, \mu_l h'_{fg}}{4L\left(T_{sat}-T_s\right)} \quad (10.41)$$

Film Condensation on Radial Systems



- A single tube or sphere:

$$\bar{h}_D = C\left[\frac{g\rho_l(\rho_l-\rho_\upsilon)k_l^3 h'_{fg}}{\mu_l(T_{sat}-T_s)D}\right]^{1/4}$$

Tube: $C = 0.729$ Sphere: $C = 0.826$

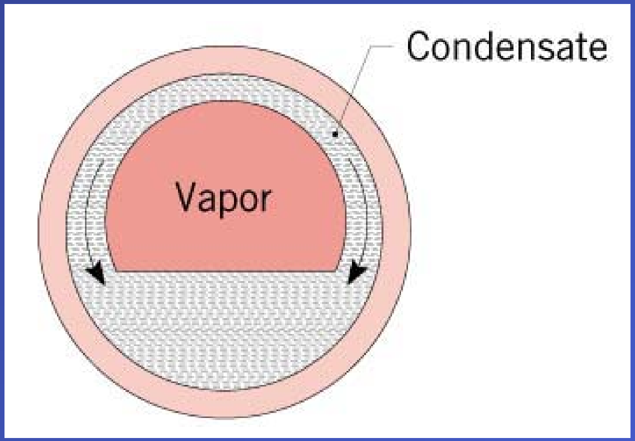
- A vertical tier of N tubes:

$$\bar{h}_{D,N} = 0.729\left[\frac{g\rho_l\left(\rho_l-\rho_\upsilon\right)k_l^3 h'_{fg}}{N\mu_l\left(T_{sat}-T_s\right)D}\right]^{1/4}$$

  - Why does $\bar{h}_{D,N}$ decrease with increasing N?
  - How is heat transfer affected if the continuous sheets (c) breakdown and the condensate *drips* from tube to tube (d)?
  - What other effects influence heat transfer?

Film Condensation for a Vapor Flow in a Horizontal Tube

- If vapor flow rate is small, condensate flow is circumferential and axial:

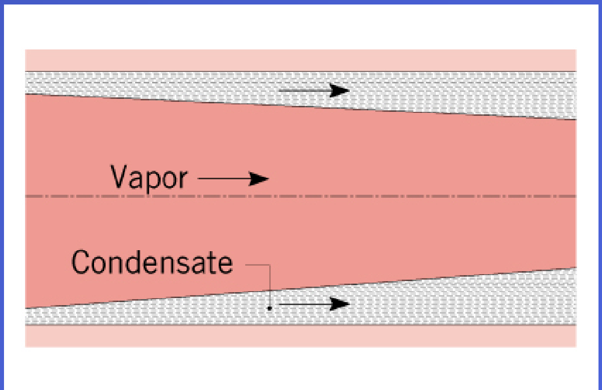


$$\mathrm{Re}_{\upsilon,\mathrm{i}} = \left(\frac{\rho_\upsilon u_{m,\upsilon} D}{\mu_\upsilon}\right)_i < 35{,}000 :$$

$$\bar{h}_D = 0.555\left[\frac{g\rho_l(\rho_l - \rho_\upsilon)k_l^3 h'_{fg}}{\mu_l(T_{sat} - T_s)D}\right]^{1/4}$$

$$h'_{fg} \equiv h_{fg} + 0.375(T_{sat} - T_s)$$

- For larger vapor velocities, flow is principally in the axial direction and characterized by two-phase annular conditions.



Dropwise Condensation

- Steam condensation on copper surfaces:

$$q = \bar{h}_{dc} A\left(T_{sat} - T_s\right)$$

$$\bar{h}_{dc} = 51{,}100 + 2044\, T_{sat} \qquad 22^\circ\mathrm{C} < T_{sat} < 100^\circ\mathrm{C}$$

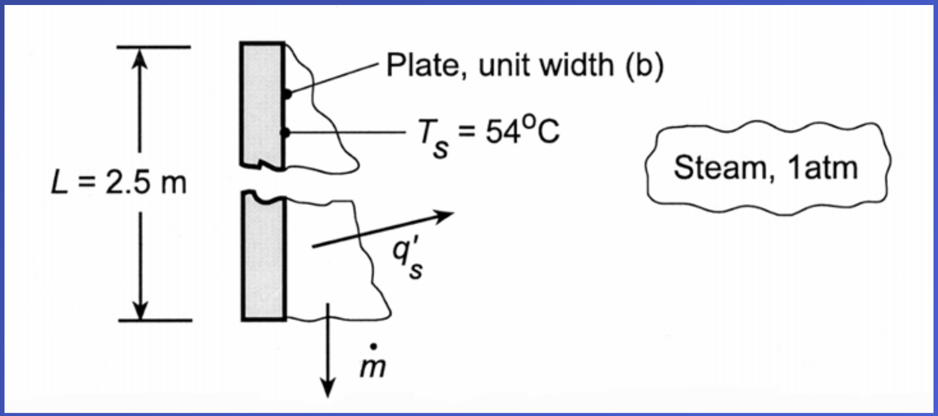
$$\bar{h}_{dc} = 255{,}500 \qquad T_{sat} > 100^\circ\mathrm{C}$$

Problem 10.48 a,b: Condensation and heat rates per unit width for saturated steam at 1 atm on one side of a vertical plate at 54°C if (a) the plate height is 2.5m and (b) the height is halved.

KNOWN: Vertical plate 2.5 m high at a surface temperature T_s = 54°C exposed to steam at atmospheric pressure.

FIND: (a) Condensation and heat transfer rates per unit width, (b) Condensation and heat rates if the height were halved.

SCHEMATIC:



ASSUMPTIONS: (1) Film condensation, (2) Negligible non-condensables in steam.

PROPERTIES: *Table A-6*, Water, vapor (1 atm): T_{sat} = 100°C, h_{fg} = 2257 kJ/kg; *Table A-6*, Water, liquid (T_f = (100 + 54)°C/2 = 350 K): $\rho_\ell = 973.7$ kg/m^3, $k_\ell = 0.668$ W/m·K, $\mu_\ell = 365 \times 10^{-6}$ N·s/m^2 , $c_{p,\ell}$ = 4195 J/kg·K, Pr_ℓ = 2.29, $\nu_\ell = \mu_\ell / \rho_\ell = 3.75 \times 10^{-7}$ m^2/s.

ANALYSIS: (a) For the long plate length, assume turbulent film condensation, Eq. 10.44.

$$Re_\delta = \left[\frac{0.069 k_\ell L (T_{sat} - T_s)}{\mu_\ell h'_{fg} (\nu_\ell^2 / g)^{1/3}} Pr_\ell^{0.5} - 151 Pr_\ell^{0.5} + 253 \right]^{4/3}$$

$$Re_\delta = \left[\frac{0.069 \times 0.668 \text{ W/m} \cdot \text{K} \times 2.5 \text{ m}(100-54)\text{K}}{365 \times 10^{-6} \text{ N} \cdot \text{s/m}^2 \times 2388 \times 10^3 \text{ J/kg} \left[\left(3.75 \times 10^{-7} \text{ m}^2/\text{s} \right)^2 / 9.8 \text{ m/s}^2 \right]^{1/3}} 2.29^{0.5} - 151(2.29)^{0.5} + 2$$

$$Re_\delta = 2979$$

where $h'_{fg} = h_{fg} + 0.68 c_{p,\ell} (T_{sat} - T_s)$= 2388 kJ/kg. The turbulent assumption is correct. Then from Eqs. 10.36 and 10.34,

$$\dot{m}' = \frac{Re_\delta \, \mu_\ell}{4} = 2979 \times 365 \times 10^{-6} \text{ N} \cdot \text{s/m}^2/4 = 0.272 \text{ kg/s} \cdot \text{m}$$

$$q' = \dot{m}' h'_{fg} = 0.272 \text{ kg/s} \cdot \text{m} \times 2.388 \times 10^6 \text{ J/kg} = 649 \text{ kW/m} \qquad <$$

(b) If the length is halved, L = 1.25 m, Re_δ will decrease and we begin by trying Eq. 10.43,

$$Re_\delta = \left[\frac{3.70 k_\ell L(T_{sat} - T_s)}{\mu_\ell h'_{fg}(\nu_\ell^2/g)^{1/3}} + 4.8\right]^{0.82} = 1375$$

and the assumption of wavy laminar flow was correct. The flow regime changes.

We find $\dot{m}' = \frac{Re_\delta \, \mu_\ell}{4} = 0.125 \mathrm{kg/s \cdot m}$ and $q' = \dot{m}' h'_{fg}$ = 300 kW/m .

COMMENT:

Note that the height was decreased by a factor of 2, while the rates decreased by a factor of 2.2. Would you have expected this result?