Transferência de calor com Mudança de fase

Ebulição e Condensação

Considerações Gerais

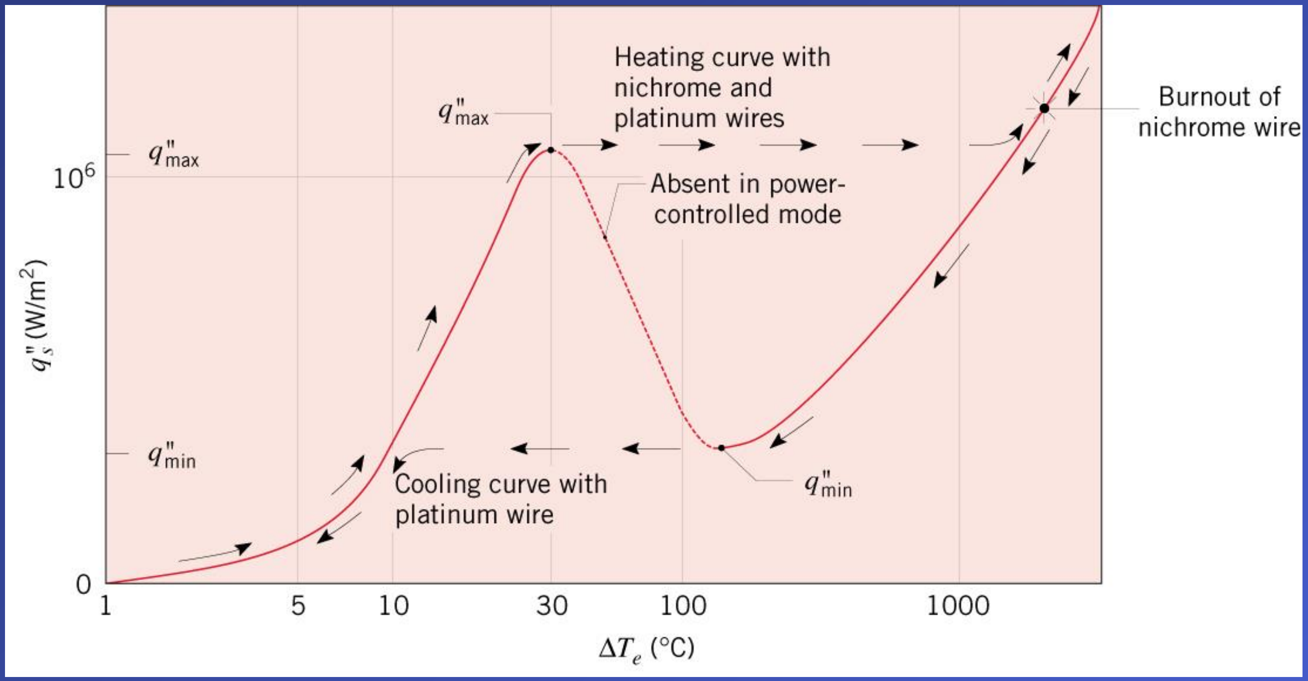
- Lei de Newton para o resfriamento:

$$q''_s = h\left(T_s - T_{sat}\right) = h \,\Delta T_e$$

- $T_{sat} \rightarrow$ **Temperatura de Saturação**
- $\Delta T_e \equiv \left(T_s - T_{sat}\right) \rightarrow$ **Temperatura de excesso**

Curvas de ebulição

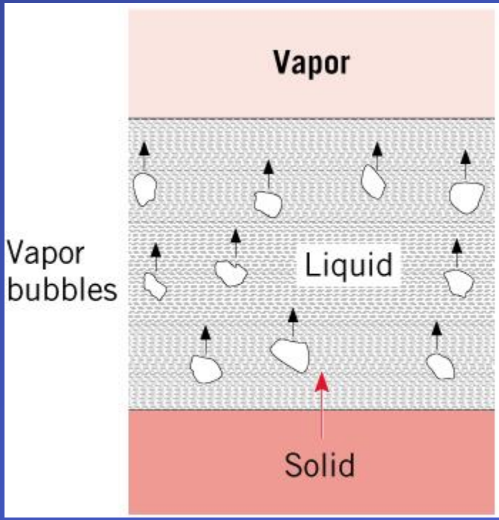
Água a pressão atmosférica



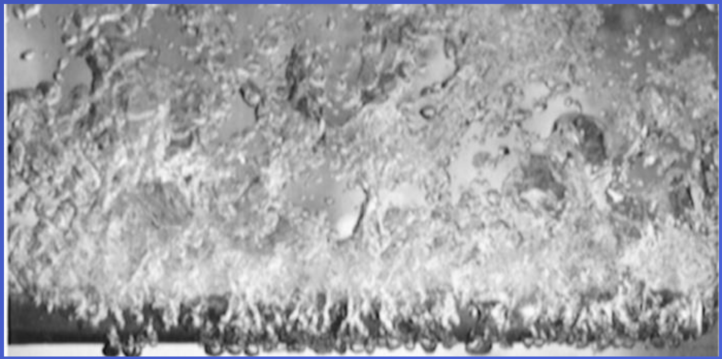
Nukiyama, 1934
Drew e Mueller, 1937

- Ebulição com convecção livre $\left(\Delta T_e < 5^\circ C\right)$
  - Pouca formação de vapor.
  - Movimentação é devido a convecção livre.
- Início da Ebulição Nucleada $ONB\left(\Delta T_e \approx 5^\circ C\right)$

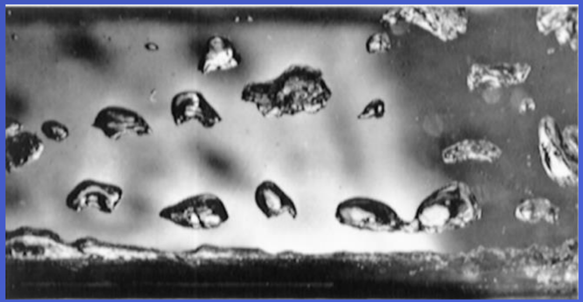
- Ebulição Nucleada $\left(5 < \Delta T_e < 30^\circ\mathrm{C}\right)$
  - Bolhas individuais $\left(5 < \Delta T_e < 10^\circ\mathrm{C}\right)$
    - Liquid motion is strongly influenced by nucleation of bubbles at the surface.
    - h and q''_s increase sharply with increasing ΔT_e.
    - Heat transfer is principally due to contact of liquid with the surface (single-phase convection) and not to vaporization.



  - Jatos e colunas $\left(10 < \Delta T_e < 30^\circ\mathrm{C}\right)$
    - Increasing number of nucleation sites causes bubble interactions and coalescence into jets and slugs.
    - Liquid/surface contact is impaired.
    - q''_s continues to increase with ΔT_e while h begins to decrease.



- *Fluxo de calor crítico- CHF,* $q''_{\max}\left(\Delta T_e \approx 30^\circ\mathrm{C}\right)$
  - Maximum attainable heat flux in nucleate boiling.
  - $q''_{\max} \approx 1\ \mathrm{MW/m^2}$ for water at atmospheric pressure.
- Potential Burnout for Power-Controlled Heating
  - An increase in q''_s beyond $q''_{\max}$ causes the surface to be blanketed by vapor, and the surface temperature can spontaneously achieve a value that potentially exceeds its melting point $\left(\Delta T_s > 1000^\circ\mathrm{C}\right)$.
  - If the surface survives the temperature shock, conditions are characterized by *film boiling*.
- Película
  - Heat transfer is by conduction and radiation across the vapor blanket.
  - A reduction in q''_s follows the cooling curve continuously to the Leidenfrost point corresponding to the minimum heat flux $q''_{\min}$ for film boiling.



- A reduction in q''_s below $q''_{\min}$ causes an abrupt reduction in surface temperature to the nucleate boiling regime.

- Transition Boiling for Temperature-Controlled Heating
  - Characterized by a continuous decay of q''_s $\left(\text{from } q''_{\max} \text{ to } q''_{\min}\right)$ with increasing ΔT_e.
  - Surface conditions oscillate between nucleate and film boiling, but portion of surface experiencing film boiling increases with ΔT_e.
  - Also termed unstable or partial film boiling.

Correlações de Ebulição em vaso

- Ebulição Nucleada

  - Correlação de Rohsenow

$$q_s'' = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left(\frac{c_{p,l}\, \Delta T_e}{C_{s,f}\, h_{fg}\, \mathrm{Pr}_l^n} \right)^3$$

$C_{s,f}, n \rightarrow$ Surface/Fluid Combination (Table 10.1)

- Fluxo de calor crítico

$$q''_{\max} = C h_{fg} \rho_v \left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2} \right]^{1/4}$$

$C \rightarrow$ surface geometry dependent

- Eblulição com formação de película

The cumulative (and coupled effects) of convection and radiation across the vapor layer ⟶

$$\bar{h}^{4/3} \approx \bar{h}_{conv}^{4/3} + \bar{h}_{rad}\,\bar{h}^{1/3}$$

$$\overline{Nu}_D = \frac{\bar{h}_{conv} D}{k_v} = C\left[\frac{g(\rho_l - \rho_v) h'_{fg} D^3}{\nu_v k_v (T_s - T_{sat})}\right]^{1/4}$$

Geometry	C
Cylinder(Hor.)	0.62
Sphere	0.67

$$h'_{fg} = h_{fg} + 0.80\, c_{p,v}(T_s - T_{sat})$$

$$\bar{h}_{rad} = \frac{\varepsilon\sigma(T_s^4 - T_{sat}^4)}{T_s - T_{sat}}$$

If $\bar{h}_{conv} > \bar{h}_{rad}$,

$$\bar{h} \approx \bar{h}_{conv} + 0.75\,\bar{h}_{rad}$$

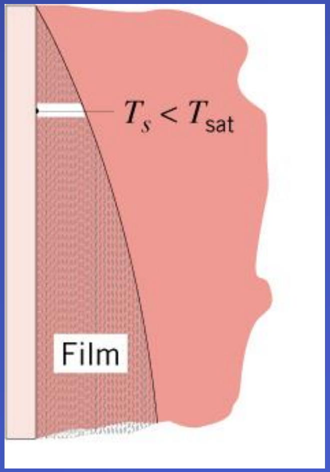
Condensação

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.

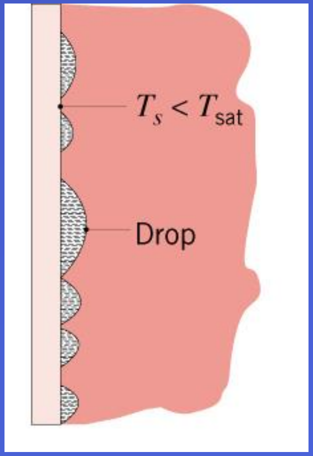


  - Thermal resistance is reduced through use of short vertical surfaces and horizontal cylinders.

  - Characteristic of clean, uncontaminated surfaces.

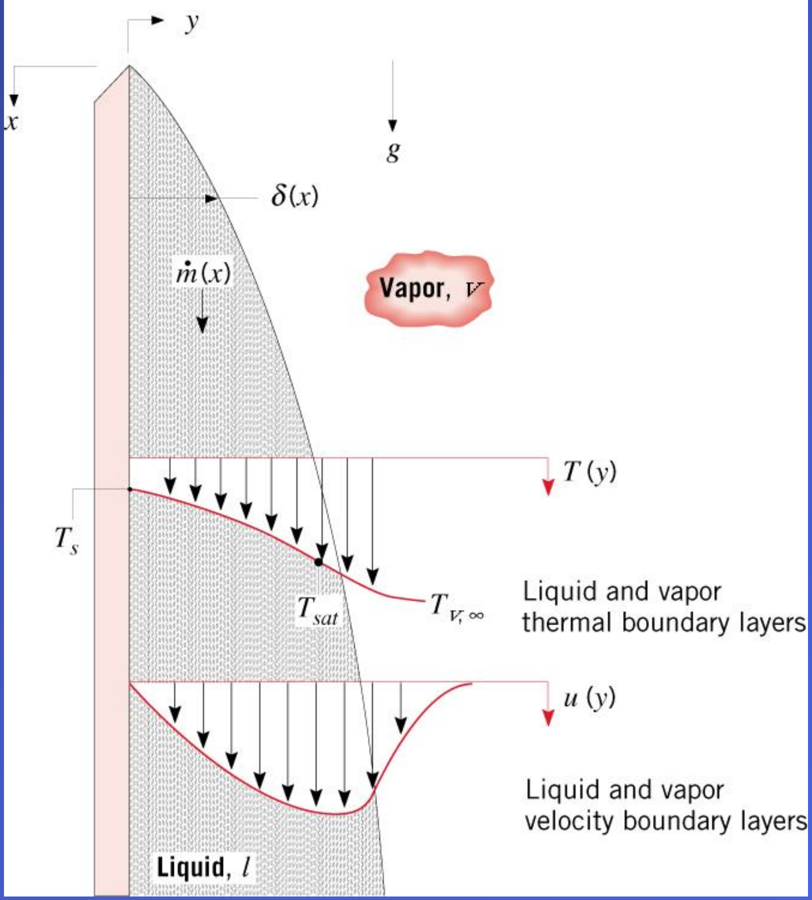
- Dropwise Condensation

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



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 $\left(T_{v,\infty} > T_{sat}\right)$ 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:

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

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

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

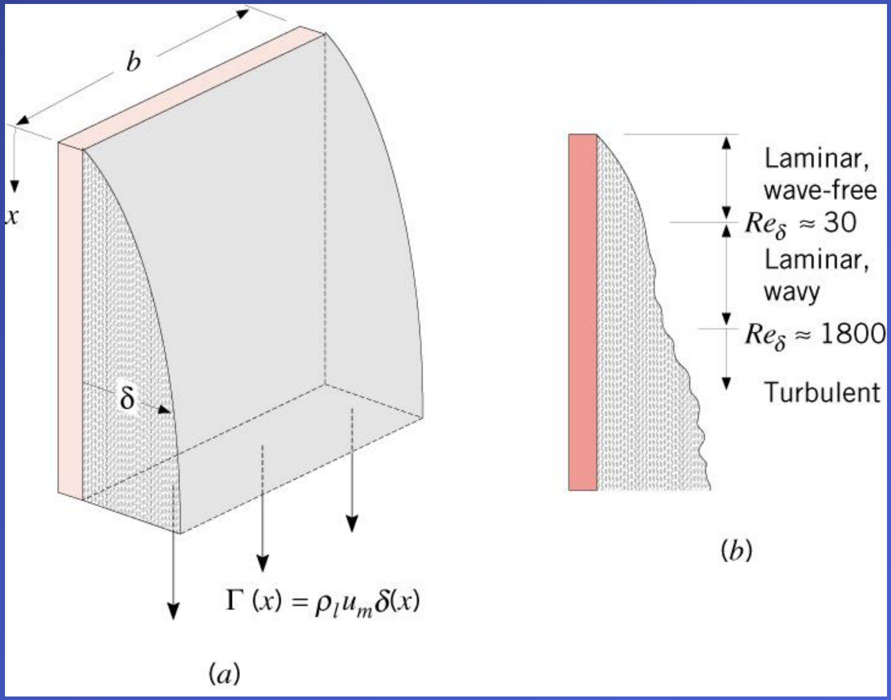
Total heat transfer and condensation rates:

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

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

- 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

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



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 $\left(\mathrm{Re}_\delta < 30\right)$:

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

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

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

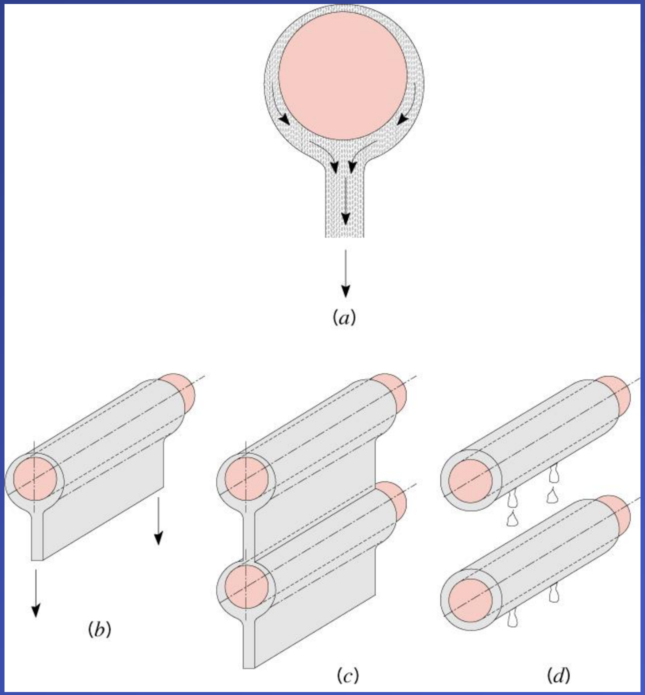
- Turbulent region $\left(\mathrm{Re}_\delta > 1800\right)$:

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

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

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

Film Condensation on Radial Systems



- A single tube or sphere:

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

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

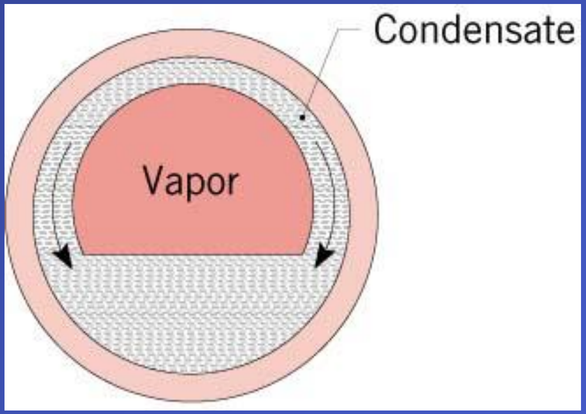
- A vertical tier of *N* tubes:

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

  - Why does $\overline{h}_{D,N}$ 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:

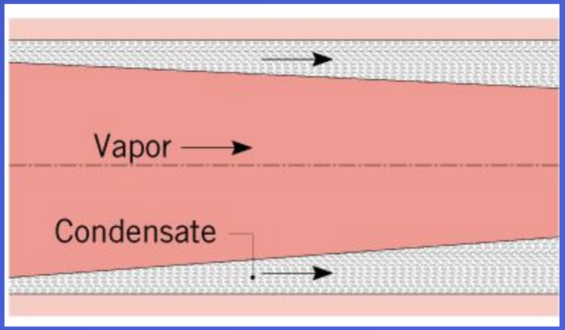


$$\mathrm{Re}_{\upsilon,\mathrm{i}} = \left(\frac{\rho_\upsilon u_{m,\upsilon} D}{\mu_\upsilon}\right)_i < 35{,}000:$$

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

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

- 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:

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

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

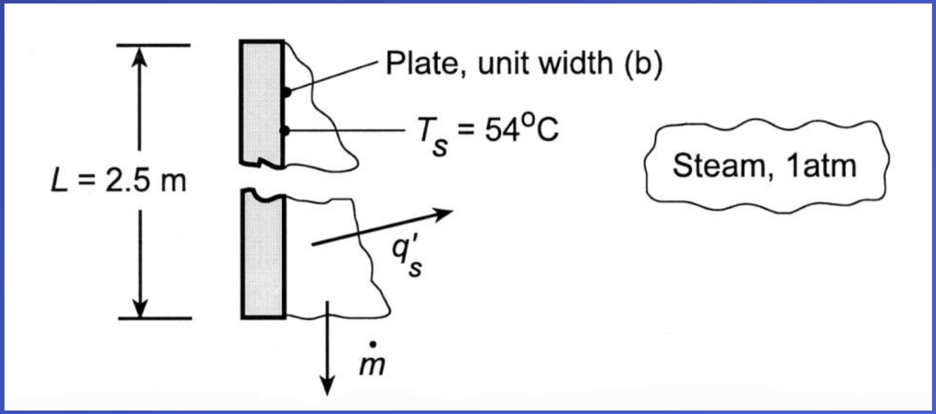
$$\bar{h}_{\text{dc}} = 255{,}500 \qquad T_{sat} > 100^\circ\text{C}$$

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.

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

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

$$Re_\delta = 2979$$

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

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

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

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

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

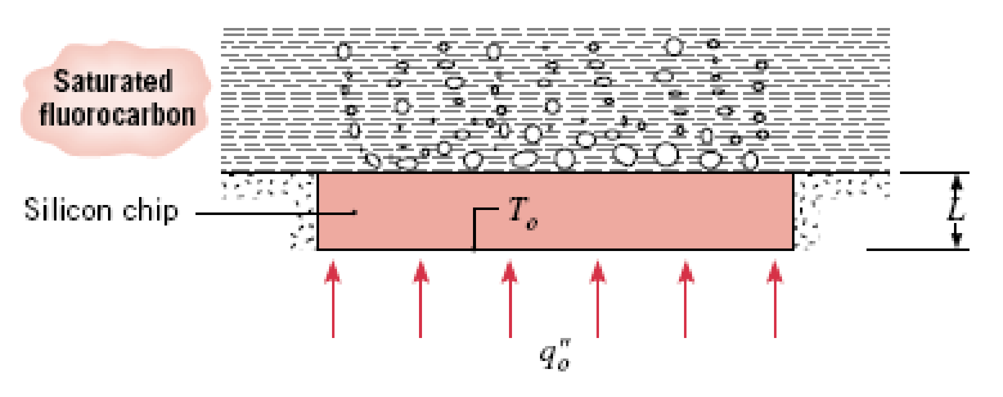
and the assumption of wavy laminar flow was correct. The flow regime changes.

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

COMMENT:

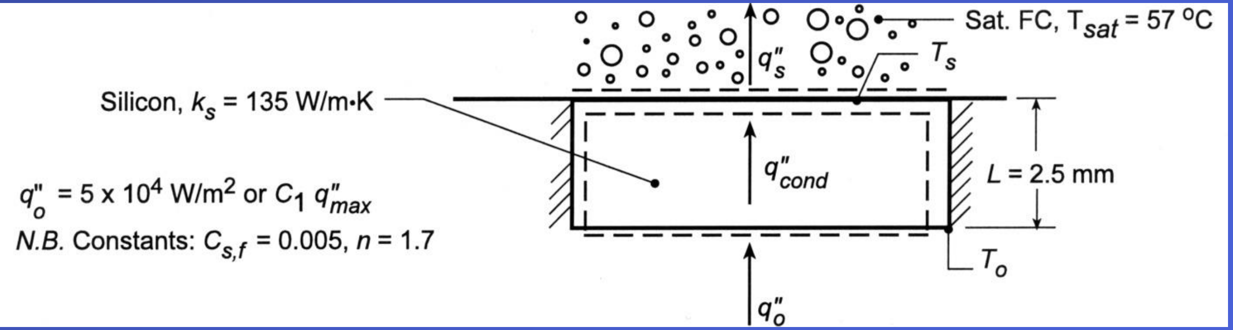
Note that the height was decreased by a factor of 2, while the rates decreased by a factor of 2.2. Would you have expected this result?

Problem 10.23: Chip thermal conditions associated with cooling by immersion in a fluorocarbon.



KNOWN: Thickness and thermal conductivity of a silicon chip. Properties of saturated fluorocarbon liquid.

FIND: (a) Temperature at bottom surface of chip for a prescribed heat flux and for a flux that is 90% of CHF, (b) Effect of heat flux on chip surface temperatures; maximum allowable heat flux for a surface temperature of 80°C.



ASSUMPTIONS: (1) Steady-state conditions, (2) Uniform heat flux and adiabatic sides, hence one-dimensional conduction in chip, (3) Constant properties, (4) Nucleate boiling in liquid.

PROPERTIES: Saturated fluorocarbon (given): $c_{p,\ell}$ = 1100 J/kg·K, h_{fg} = 84,400 J/kg, ρ_ℓ = 1619.2 kg/m^3, ρ_v = 13.4 kg/m^3, σ = 8.1 × 10^{-3} kg/s^2, μ_ℓ = 440 × 10^{-6} kg/m·s, Pr_ℓ = 9.01.

ANALYSIS: (a) Energy balances at the top and bottom surfaces yield $q''_o = q''_{cond} = k_s\left(T_o - T_s\right)/L = q''_s$; where T_s and q''_s are related by the Rohsenow correlation,

$$T_s - T_{sat} = \frac{C_{s,f}\, h_{fg}\, Pr_\ell^n}{c_{p,\ell}}\left(\frac{q''_s}{\mu_\ell h_{fg}}\right)^{1/3}\left[\frac{\sigma}{g\left(\rho_\ell - \rho_v\right)}\right]^{1/6}$$

Hence, for q''_s = 5 × 10^4 W/m^2,

$$T_s - T_{sat} = \frac{0.005\left(84,400\,J/kg\right)9.01^{1.7}}{1100\,J/kg\cdot K}\left(\frac{5\times10^4\,W/m^2}{440\times10^{-6}\,kg/m\cdot s\times 84,400\,J/kg}\right)^{1/3}$$

$$\times\left[\frac{8.1\times10^{-3}\,kg/s^2}{9.807\,m/s^2\,(1619.2-13.4)\,kg/m^3}\right]^{1/6} = 15.9^\circ C$$

$$T_s = \left(15.9+57\right)^\circ C = 72.9^\circ C$$

From the rate equation,

$$T_o = T_s + \frac{q_o'' L}{k_s} = 72.9^\circ C + \frac{5 \times 10^4\ W/m^2 \times 0.0025\,m}{135\,W/m \cdot K} = 73.8^\circ C$$

For a heat flux which is 90% of the critical heat flux ($C_1 = 0.9$),

$$q_o'' = 0.9 q_{max}'' = 0.9 \times 0.149 h_{fg} \rho_v \left[\frac{\sigma g (\rho_\ell - \rho_v)}{\rho_v^2} \right]^{1/4} = 0.9 \times 0.149 \times 84,400\,J/kg \times 13.4\,kg/m^3$$

$$\times \left[\frac{8.1 \times 10^{-3}\,kg/s^2 \times 9.807\,m/s^2\,(1619.2 - 13.4)\,kg/m^3}{\left(13.4\,kg/m^3\right)^2} \right]^{1/4}$$

$$q_o'' = 0.9 \times 15.5 \times 10^4\ W/m^2 = 13.9 \times 10^4\ W/m^2$$

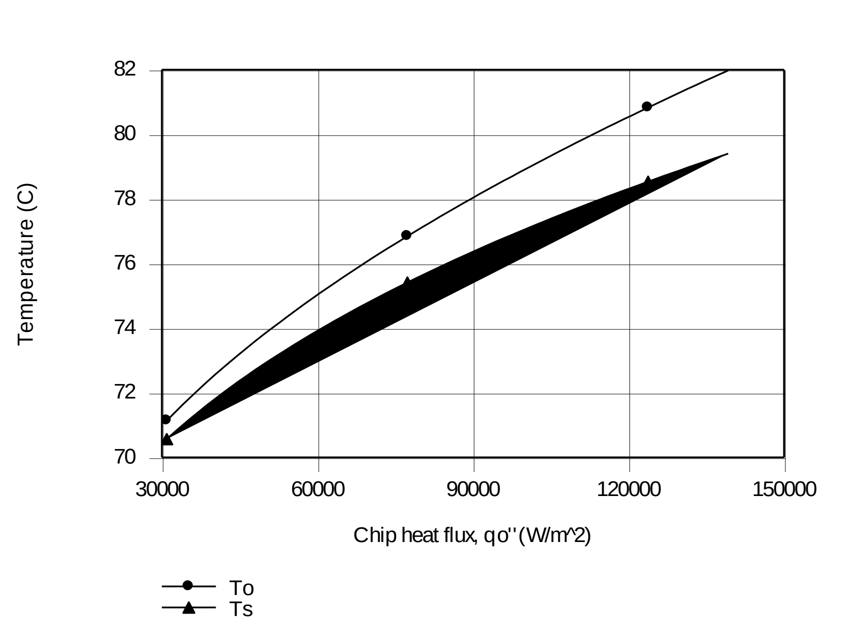
From the results of the previous calculation and the Rohsenow correlation, it follows that

$$\Delta T_e = 15.9^\circ C \left(q_o'' / 5 \times 10^4\ W/m^2 \right)^{1/3} = 15.9^\circ C\,(13.9/5)^{1/3} = 22.4^\circ C$$

Hence, $T_s = 79.4°C$ and

$$T_o = 79.4^\circ C + \frac{13.9 \times 10^4\ W/m^2 \times 0.0025\,m}{135\,W/m \cdot K} = 82^\circ C$$

(b) Parametric calculations for $0.2 \le C_1 \le 0.9$, yield the following variations of T_s and T_o with q''_o.



The chip surface temperatures, as well as the difference between temperatures, increase with increasing heat flux. The maximum chip temperature is associated with the bottom surface, and T_o = 80°C corresponds to

$$q''_{o,max} = 11.3 \times 10^4 \text{ W/m}^2$$ <

which is 73% of CHF ($q''_{max} = 15.5 \times 10^4$ W/m^2).

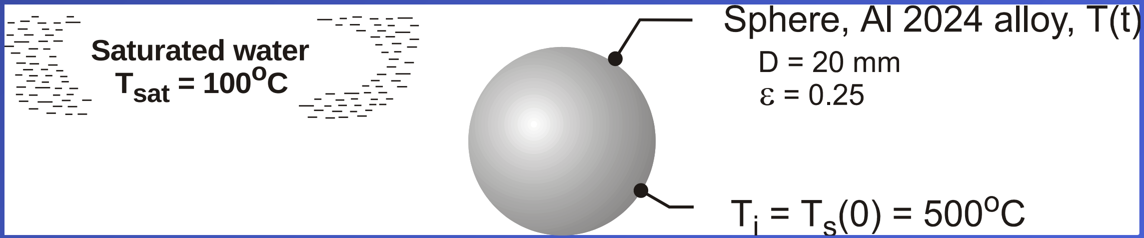
COMMENTS: Many of today's VLSI chip designs involve heat fluxes well in excess of 15 W/cm^2, in which case pool boiling in a fluorocarbon would not be an appropriate means of heat dissipation.

Problem 10.26: Initial heat transfer coefficient for immersion of an aluminum sphere in a saturated water bath at atmospheric pressure and its temperature after immersion for 30 seconds.

KNOWN: A sphere (aluminum alloy 2024) with a uniform temperature of 500°C and emissivity of 0.25 is suddenly immersed in a saturated water bath maintained at atmospheric pressure.

FIND: (a) The total heat transfer coefficient for the initial condition; fraction of the total coefficient contributed by radiation; and (b) Estimate the temperature of the sphere 30 s after it has been immersed in the bath.

SCHEMATIC



ASSUMPTIONS: (1) Water is at atmospheric pressure and uniform temperature, T_{sat}, and (2) Lumped capacitance method is valid.

PROPERTIES:

Table A-4, Water vapor $\left(T_{f,i} = 573\text{K}\right)$: $k_v = 0.0399$ W/m·K, $c_{p,v} = 2010$ J/kg·K,
$\rho_v = 0.3843\,\text{kg/m}^3$, $\nu_v = 51.44\times 10^{-6}\,\text{m}^2/\text{s}$, Table A-6, Water ($T_{sat}$ =373K):
$\rho_l = 958\ \text{kg/m}^3, h_{fg} = 2.257\times 10^6\,\text{J/kg}$.

Aluminum Alloy: $\rho_s = 2700\ \text{kg/m}^3, c_{p,s} = 875\ \text{J/kg}\cdot\text{K},\ k_s = 186\,\text{W/m}\cdot\text{K}$.

ANALYSIS: (a) For the initial condition with T_s = 500°C, *film boiling* will occur and the coefficients due to convection and radiation are estimated using Eqs. 10.8 and 10.11, respectively,

$$\overline{Nu}_D = \frac{\bar{h}_{conv} D}{k_v} = C\left[\frac{g\left(\rho_\ell - \rho_v\right) h'_{fg} D^3}{\nu_v k_v \left(T_s - T_{sat}\right)}\right]^{1/4} \qquad (1)$$

$$\bar{h}_{rad} = \frac{\varepsilon\sigma\left(T_s^4 - T_{sat}^4\right)}{T_s - T_{sat}} \qquad (2)$$

where C = 0.67 for spheres and $\sigma = 5.67 \times 10^{-8}$ W/m^2·K^4. The corrected latent heat is

$$h'_{fg} = h_{fg} + 0.8\, c_{p,v}\left(T_s - T_{sat}\right) \qquad (3)$$

The total heat transfer coefficient is given by Eq. 10.9 as

$$\bar{h}^{4/3} = \bar{h}_{conv}^{4/3} + \bar{h}_{rad} \cdot \bar{h}^{1/3} \tag{4}$$

Using the foregoing relations, the following results are obtained.

$\overline{Nu}_D$	$\bar{h}_{cnv}\left(W/m^2 \cdot K\right)$	$\bar{h}_{rad}\left(W/m^2 \cdot K\right)$	$\bar{h}\left(W/m^2 \cdot K\right)$
85.5	171	12.0	180

The radiation process contribution is 6.7% of the total heat rate.

(b) For the lumped-capacitance method, from Section 5.3, the energy balance is

$$-\bar{h}A_s\left(T_s - T_{sat}\right) = \rho_s V c_s \frac{dT_s}{dt} \tag{5}$$

where ρ_s and c_s are properties of the sphere. Numerically integrating Eq. (5) and evaluating $\bar{h}$ as a function of T_s, the following result is obtained for the sphere temperature after 30s.

$$T_s\left(30s\right) = 300°C.$$

COMMENTS: The Biot number associated with the aluminum alloy sphere cooling process for the initial condition is Bi = 0.09. Hence, the lumped-capacitance method is valid.