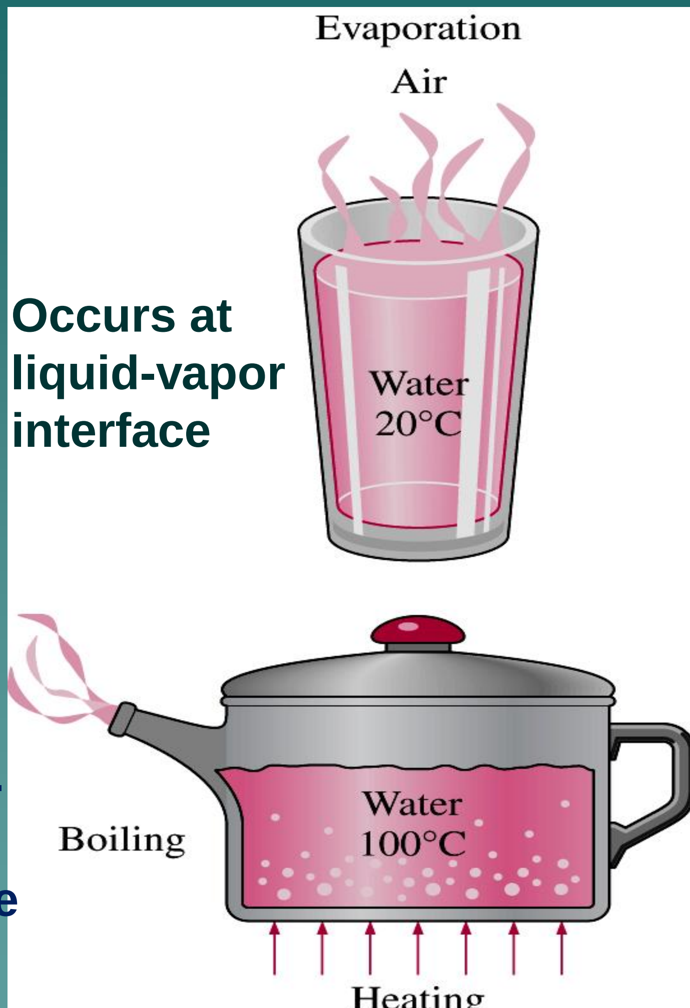
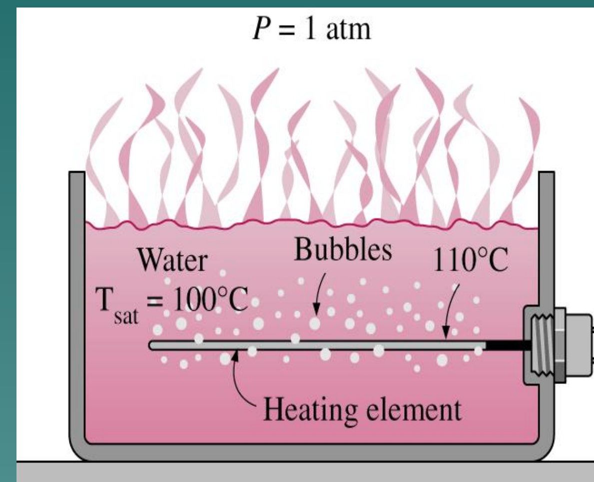
Boiling Heat transfer

Boiling Heat transfer is characterized by change of phase + convection heat transfer

Occurs at liquid-vapor interface



Occurs at solid-liquid interface



Boiling occurs when a liquid is brought into contact with a surface at a temp above the sat temp of the liquid

Boiling

- Boiling is evaporation at a solid-liquid interface, and occurs when $T_s > T_{sat}$ where T_{sat} is the temperature for liquid-to-gas phase change, and is a function of pressure.

e.g., for water at 1 atm, $T_{sat} = 100^{\circ}C$ & $h_{fg} = 2257$ kJ/kg

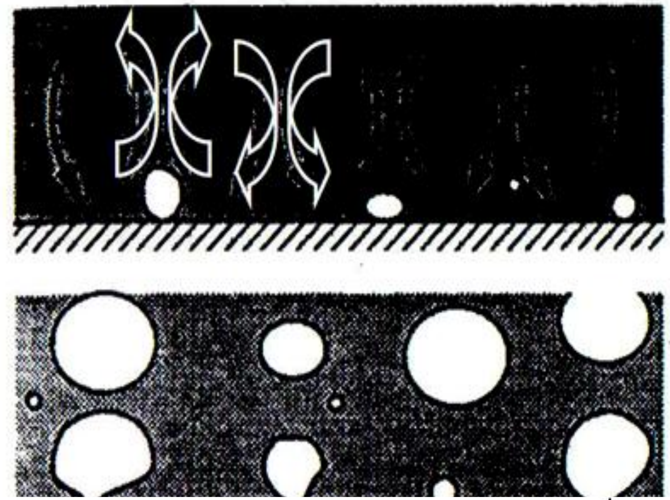
- In boiling, the rate equation (Newton's law of cooling) is:

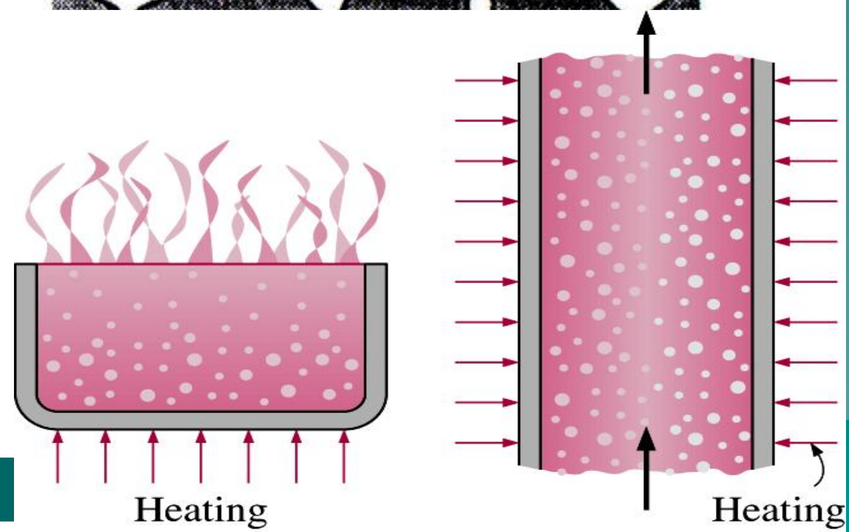
$$q_s'' = h\left(T_s - T_{sat}\right) = h\,\Delta T_e$$

where ΔT_e is the "excess" temperature

Modes of Boiling

- Boiling can be classified as
  - Pool Boiling
    - quiescent liquid, motion near the surface is due to free convection and mixing due to bubble growth and detachment
  - Forced Convection Boiling **(Flow boiling)**
    - external means drive fluid motion

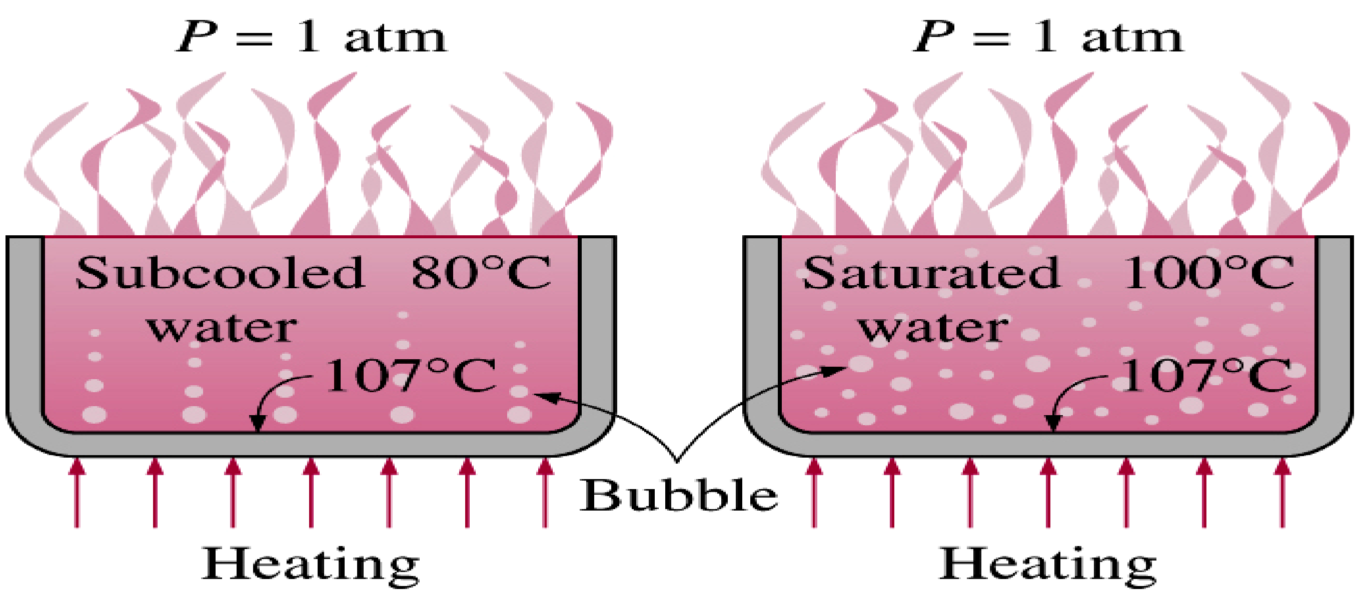




(*a*) Pool boiling (*b*) Flow boiling

Modes of Boiling

- Boiling can also be classified, alternatively, as:
  - Subcooled (local) boiling
    - T_{liq} is below T_{sat}
    - bubbles formed at the solid surface condense in the liquid
  - Saturated boiling
    - T_{liq} is slightly > T_{sat}
    - bubbles can rise and escape



(a) Subcooled boiling (b) Saturated boiling

Dimensionless Parameters

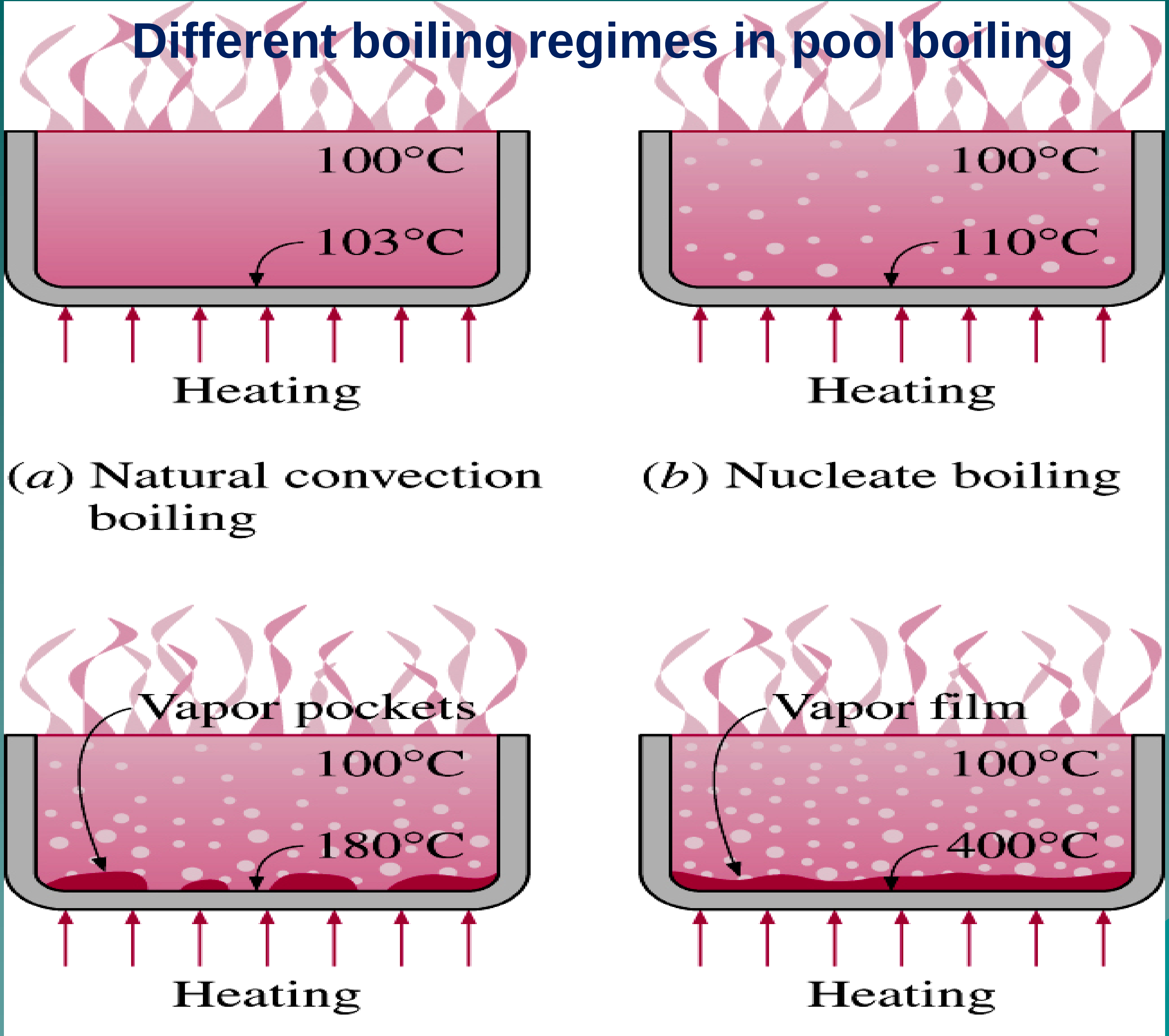
The dimensionless parameters relevant in boiling heat transfer

- Nusselt number, hL/k
- Prandtl number, $\mu C_p/k$
- Jakob number, $Ja = (C_p\, \Delta T)/h_{fg}$ where $\Delta T = (T_s - T_{sat})$
  (ratio of sensible to latent heat)
- Bond number, $Bo = [g\,(\rho_l - \rho_v)\,L^2] / \sigma$
  (ratio of gravitational to surface tension forces)
- Grashof-like number, $[\rho\, g\,(\rho_l - \rho_v)\,L^3] / \mu^2$
  (quantifies buoyancy-induced fluid motion and its effect on heat transfer)

Pool Boiling

- Pool boiling is boiling at the surface of a body in an extensive pool of a motionless liquid
- Examples:
  - quenching, flooded evaporators, immersion cooling of electronic components
- Variables:
  - heat flux
  - thermophysical properties (liquid and vapor)
  - surface material and finish
  - size of the heated surface
- Two possibilities:
  - Temperature control
  - Heat flux control

Different boiling regimes in pool boiling



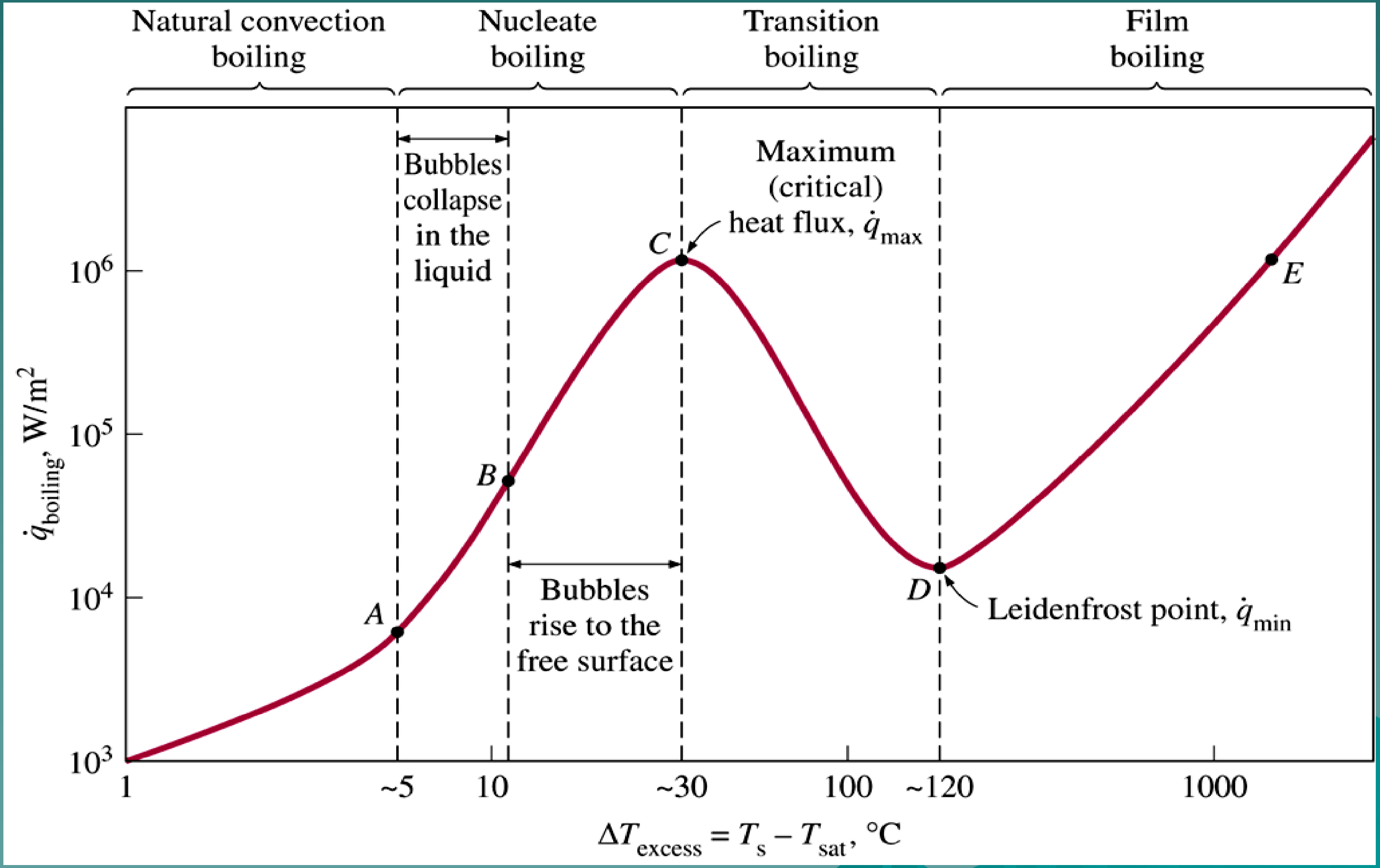
(*a*) Natural convection boiling

(*b*) Nucleate boiling

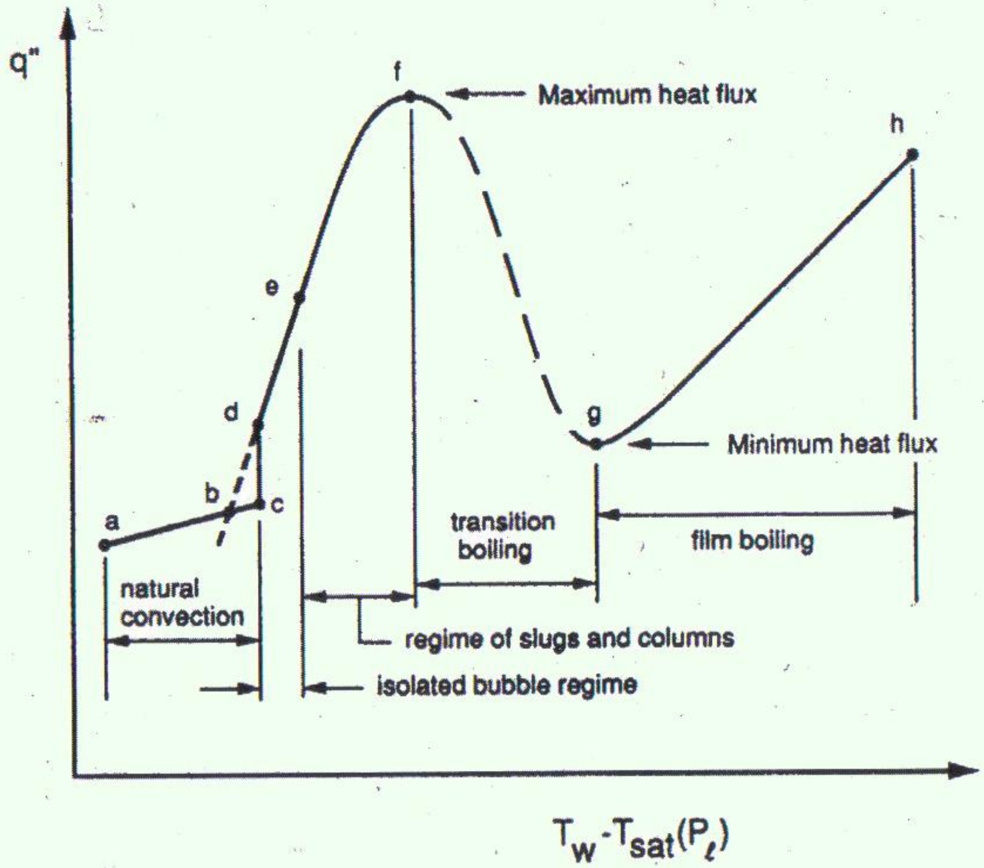
(*c*) Transition boiling

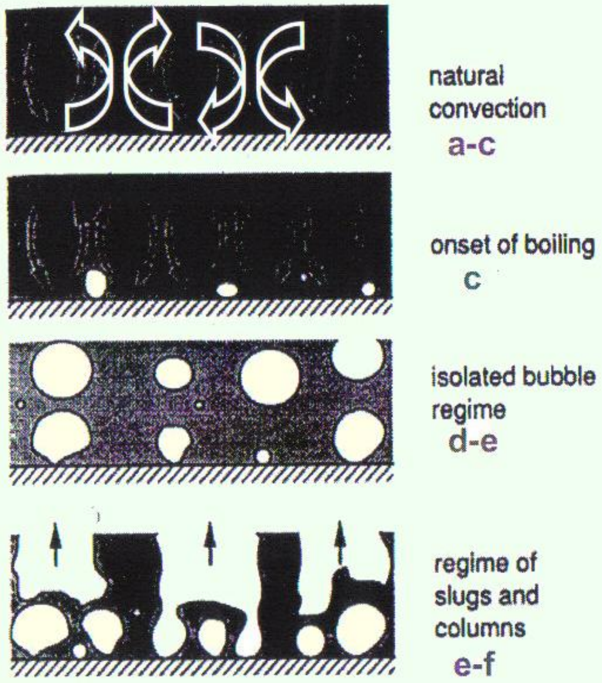
(*d*) Film boiling

Typical boiling curve for water at 1 atm pressure



Boiling Curve - Temperature Control





Consider inflection point e (heat transfer coefficient is max here; after this point, h drops, but ΔT increases; hence q" still increases)

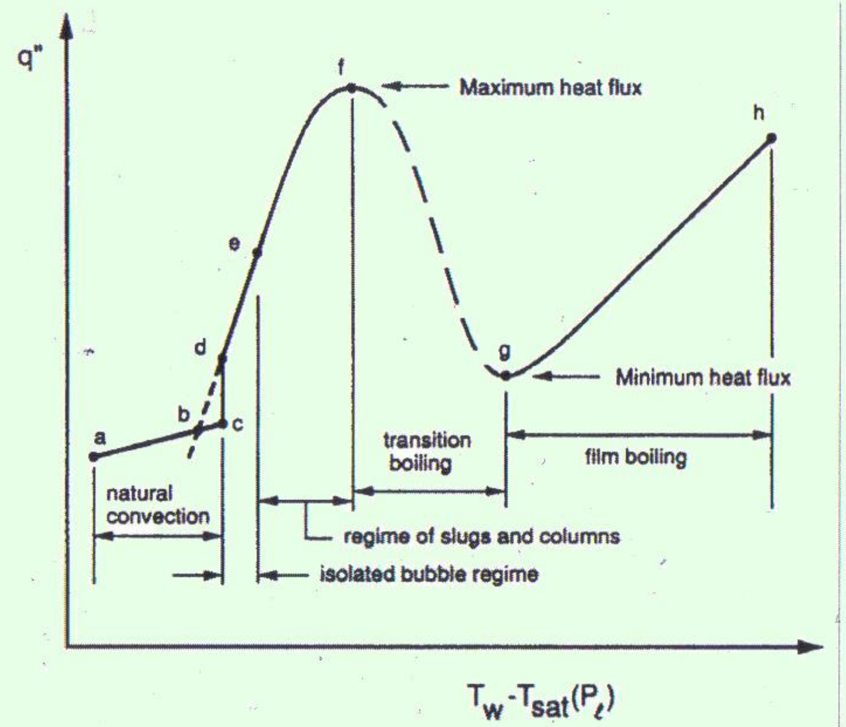
Boiling Curve - Temperature Control

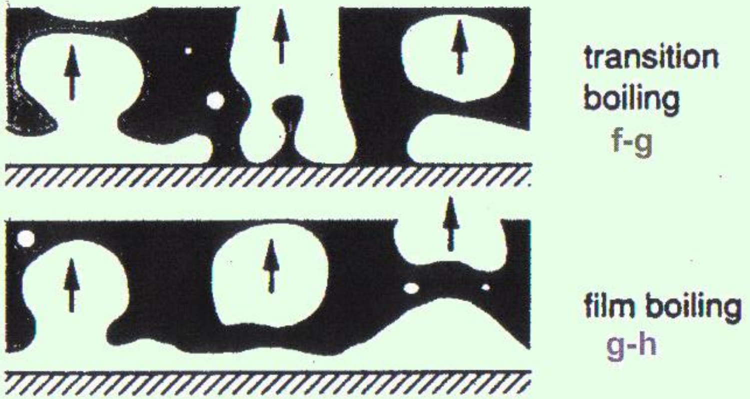
f: $\Delta T_e \uparrow$, vapor drag prevents liquid from reaching surface, some portions not completely wet $\Rightarrow$ dry surface. q" to vapor film much lower. Mean q" $\downarrow$, Peak heat flux $\Rightarrow$ *Critical Heat Flux (CHF)*

f-g: as $T_{wall} \uparrow$, q" $\downarrow$, *transition boiling regime*. Rapid, severe q" variations. Dry regions unstable, leading to fluctuations (dry ~ wet)

g: sustained vapor film (blanket) $\Rightarrow$ *film boiling regime*

g-h: q" monotonically $\uparrow$ as $T_w \uparrow$ (increased conduction, convection, radiation)





Pool Boiling Correlations

1. Nucleat boiling

$$q = \mu_\ell h_{fg}\left[\frac{g(\rho_\ell - \rho_v)}{\sigma}\right]^{1/2}\left[\frac{c_{p_\ell}(T_s - T_{sat})}{C_{s,f}\, h_{fg}\, Pr_\ell^{n}}\right]^{3}$$

2. Critical heat flux

$$q_{max} = \frac{\pi}{24} h_{fg}\, \rho_v\left[\frac{\sigma g(\rho_\ell - \rho_v)}{\rho_v^2}\right]^{1/4}\left(\frac{\rho_\ell + \rho_v}{\rho_\ell}\right)^{1/2}$$

3. Minimum heat flux

$$q_{min} = 0.09\, \rho_v\, h_{fg}\left[\frac{g\sigma(\rho_\ell - \rho_v)}{(\rho_\ell + \rho_v)^2}\right]^{1/4}$$

4. Film Boiling

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

$c = 0.62$ horz cylinder

$c = 0.67$ sphere

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

where

$\bar{h}_{conv}$: average boiling H.T.C. in absence of Radiation

At high Temp. $T_s \gtrsim 300^\circ C$; radiation mode affect the process: Total H.T.C is

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

If $\bar{h}_{rad} < \bar{h}_{conv} \Rightarrow$

$$\bar{h} = \bar{h}_{conv} + \frac{3}{4}\bar{h}_{rad}$$

The effective rad. coeff, $\bar{h}_{rad}$ is obtained from

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

where

σ : Stefan-Boltzman cons.
ϵ : emissivity of the solid

Note

It is recommended to operate near or below the temp. excess that corresponds to critical flux "peak point".

Table 12–1 Values of C_{sf} and n for various surface-fluid combinations.

Fluid	Surface	C_{sf}
Water	Brass	0.0060
	Copper, polished	0.0130
	Copper, lapped	0.0147
	Copper, scored	0.0068
	Nickel	0.0060
	Platinum	0.0130
	Stainless steel, chemically etched	0.0130
	Stainless steel, ground and polished	0.0060
	Stainless steel, mechanically polished	0.0130
	Stainless steel, teflon pitted	0.0058
Benzene	Chromium	0.1010
Carbon tetrachloride	Copper polished	0.0070
Ethyl alcohol	Chromium	0.0027
Isopropyl alcohol	Copper	0.0025
n-butyl alcohol	Copper	0.0030
n-pentane	Copper, polished	0.0154
	Copper, lapped	0.0049
	Copper, emery rubbed	0.0074
	Chromium	0.0150
	Nickel, polished	0.0127