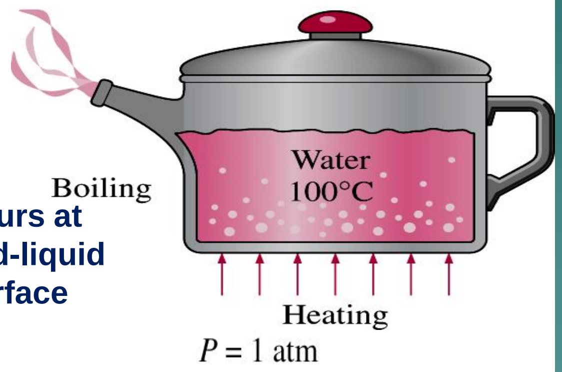
Boiling Heat transfer

Introduction

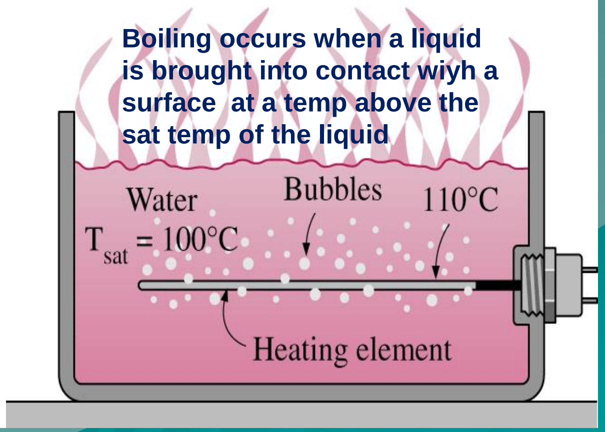
- Phase change + convective fluid motion
- Important features:
  - Large heat transfer rates with small temperature differences (nearly isothermal)
  - High heat transfer coefficients
  - Excellent for high heat fluxes (compact)
- Applications:
  - Refrigeration, boilers, heat exchangers
  - Petroleum refining, chemical processing, cryogenics, physical separation of gases (N_2, etc.)
  - Atmospheric precipitation
  - Maintaining constant temperature (e.g. electronics, computers)
  - Nuclear heat transfer - normal and accident scenarios

Occurs at liquid-vapor interface



Occurs at solid-liquid interface

Boiling occurs when a liquid is brought into contact wiyh 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} = 100ºC & h_{fg} = 2257 kJ/kg

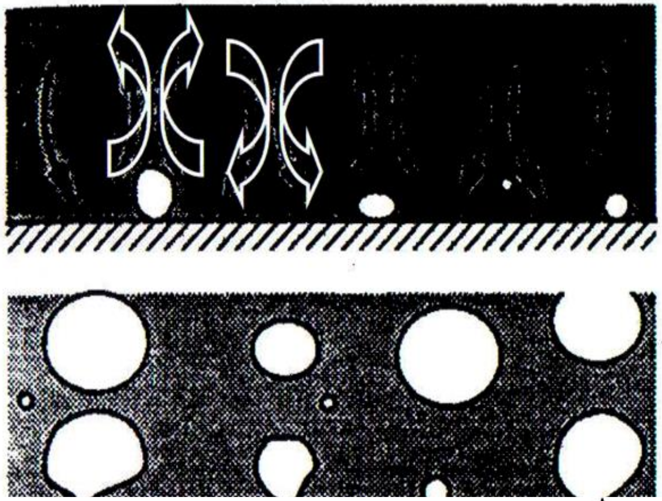
- In boiling, the rate equation (Newton's law of cooling) is:

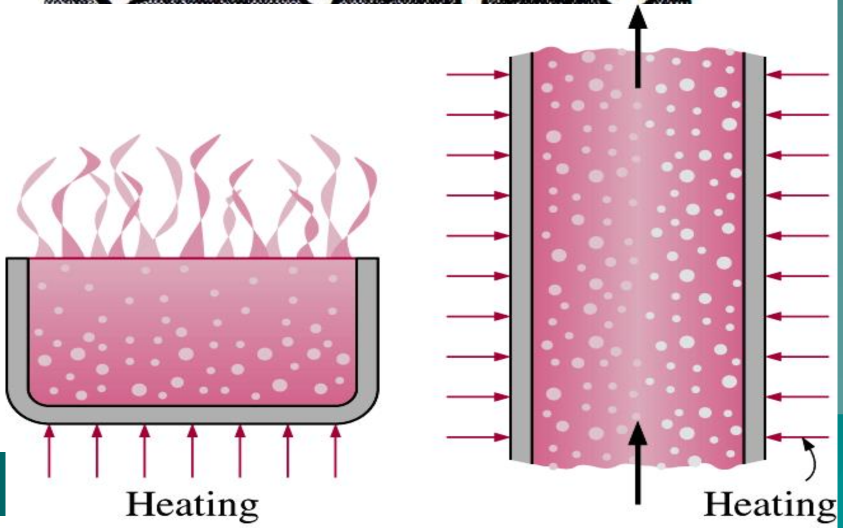
$$q_s'' = h\left(T_s - T_{sat}\right) = h\,\Delta T_e$$

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

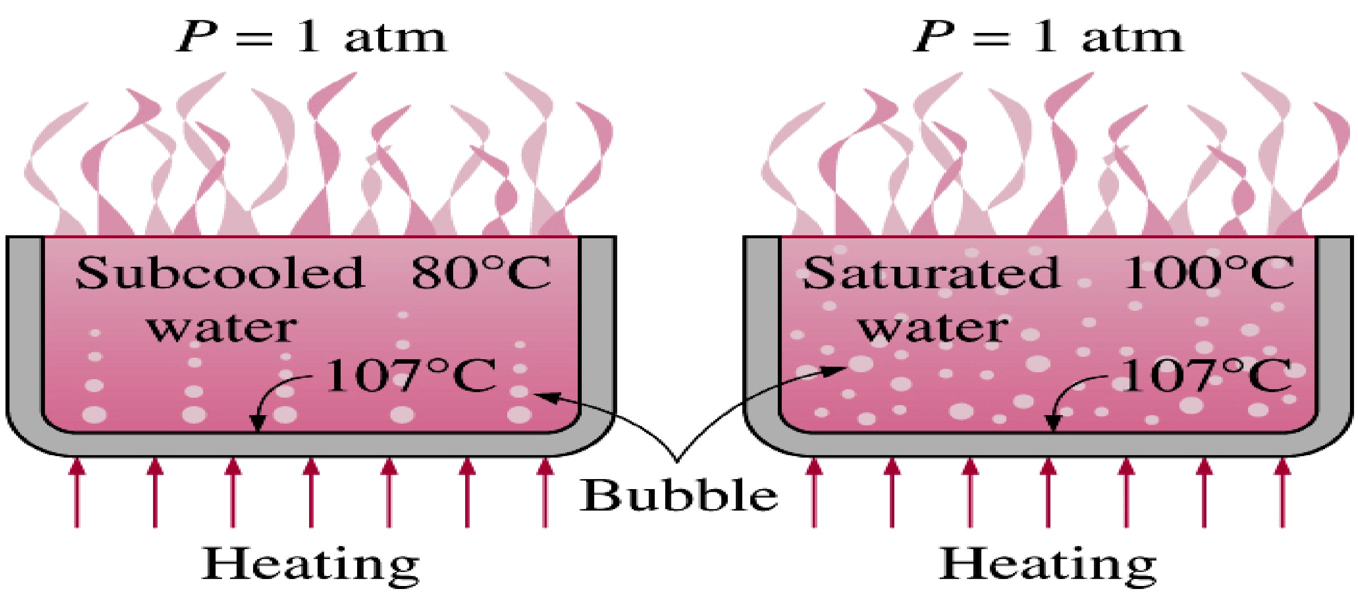




(*a*) Pool boiling (*b*) Flow boiling

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

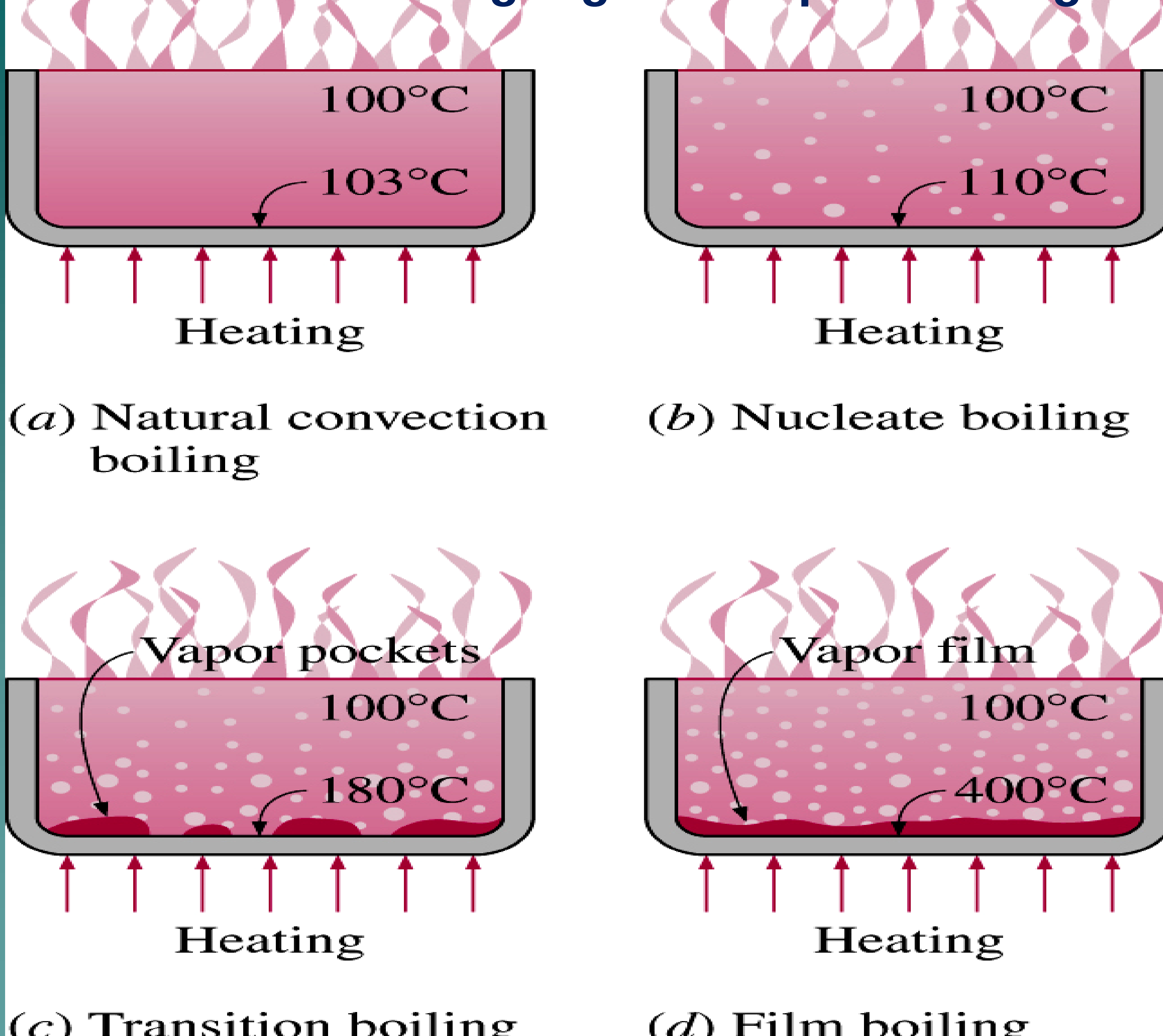
The dimensionless parameters relevant in boiling heat transfer

- 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) **{Ratio of Buoyancy forces to viscous forces}**

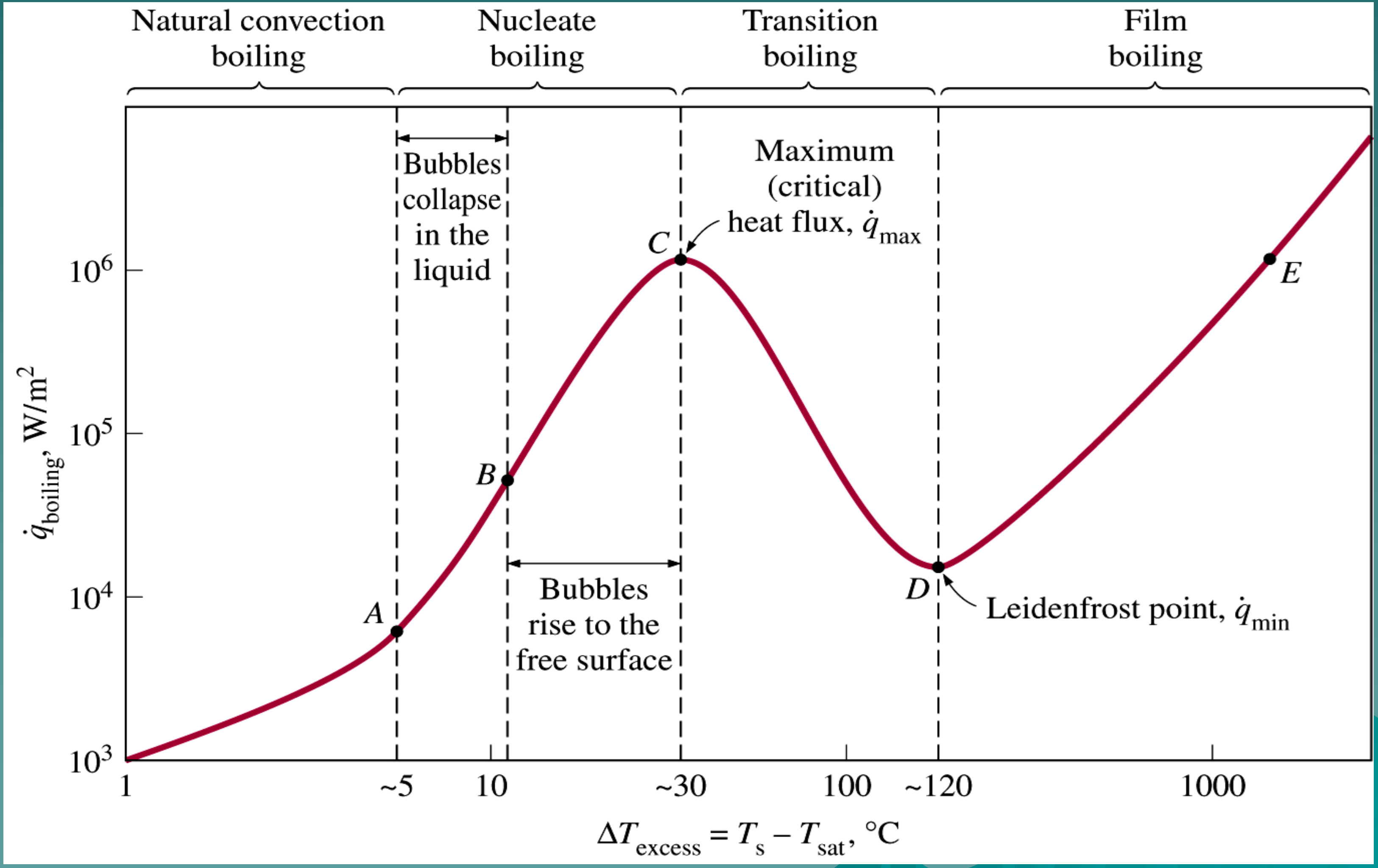
Pool Boiling

- 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



Typical boiling curve for water at 1 atm pressure



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. $T_s \gtrsim 300°C$; 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

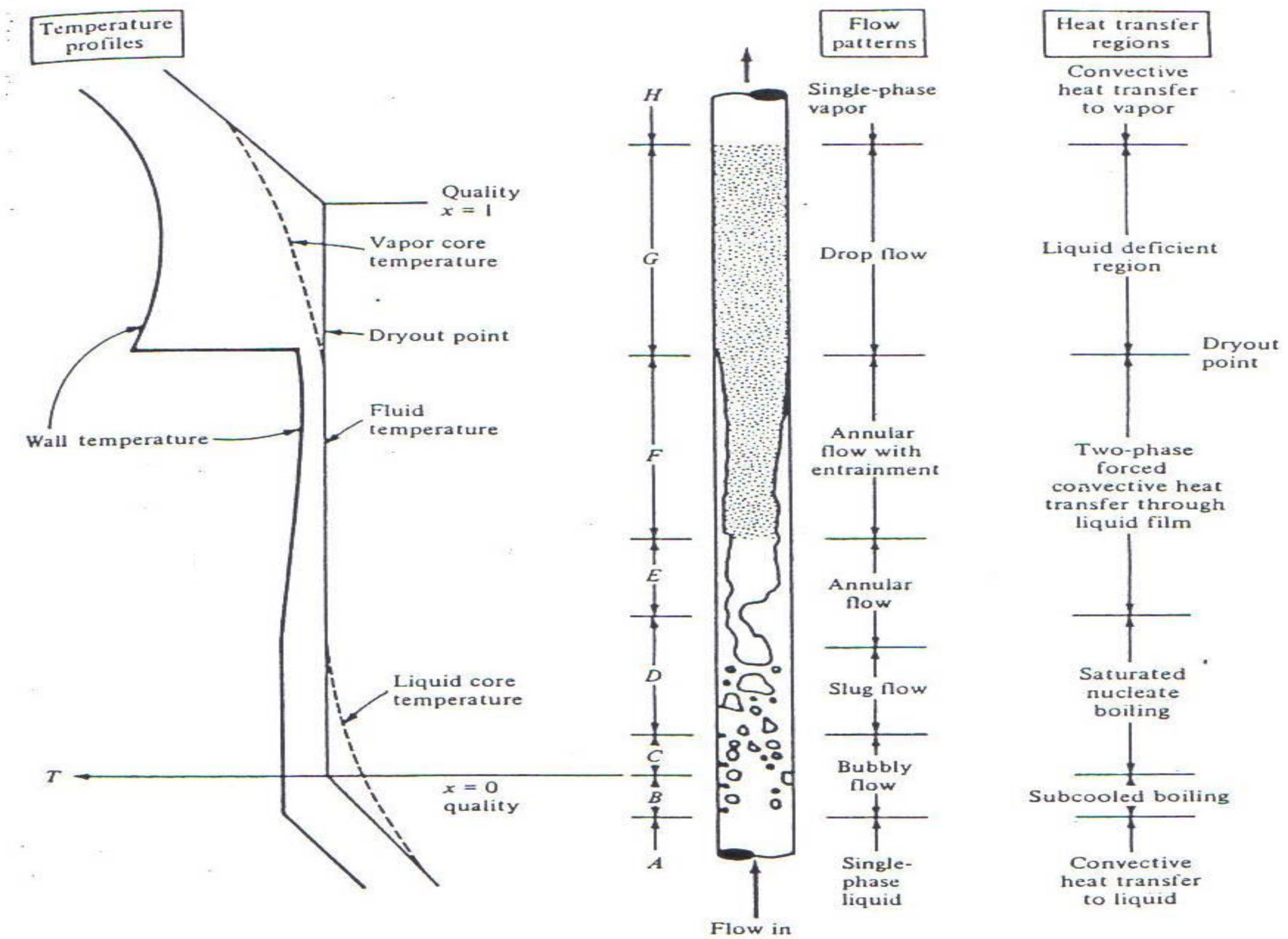
Note

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

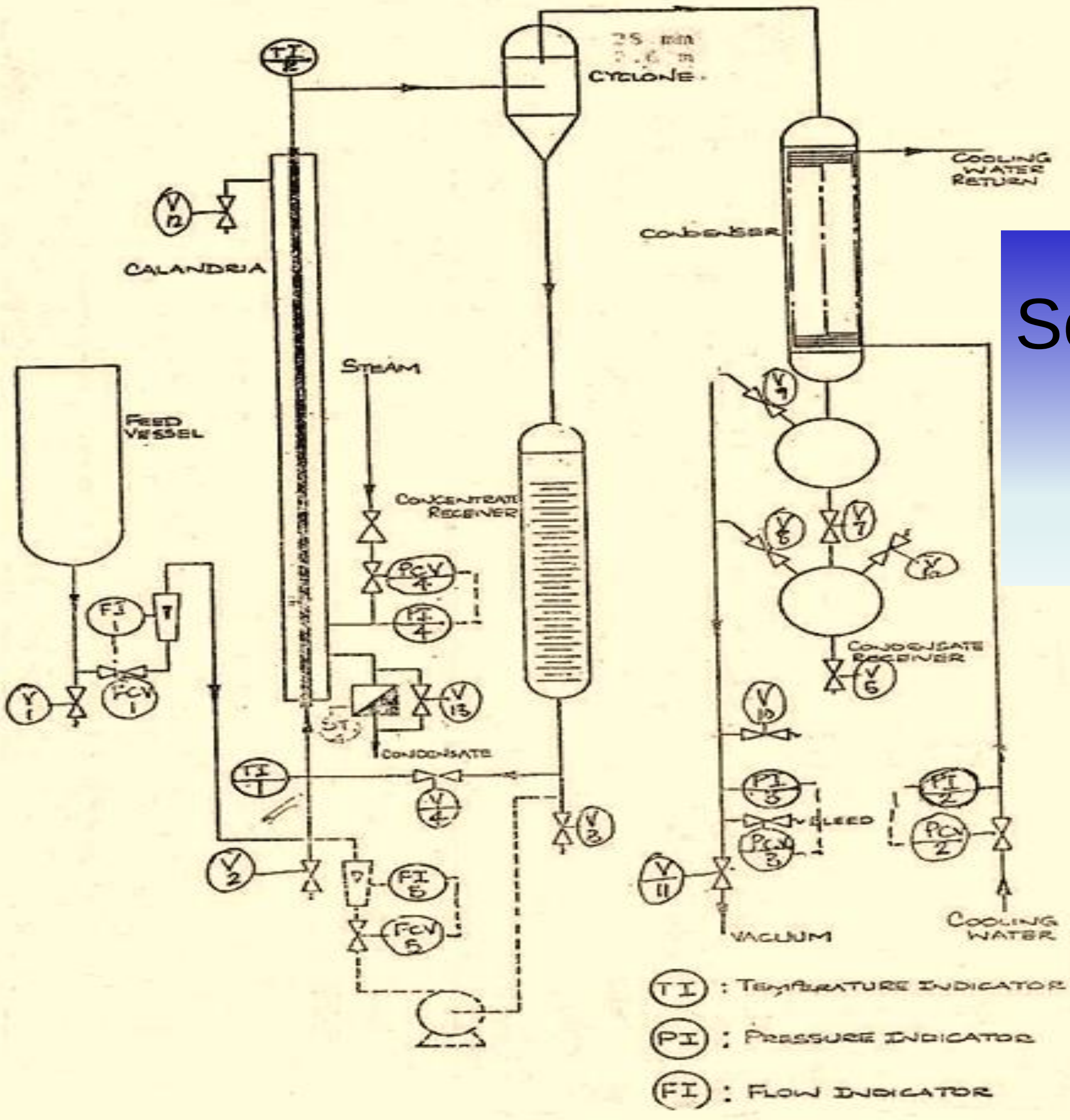
Values of $C_{s,f}$ for various surface–fluid combinations

Surface–Fluid Combination		$C_{s,f}$	n
Water–copper			
Scored		0.0068	1.0
Polished	{soft surface}	0.0128	1.0
Water–stainless steel			
Chemically etched		0.0133	1.0
Mechanically polished		0.0132	1.0
Ground and polished		0.0080	1.0
Water–brass		0.0060	1.0
Water–nickel		0.006	1.0
Water–platinum		0.0130	1.0
n-Pentane–copper			
Polished		0.0154	1.7
Lapped	{Coarse surface}	0.0049	1.7
Benzene–chromium		0.0101	1.7
Ethyl alcohol–chromium		0.0027	1.7

- Flow patterns and heat transfer regions in forced convection inside a vertical tube subjected to **uniform heat flux**.



Schematic diagram for climbing evaporator



Forced Convection Boiling

- Region A ~ Forced convection heat transfer (only liquid; no change of phases)

  for turbulent

$$\overline{Nu} = \frac{\overline{h}D}{k} = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$$

$$L/D > 60, \qquad \mathrm{Re} > 10{,}000$$

$$q'' = \overline{h}(T_w - T_l)$$

- Region B ~ Subcooling boiling

$$\frac{c_{p,l}\Delta T}{h_{fg}\Pr^{n}} = C_{sf}\left[\frac{q''}{\mu_l h_{fg}}\sqrt{\frac{g_c\sigma}{g(\rho_l - \rho_v)}}\right]^{0.33}$$

Where n=1 for water , n=1.7 for other liquid

Geometry	Liquid-surface combination	C_{sf}
Horizontal tube (14.9mm ID)	Water-stainless steel	0.015
Vertical tube (27.1mmID)	Water-copper	0.013

Regions C, D, E and F

$$h_{TP} = h_{NB} + h_C$$

Two-Phase H.T.C

Nucleate boiling H.T.C.

Forced conv H.T.C.

$$h_c = 0.023\left(\frac{k_l}{D}\right)\mathrm{Re}_l^{0.8}\,\mathrm{Pr}_l^{0.4}\,F$$

$$\text{Where } \mathrm{Re}_l = \frac{G(1-x)D}{\mu_l}$$

G: mass flow rate through tube /area of tube

D: tube diam

F: conv boiling factor (see chart)

x: vapor mass quality

$$h_{NB} = 0.00122\left(\frac{k_l^{0.79} c_{pl}^{0.45} \rho_l^{0.49}}{\sigma^{0.5} \mu_l^{0.29} h_{fg}^{0.24} \rho_v^{0.24}}\right) \Delta T_{sat}^{0.24} \Delta P_{sat}^{0.75} S$$

Where $\Delta T_{sat} = T_s - T_{sat}, {}^{\circ}C$

$$\Delta P_{sat} = P_{sat\ at T_s} - P_{sat\ at T_{sat}},\ N/m^2$$

$$\sigma = \text{surface tension},\ N/m$$

$$S = \text{suppression factor}$$

Note

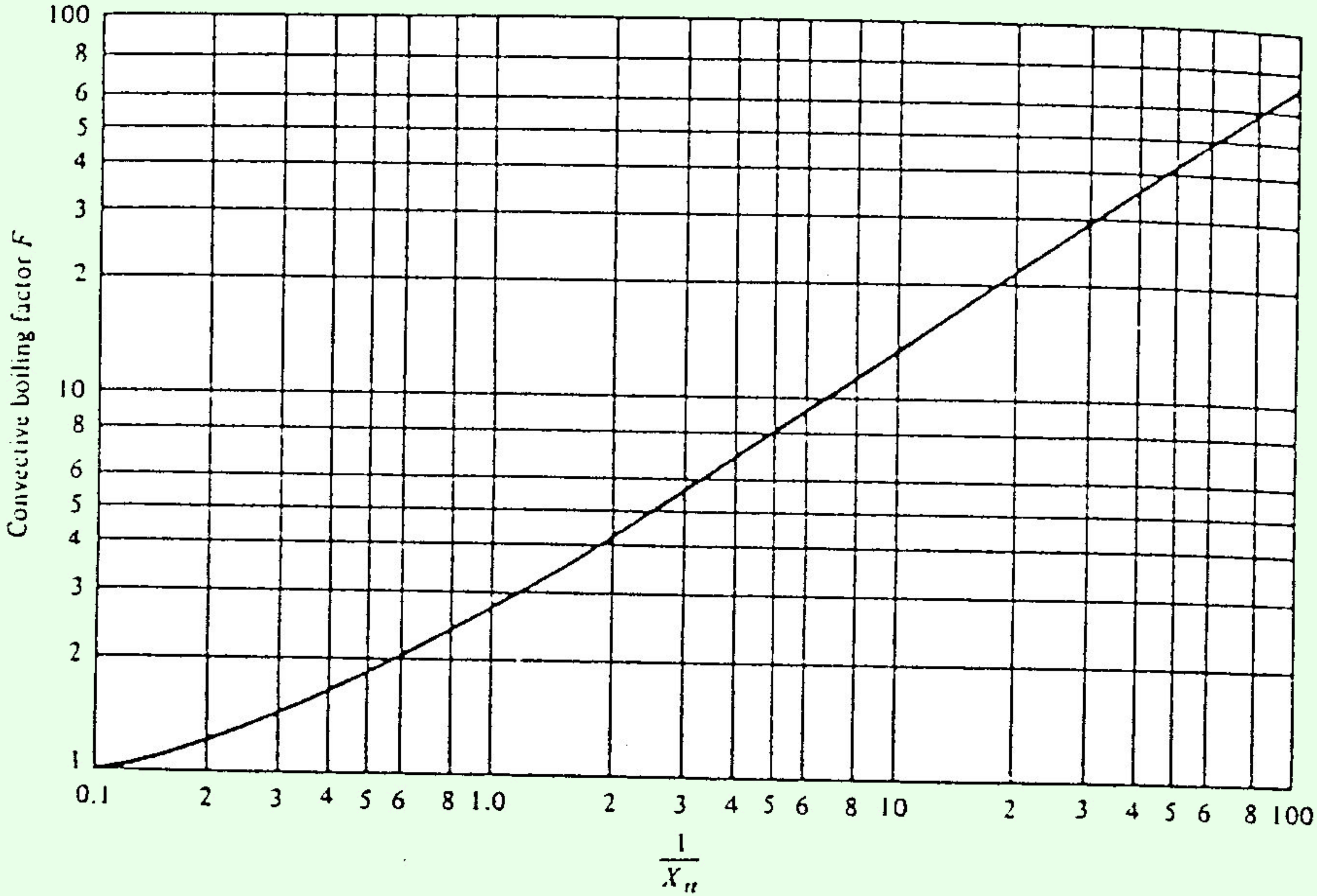
- In order to obtain S, you need to define the following parameters and to use the charts below:

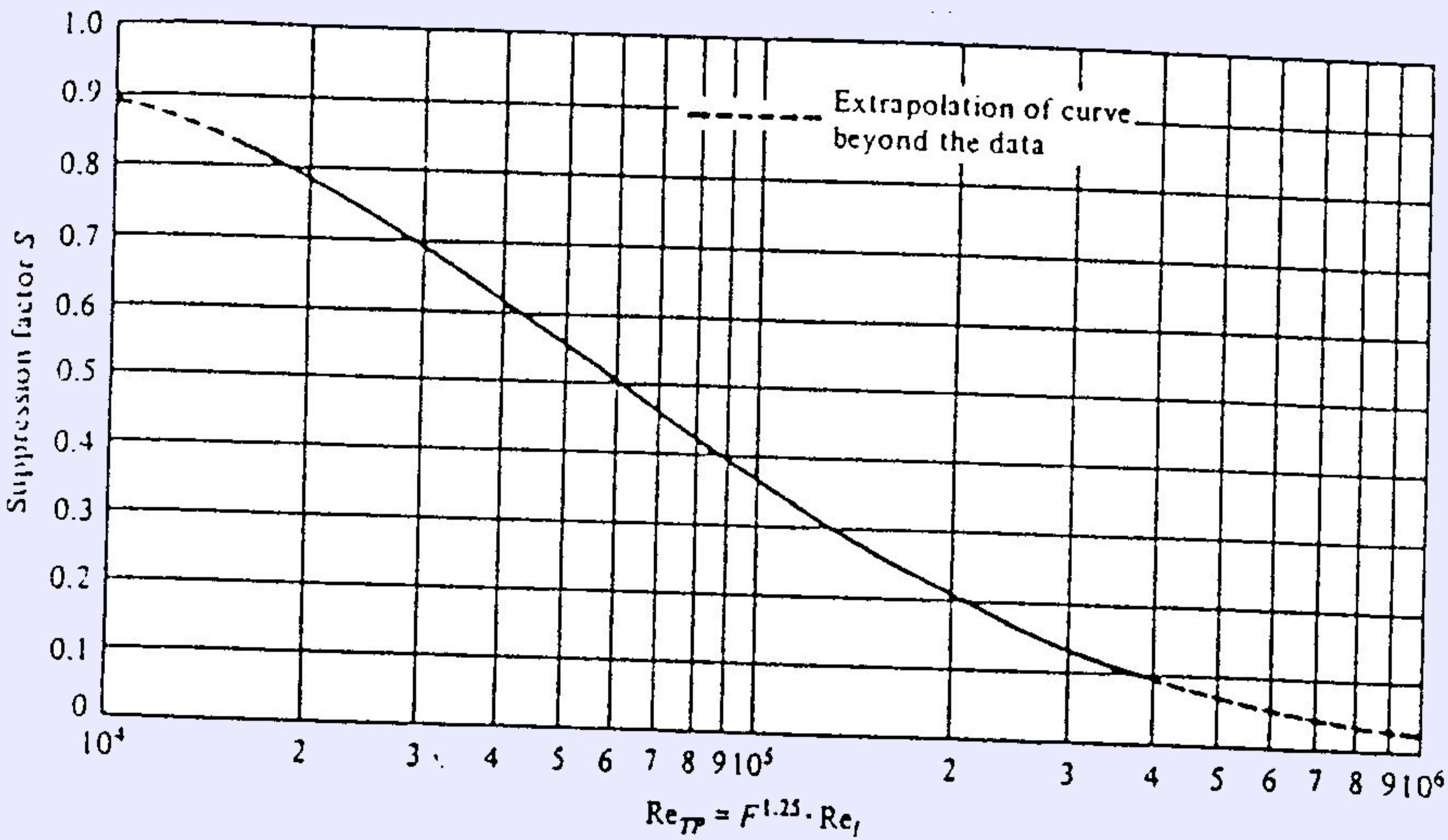
Two - phase Reynolds number, Re_{TP} is

$$Re_{TP} = F^{1.25} Re_l = F^{1.25}[\frac{G(1-x)D}{\mu_l}]$$

The Martinelli parameter X_{tt} is defined as

$$X_{tt} = (\frac{1-x}{x})^{0.9}(\frac{\rho_v}{\rho_l})^{0.5}(\frac{\mu_l}{\mu_v})^{0.1}$$


Convective boiling factor F
100
8
6
5
4
3
2
10
8
6
5
4
3
2
1
0.1
2
3
4
5
6
8
1.0
2
3
4
5
6
8
10
2
3
4
5
6
8
100
1/X_tt



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Suppression factor S
Extrapolation of curve beyond the data
10⁴
2
3
4
5
6
7
8
9
10⁵
2
3
4
5
6
7
8
9
10⁶
$Re_{TP} = F^{1.25} \cdot Re_l$

Finally

- The heat flux is:

$$q'' = h_{TP}\Delta T_{sat} = h_{TP}(T_s - T_{sat})$$