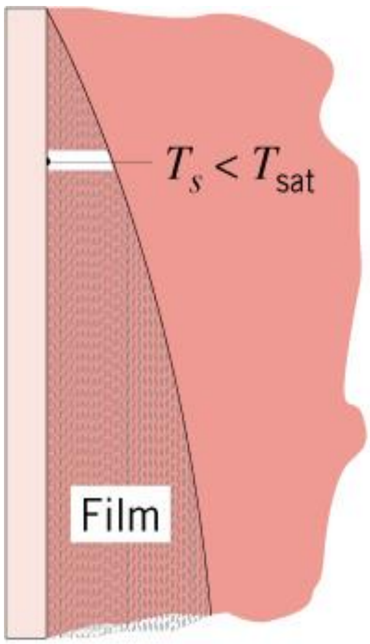
Condensation Heat Transfer

Condensation on a Vertical Surface

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.



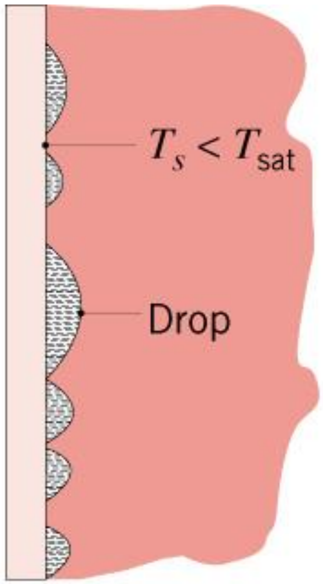
Dropwise Condensation

- Dropwise Condensation

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

  - Thermal resistance is greatly reduced due to absence of a continuous film

  - Surface coatings may be applied to inhibit *wetting* and stimulate dropwise condensation.



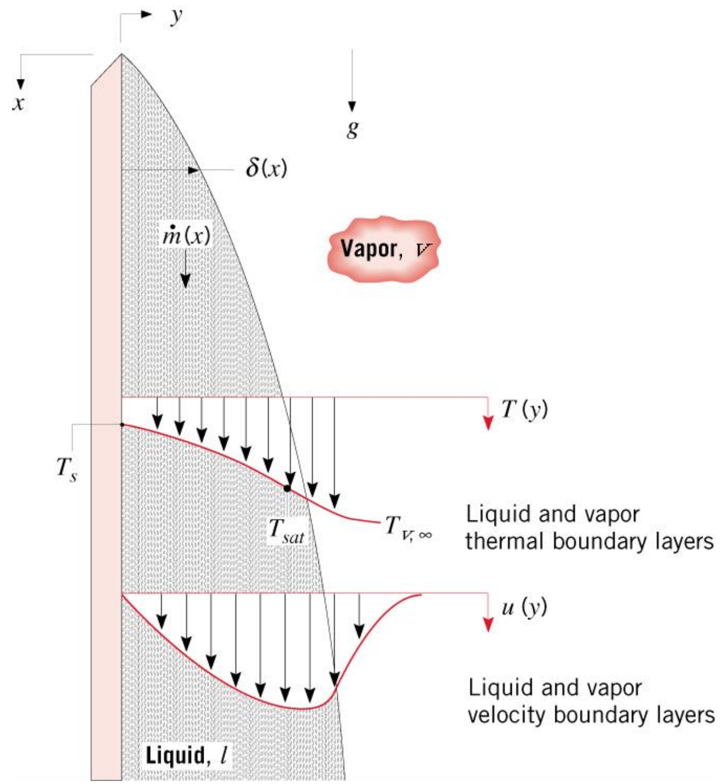
Film Condensation – Nusselt Analysis

Refer to Class Notes

Film Condensation on a Vertical Plate

- Refer to class notes for derivations of momentum and energy equations

- Derived expressions



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:

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

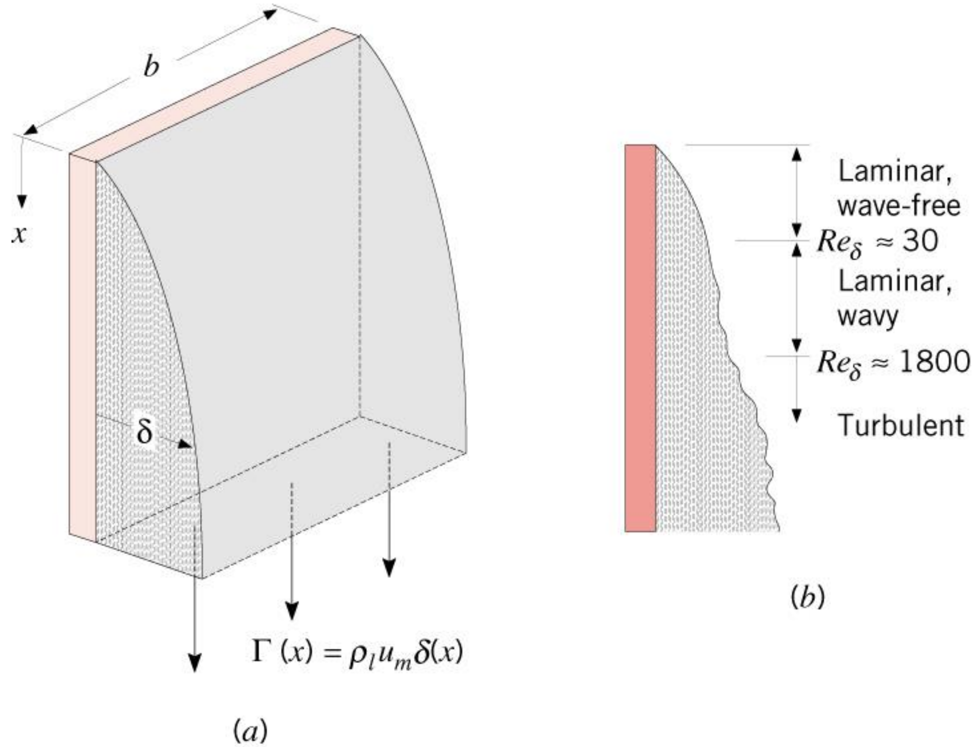
$$h'_{fg} = h_{fg}(1 + 0.68\ Ja)$$

$$Ja \equiv \frac{c_p(T_{sat} - T_s)}{h_{fg}} \rightarrow \text{Jakob number}$$

Total heat transfer and condensation rates:

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

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



- 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

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

Correlations – Laminar to Turbulent

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

$$\frac{\bar{h}_L \left(\nu_l^2 / g\right)^{1/3}}{k_l} = 1.47\ \mathrm{Re}_\delta^{-1/3}$$

$$\mathrm{Re}_\delta = \frac{4 g \rho_l \left(\rho_l - \rho_v\right) \delta^3}{3 \mu_l^2}$$

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

$$\frac{\bar{h}_L \left(\nu_l^2 / g\right)^{1/3}}{k_l} = \frac{\mathrm{Re}_\delta}{1.08\ \mathrm{Re}_\delta^{1.22} - 5.2}$$

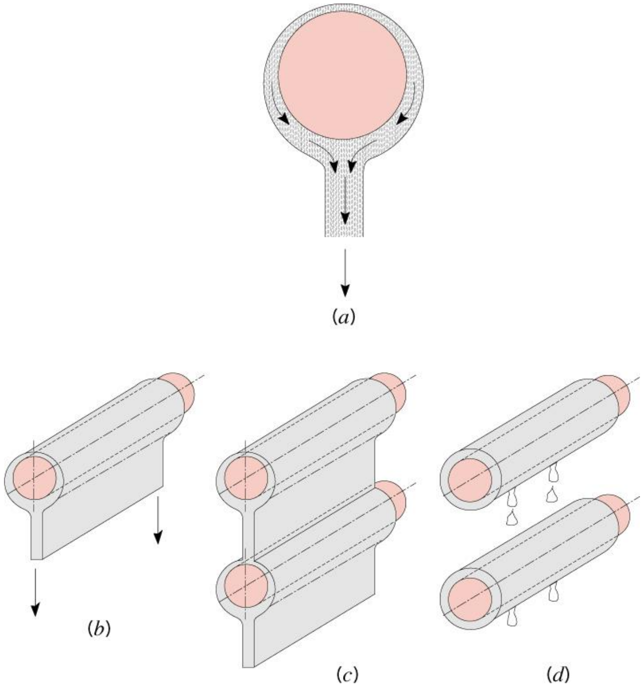
- **Turbulent region** $\left(\mathrm{Re}_\delta > 1800\right)$:

$$\frac{\bar{h}_L \left(\nu_l^2 / g\right)^{1/3}}{k_l} = \frac{\mathrm{Re}_\delta}{8750 + 58\ \mathrm{Pr}^{-0.5} \left(\mathrm{Re}_\delta^{0.75} - 253\right)}$$

Calculation procedure:

- Assume a particular flow regime and use the corresponding expression for *h* to determine *Re*
- If value of *Re* is consistent with assumption, proceed to determination of *h* and *q*
- If value of *Re* is inconsistent with the assumption, recompute its value using a different expression for *h*, and proceed to determination of *q*

Film Condensation on Radial Systems



- Single tube or sphere:

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

Tube: C =0.729 Sphere: C=0.826

- Vertical stack of N tubes

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

Dropwise Condensation

- Steam condensation on copper surfaces [Griffith]:

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

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

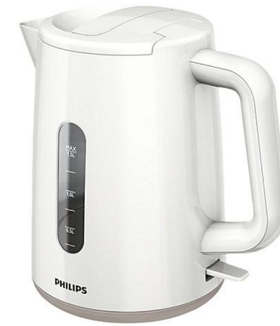
$$\bar{h}_{\mathrm{dc}} = 255{,}500 \qquad T_{sat} > 100^\circ\mathrm{C}$$

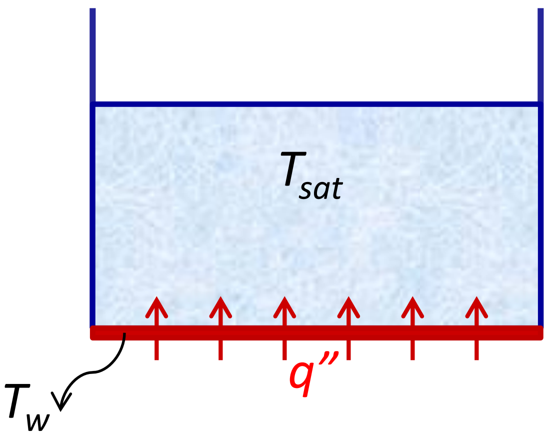
Boiling Heat Transfer

When does boiling occur?

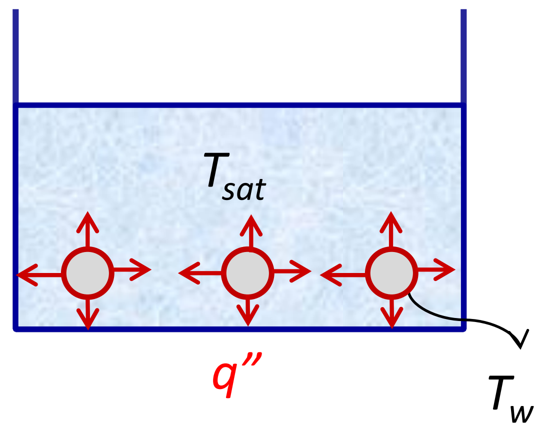
When heat is added to a liquid from a submerged solid surface which is at a temperature higher than the saturation temperature of the liquid it is usual for a part of the liquid to change phase and become vapour. This change of phase is called BOILING.

Pool boiling



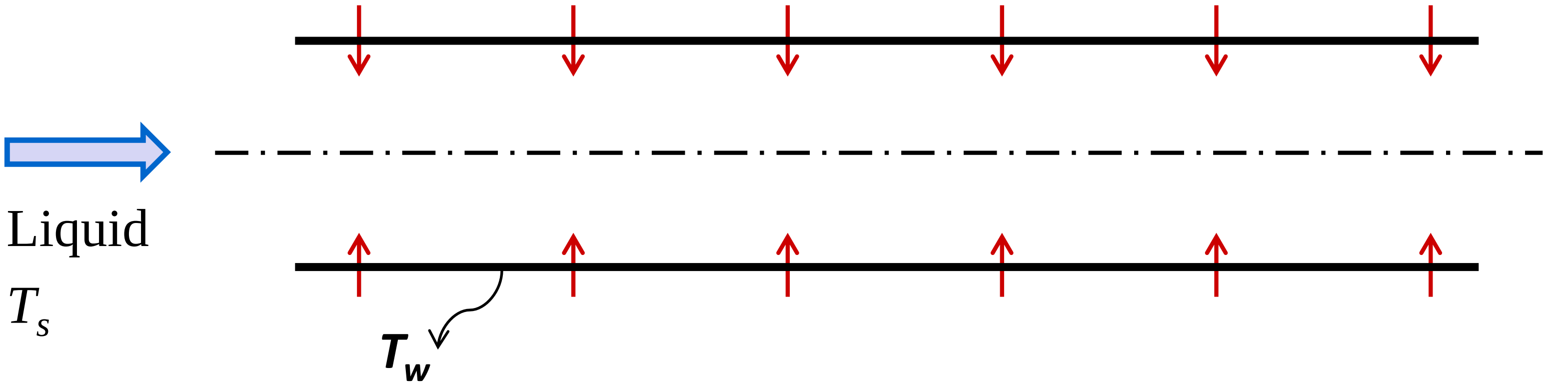


(a) Heat transfer through heater plate at bottom



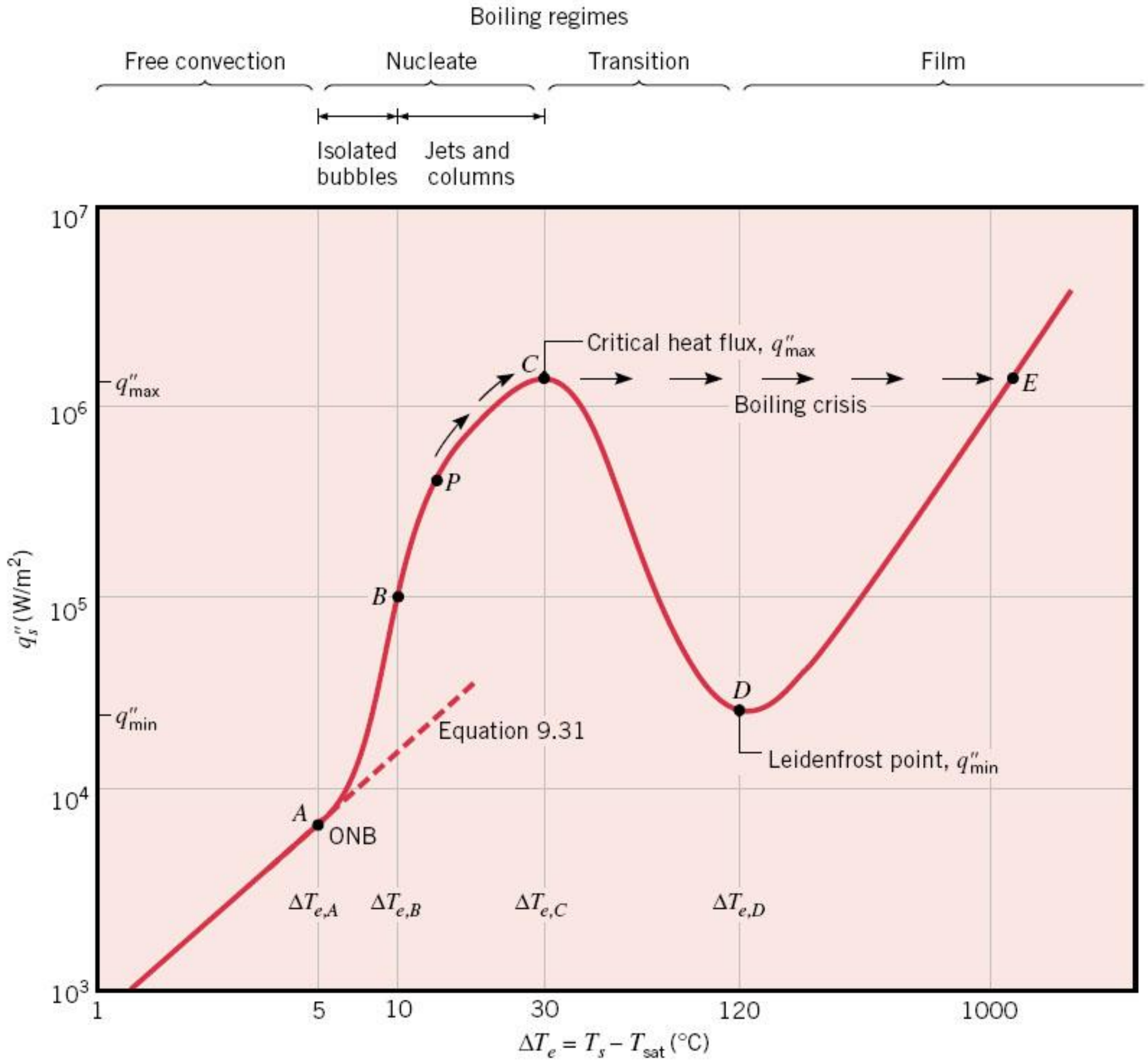
(b) Heat transfer through immersed heater coil

Flow Boiling

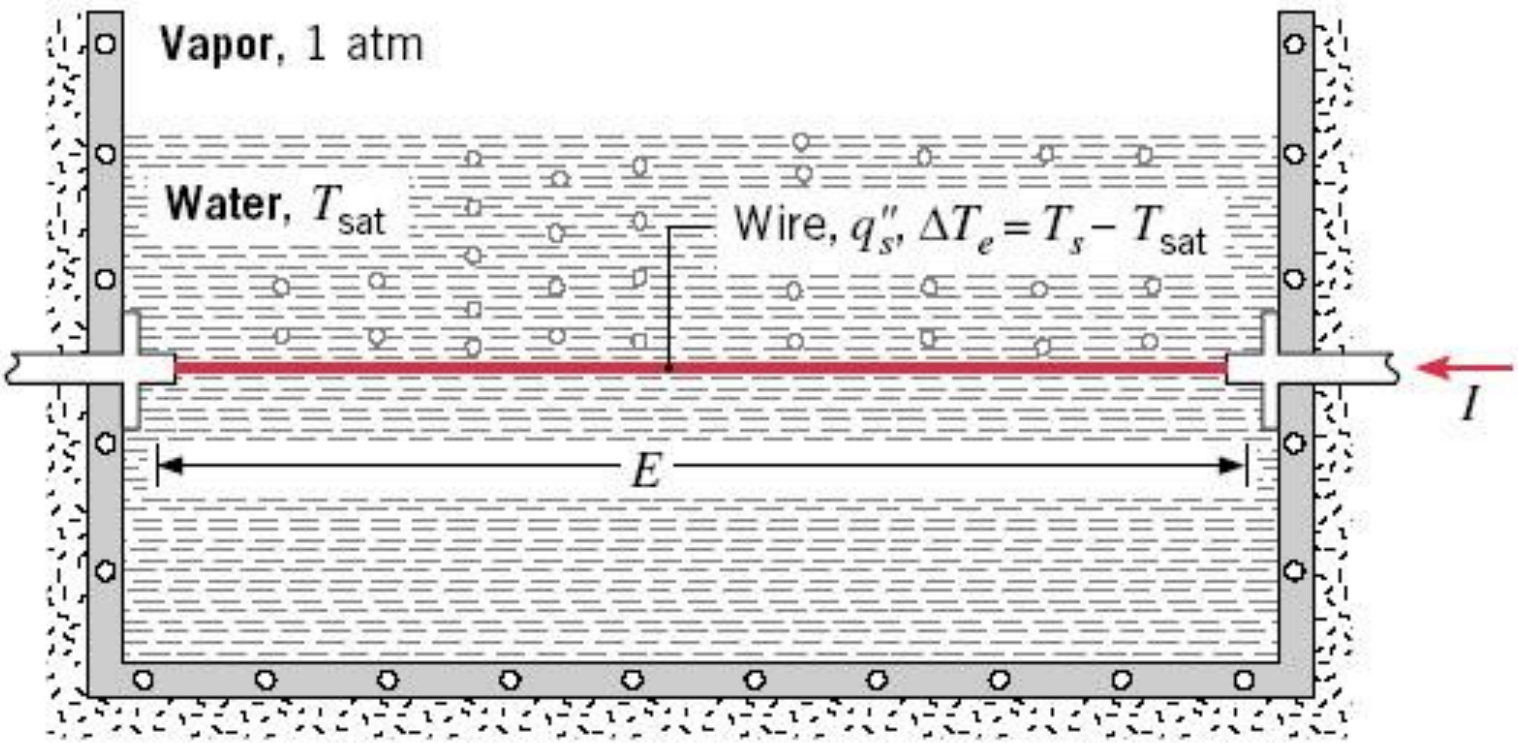


- Liquid is forced to move by an external agency like a pump

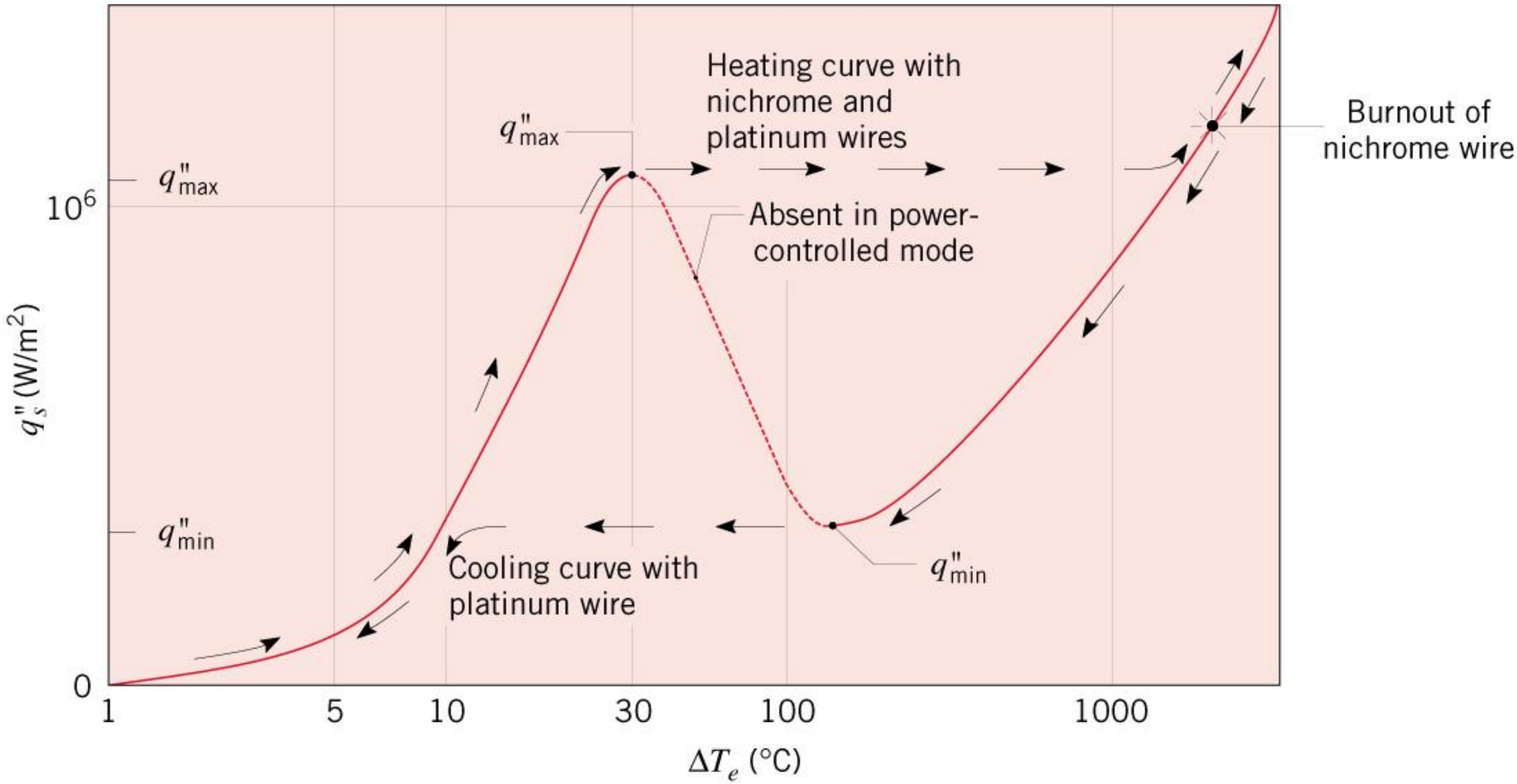
Boiling Curve



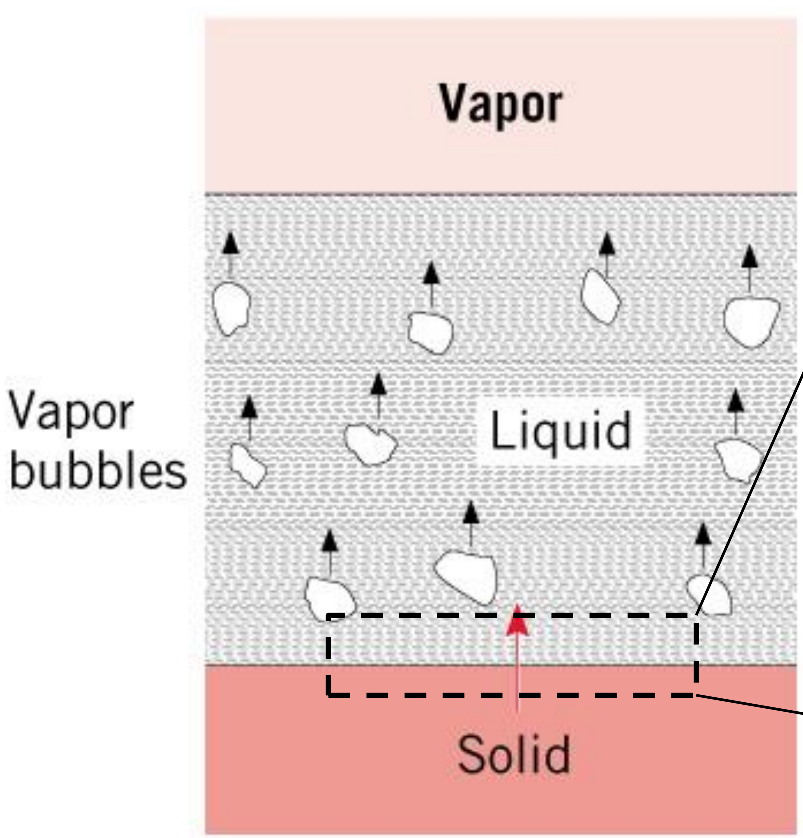
Nukiyama's Experiment

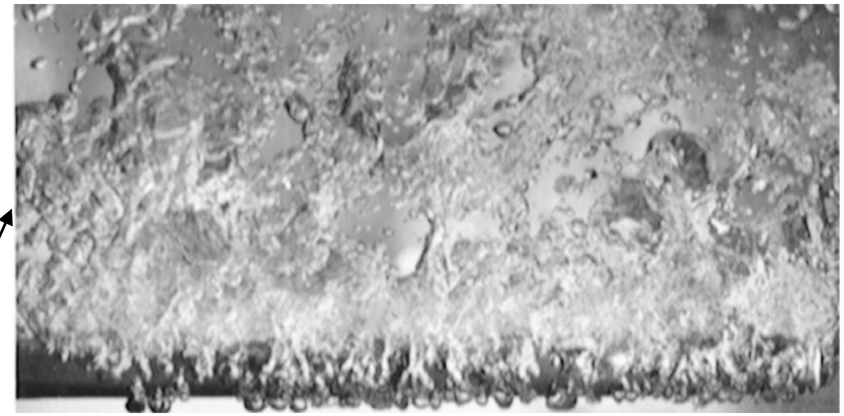


Nukiyama's Curve – Hysteresis Effect

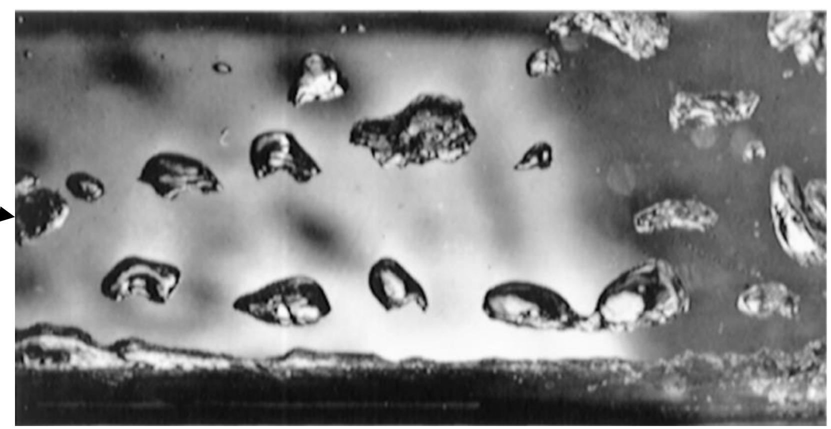


Pool Boiling - pictures





Nucleate Boiling



Film Boiling

Animation

https://www.youtube.com/watch?v=N1yZwRcQSZw

Pool Boiling Modes

1. Natural Convection Boiling: $\Delta T_e \leq 5$ C

2. Nucleate Boiling: $5C \leq \Delta T_e \leq 30$ C

3. Transition Boiling: $30C \leq \Delta Te \leq 120$ C

4. Film Boiling: $\Delta Te \geq 120$ C

Correlation – Natural Convection Regime

Natural Convection Boiling: *all single phase natural convection correlations are valid*

For horizontal wire or cylinder inside a pool of liquid:

$$q'' = \frac{k}{D}\left(T_w - T_s\right)\left\{0.36 + \frac{0.518 Ra_D^{1/4}}{\left[1+\left(0.559/\Pr\right)^{9/16}\right]^{4/9}}\right\} \qquad \textit{for } 10^{-6} < Ra_D < 10^{9}$$

$$= \frac{k}{D}\left(T_w - T_s\right)\left\{0.60 + \frac{0.387 Ra_D^{1/6}}{\left[1+\left(0.559/\Pr\right)^{9/16}\right]^{8/9}}\right\} \qquad \textit{for } 10^{9} < Ra_D < 10^{12}$$

Correlation: Nucleate boiling

Rohsenow Correlation

$$q_s'' = \mu_l h_{fg} [\frac{g(\rho_l - \rho_v)}{\sigma}]^{1/2} (\frac{c_{p,l}(T_w - T_s)}{C_{s,f} h_{fg} \Pr_l^n})^3$$

n = 1.0 for water
= 1.7 for other liquids

- Rohsenow's correlation is used for horizontal wires, tubes and plates
- $C_{s,f}$ depends on surface fluid combination
  - all properties evaluated at liquid saturation temp

$$q_s'' \alpha (T_w - T_s)^3$$

Correlation: Critical Heat Flux

Infinite horizontal surface facing up (*Kutateladze, Zuber*)

$$q''_{\max} = \frac{\pi}{24} h_{fg} \rho_v \left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}\right]^{1/4} \left(\cancelto{1}{\frac{\rho_l + \rho_v}{\rho_v}}\right)^{1/2}$$

If the plate is finite size *(Lienhard and Dhir)*

$$q''_{\max} = 0.149 h_{fg} \rho_v \left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}\right]^{1/4}$$

Correlation – Transition regime

Transition Boiling – no suitable correlation

Leidenfrost point

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

Correlation – Stable Film boiling

Film Boiling (similar to film condensation)

For cylinders or spheres

$$\overline{Nu_D} = \frac{\overline{h_{conv}} D}{k_v} = C\left[\frac{g\rho_v(\rho_l - \rho_v)h'_{fg}D^3}{\mu_v k_v (T_w - T_s)}\right]^{1/4}$$

$$h'_{fg} = h_{fg} + 0.8C_{p,v}(T_w - T_s)$$

Geometry	C
Cylinder(Hor.)	0.62
Sphere	0.67

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

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

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

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

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

Summary

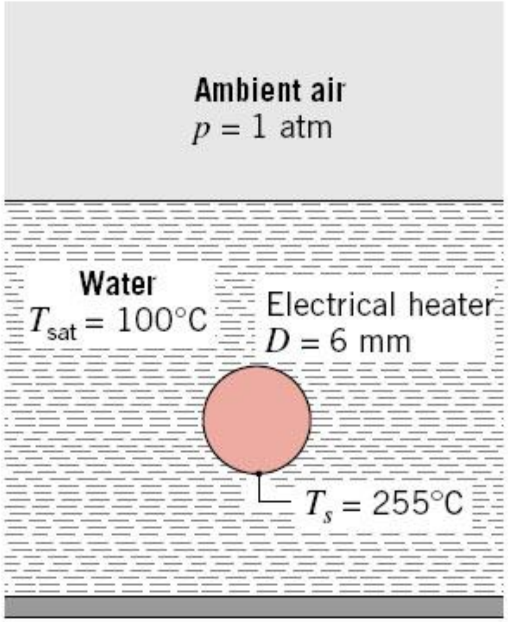
- Studied different regimes of pool boiling
- Looked at correlations governing heat transfer at each region
- Learnt the concept of Critical or Peak Heat Flux (CHF)

Example Problem

Known: Boiling from outer surface of horizontal cylinder in water

Find: Power dissipation per unit length for the cylinder, q_s'

Schematic:



Example (cont.)

Assumptions: Steady-state, Water exposed to 1 atm, at uniform T_{sat}

Properties: Saturated water, liquid at 100C: $\rho_l=1/v_f=957.9\ kg/m^3$,

$h_{fg}=2257kJ/kg$. *Saturated water vapor* ($T_f=450K$): $\rho_v=1/v_v=4.808\ kg/m^3$,

$c_{p,v}=c_{p,g}=2.56kJ/kgK$, $k_v=k_g=0.0331W/mK$, $\mu_v=\mu_g=14.85x10^{-6}Ns/m^2$.

Analysis:

$$\Delta T_e = T_s-T_{sat} = 255 - 100 = 155C > 120\ C$$

Pool film boiling conditions are met

Example (cont.)

Heat transfer rate per unit length is:

$$q_s^{'} = q_s^{''}\pi D = \overline{h}\pi D\Delta T_e$$

For combined heat transfer by convection + radiation

$$\overline{h}^{4/3} = \overline{h_{conv}}^{4/3} + \overline{h_{rad}}\,\overline{h}^{1/3}$$

$$\overline{h_{conv}} = 0.62\left[\frac{k_v^3\rho_v(\rho_l - \rho_v)g(h_{fg} + 0.8c_{p,v}\Delta T_e)}{\mu_v D\Delta T_e}\right]^{1/4} = 238W/m^2K$$

$$\overline{h_{rad}} = \frac{\varepsilon\sigma(T_s^4 - T_{sat}^4)}{T_s - T_{sat}} = 21.3W/m^2K$$

Example (cont.)

$$\bar{h}^{4/3} = 238^{4/3} + 21.3\bar{h}^{1/3}$$

Solve for $\bar{h}$

$$\bar{h} = 254.1W/m^2K$$

$$\boxed{q_s^{'} = q_s^{''}\pi D = \bar{h}\pi D\Delta T_e = 742W/m}$$

Thank You!