Chapter 8
Heat Transfer With Phase Change

By Wubishet Degife

Heat Transfer with Phase Change

So far we have discussed heat transfer at a boundary due to a temperature difference between bulk temperatures

$$\frac{q_x}{A} = h\left(T_b - T_w\right)$$

Newton's law of cooling

1. forced convection
   - laminar
   - turbulent
2. natural convection

Heat Transfer with Phase Change

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$$\frac{q_x}{A} = h\left(T_b - T_w\right)$$

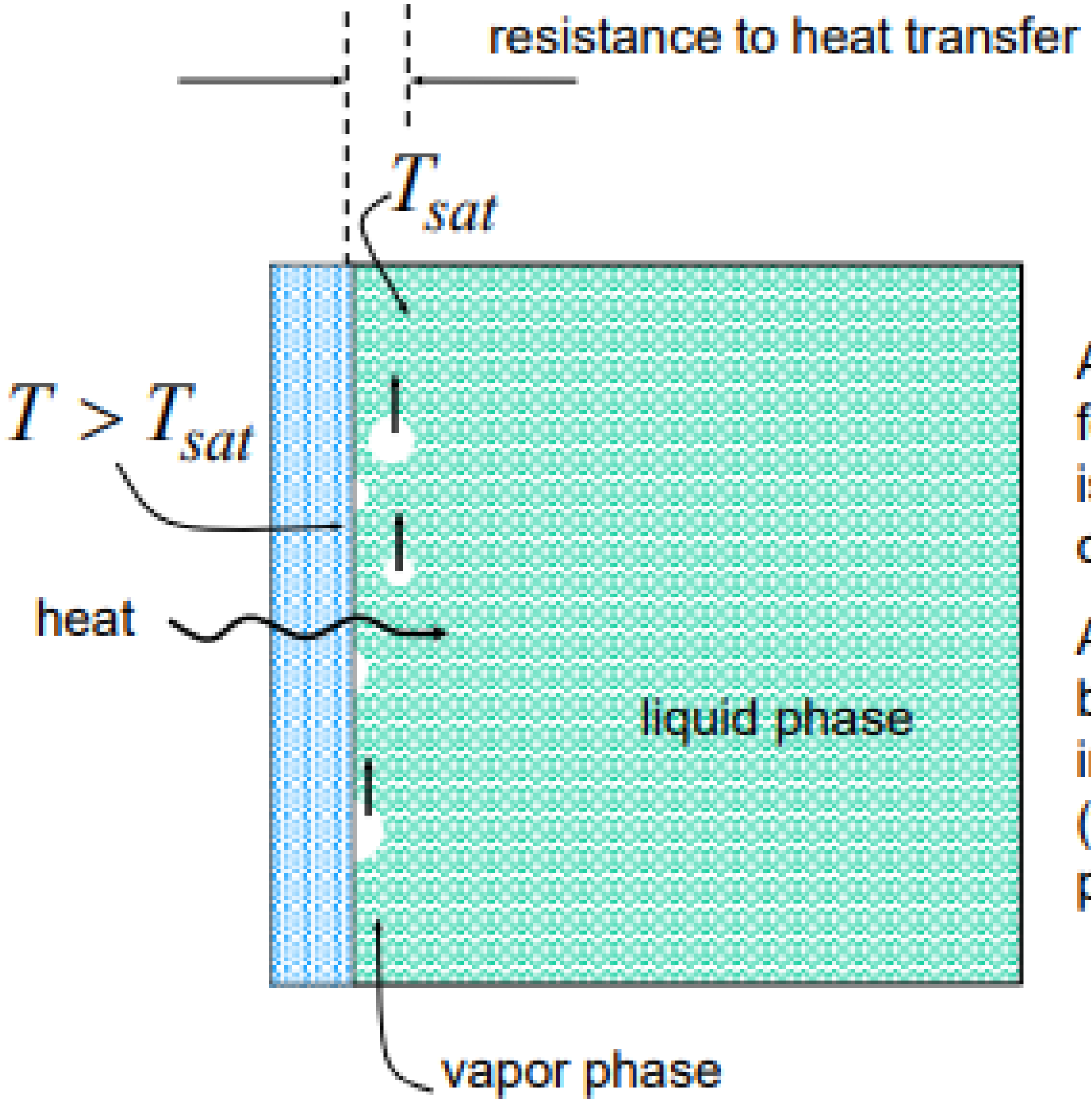
Newton's law of cooling

1. forced convection
   - laminar
   - turbulent
2. natural convection
3. phase change

When a phase change takes place, the temperature on one side is **CONSTANT**, but the presence of boiling/condensing fluids produces heat transfer.

- Important in evaporation, distillation
- **LARGE *h***
- It's important to know in which **regime** you operate
- Each regime has different correlations

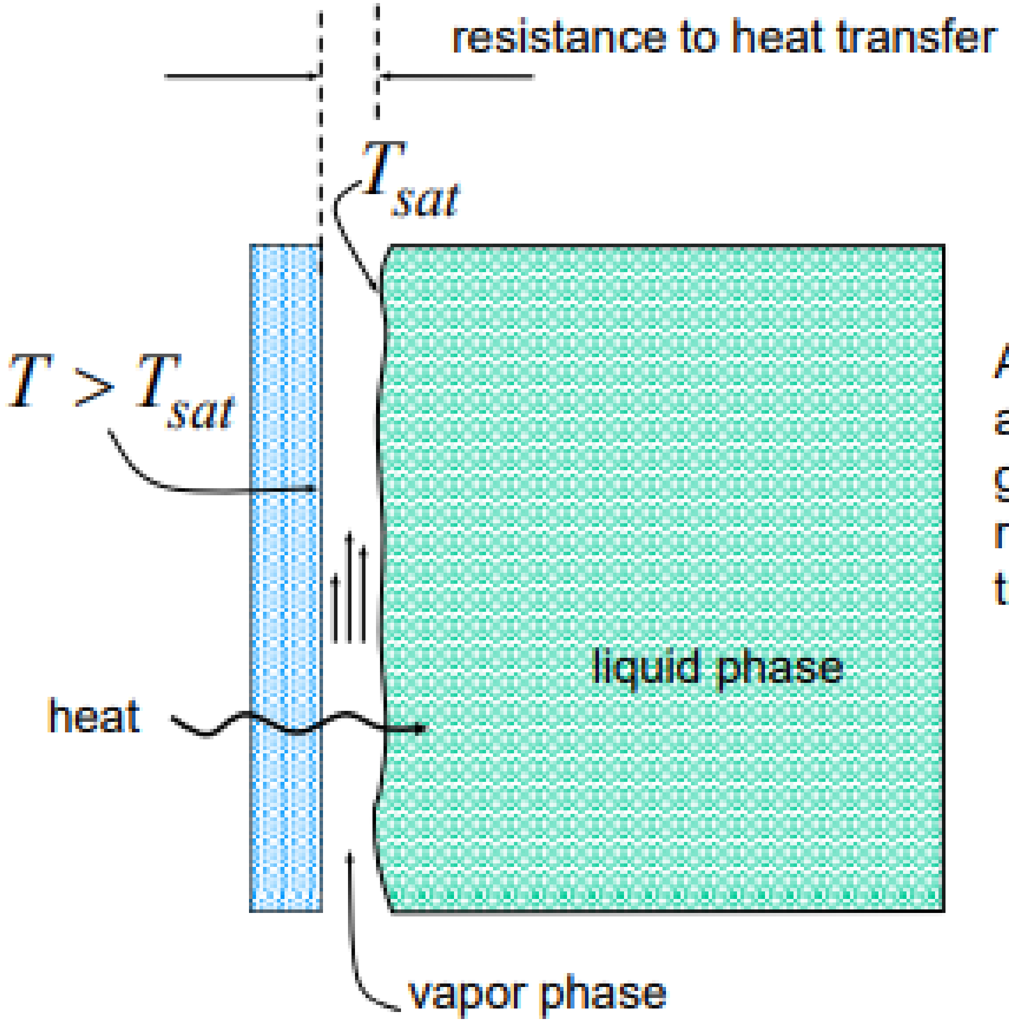
Boiling



At low DT, few bubbles form, and heat transfer is by natural convection.

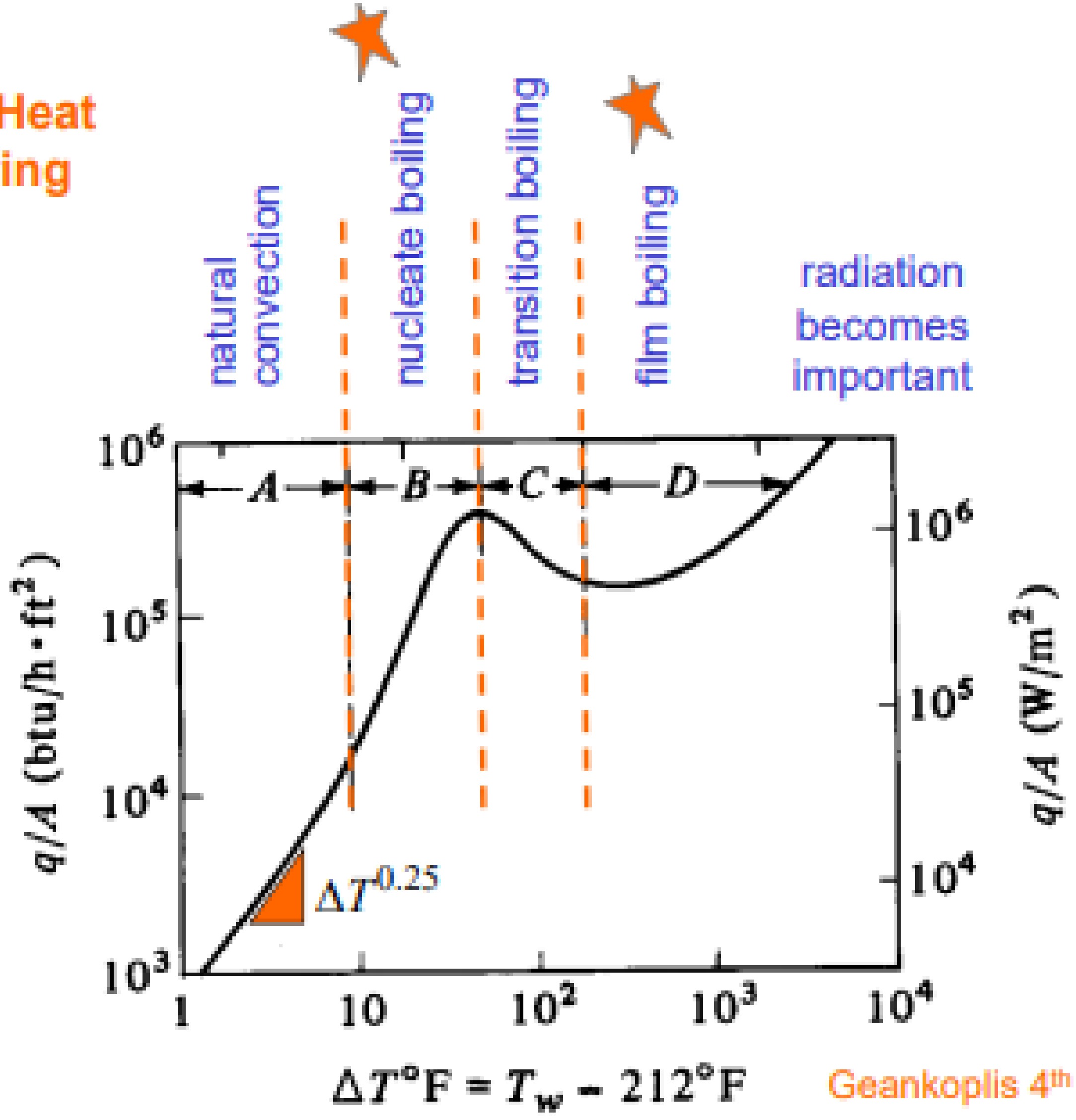
As DT increases, more bubbles form, increasing convection (flow) in the liquid phase, increasing h.

Film Boiling



As ΔT increases further, a film appears and grows, increasing resistance to heat transfer

Regimes of Heat Transfer during Boiling



There are correlations for *h* for each regime.

Geankoplis 4th ed, p284

Regimes of Heat Transfer during Boiling

There are correlations for *h* for each regime.

For example:

Nucleate boiling, horizontal surfaces

$h = 1043(\Delta \mathrm{T})^{\frac{1}{3}}$	$\frac{q}{A} < 16$
$h = 5.56(\Delta \mathrm{T})^{3}$	$16 < \frac{q}{A} < 240$

Equations good for these units:

$$\Delta T [=] K$$

$$\frac{q}{A} [=] \frac{kW}{m^2}$$

$$h [=] \frac{W}{m^2 K}$$

Geankoplis 4th ed, p284

Regimes of Heat Transfer during Boiling

There are correlations for *h* for each regime.

For example:

Nucleate boiling, vertical surfaces

$$h = 537(\Delta T)^{\frac{1}{7}} \qquad \frac{q}{A} < 3$$

$$h = 7.95(\Delta T)^{3} \qquad 3 < \frac{q}{A} < 63$$

Equations good for these units:

$$\Delta T [=] K$$

$$\frac{q}{A} [=] \frac{kW}{m^2}$$

$$h [=] \frac{W}{m^2 K}$$

Geankoplis 4th ed, p285

Regimes of Heat Transfer during Boiling

There are correlations for *h* for each regime.

For example:

Nucleate boiling, forced convection inside tubes

$$h = 2.55 \Delta T^3 e^{\frac{p}{1551}}$$

Equations good for these units:

$$\Delta T [=] K$$

$$\frac{q}{A} [=] \frac{kW}{m^2}$$

$$h [=] \frac{W}{m^2 K}$$

$$p [=] kPa$$

Geankoplis 4th ed, p285

Regimes of Heat Transfer during Boiling

There are correlations for *h* for each regime.

For example:

Film boiling, horizontal tubes

Geankoplis 4th ed, p285

$$h = 0.62\left[\frac{\left(k_v^3\rho_v(\rho_l-\rho_v)g\left[\Delta H(T_{sat})+0.4\hat{C}_{p,v}\Delta T\right]\right)}{D\mu_v\Delta T}\right]^{\frac{1}{4}}$$

Equations good for these units:

$$\Delta T[=]K$$

$$h[=]\frac{W}{m^2K}$$

$$k_v[=]\frac{W}{mK}$$

$$\rho_v,\rho_l[=]\frac{kg}{m^3}$$

$$\Delta H[=]\frac{J}{kg}$$

$$D[=]m$$

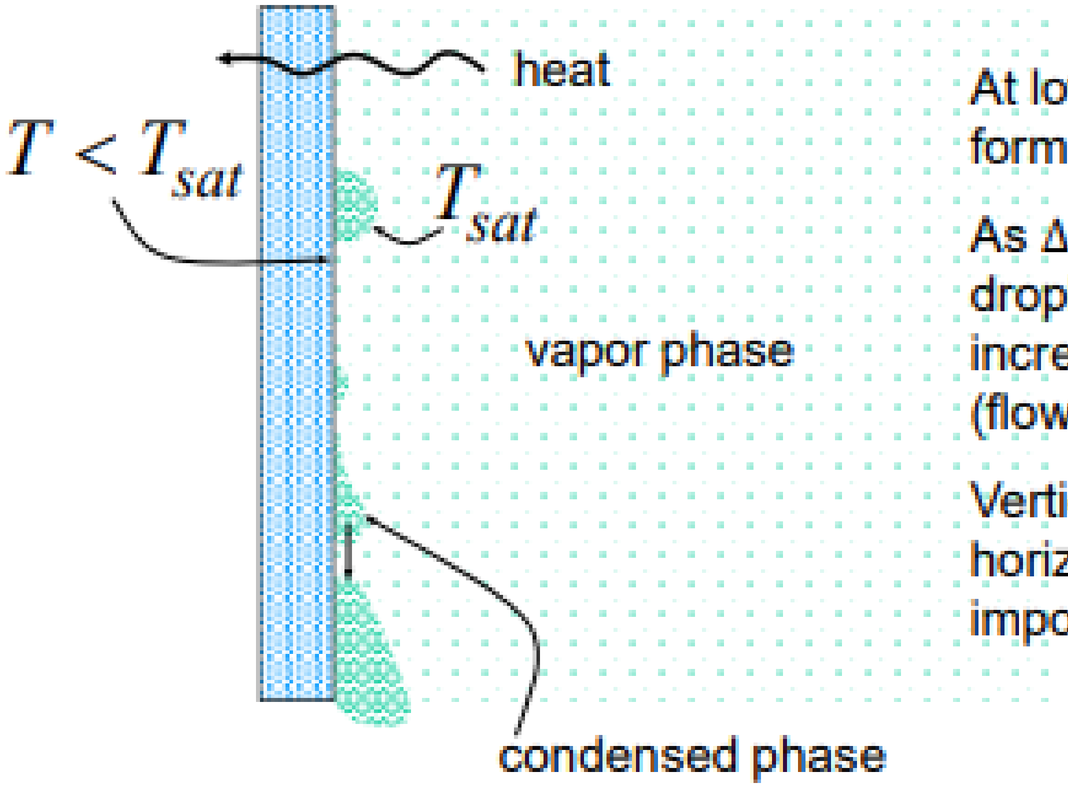
$$\mu_v[=]Pa\ s$$

$$g[=]m/s^2$$

$$T_{film}=\frac{T_{wall}+T_{sat}}{2}$$

(All material properties at the ***film temperature***)

Condensation



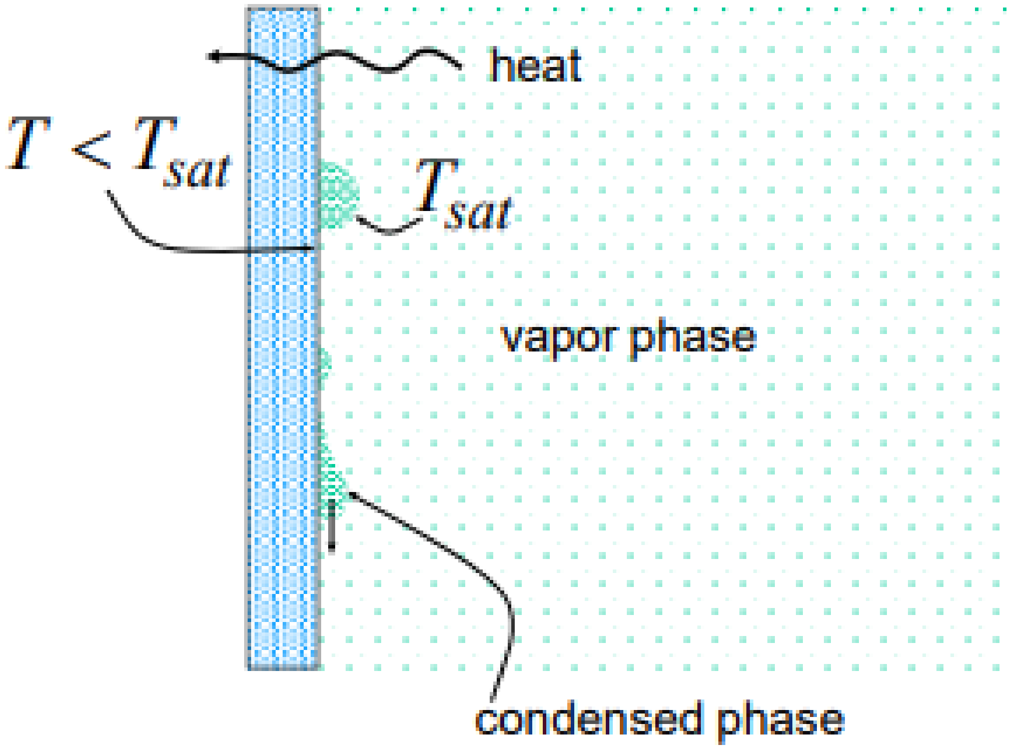
At low ΔT, few droplets form,

As ΔT increases, more droplets form, increasing convection (flow).

Vertical plates; horizontal tubes important

Dropwise Condensation

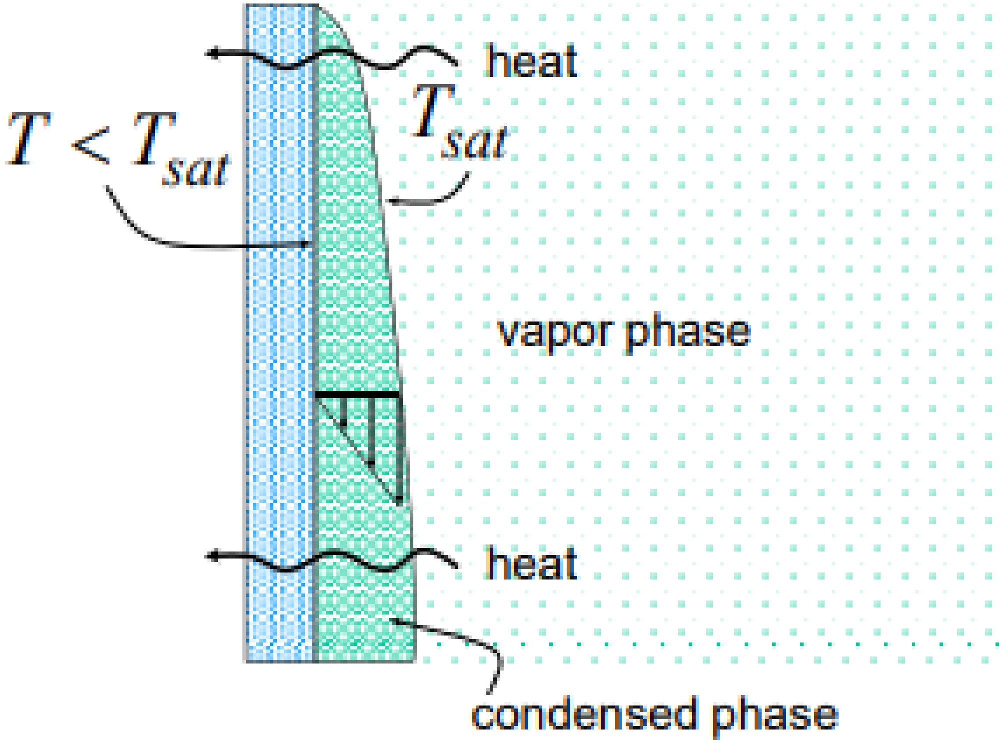
- high *h*
- hard to maintain
- not used in practice



There are correlations for *h* for each regime.

Film Condensation

- film reduces *h*
- very stable
- often used



There are correlations for *h* for each regime.

Regimes of Heat Transfer during Condensation

There are correlations for *h* for each regime.

Geankoplis 4th ed, p289

For example:

Film condensation, vertical surfaces, laminar flow

$$Nu = \frac{hL}{k_l} = 1.13\left(\frac{\rho_l(\rho_l - \rho_v)g\Delta H(T_{sat})L^3}{\mu_l k_l \Delta T}\right)^{\frac{1}{4}} \qquad \mathrm{Re} = \frac{4m}{\pi D \mu_l} < 1800$$

Equations good for these units:

$\Delta T[=]K$

$h[=]\frac{W}{m^2K}$

$m[=]\frac{kg}{s}$

$k_l[=]\frac{W}{mK}$

$\rho_v, \rho_l[=]\frac{kg}{m^3}$

$\Delta H[=]\frac{J}{kg}$

$L[=]m$

$\mu_l[=]Pa\ s$

$g[=]m/s^2$

$T_{film} = \frac{T_{wall} + T_{sat}}{2}$

(All material properties at the film temperature)

Regimes of Heat Transfer during Condensation

There are correlations for *h* for each regime.

Geankoplis 4th ed, p289

For example:

Film condensation, vertical surfaces, turbulent flow

$$Nu = \frac{hL}{k_l} = 0.0077\left(\frac{\rho_l^2 g \mathrm{L}^3}{\mu_l^2}\right)^{\frac{1}{3}} \mathrm{Re}^{0.4} \qquad \mathrm{Re} = \frac{4m}{\pi D \mu_l} > 1800$$

Equations good for these units:

$$h[=]\frac{W}{m^2 K}$$

$$m[=]\frac{kg}{s}$$

$$\rho_l[=]\frac{kg}{m^3}$$

$$L[=]m$$

$$k_l[=]\frac{W}{m}$$

$$\mu_l[=]Pa\ s$$

$$g[=]m/s^2$$

$$T_{film} = \frac{T_{wall} + T_{sat}}{2}$$

(All material properties at the film temperature)

Regimes of Heat Transfer during Condensation

There are correlations for *h* for each regime.

Geankoplis 4th ed, p285

For example:

Film condensation, outside horizontal cylinders, laminar flow

$$Nu = \frac{hL}{k_l} = 0.725\left(\frac{\rho_l(\rho_l - \rho_v)g\Delta H(T_{sat})D^3}{N\mu_l k_l \Delta T}\right)^{\frac{1}{4}} \qquad \mathrm{Re} = \frac{4m}{\pi D \mu_l} < 1800$$

Equations good for these units:

$\Delta T[=]K$

$h[=]\frac{W}{m^2K}$

$m[=]\frac{kg}{s}$

$T_{sat}[=]K$

$k_l[=]\frac{W}{mK}$

$\rho_v, \rho_l[=]\frac{kg}{m^3}$

$\Delta H[=]\frac{J}{kg}$

$D[=]m$

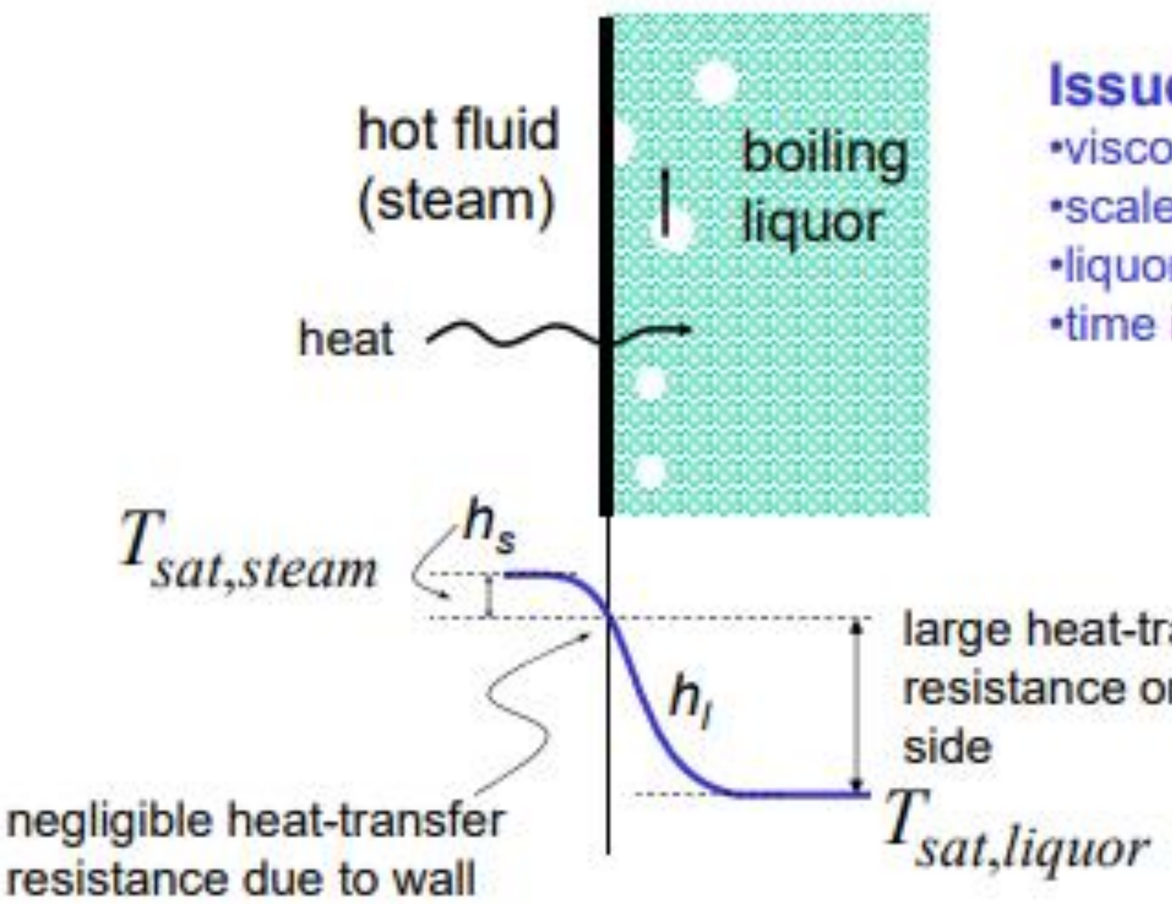
$\mu_l[=]Pa\ s$

$g[=]m/s^2$

$$T_{film} = \frac{T_{wall} + T_{sat}}{2}$$

(All material properties at the film temperature)

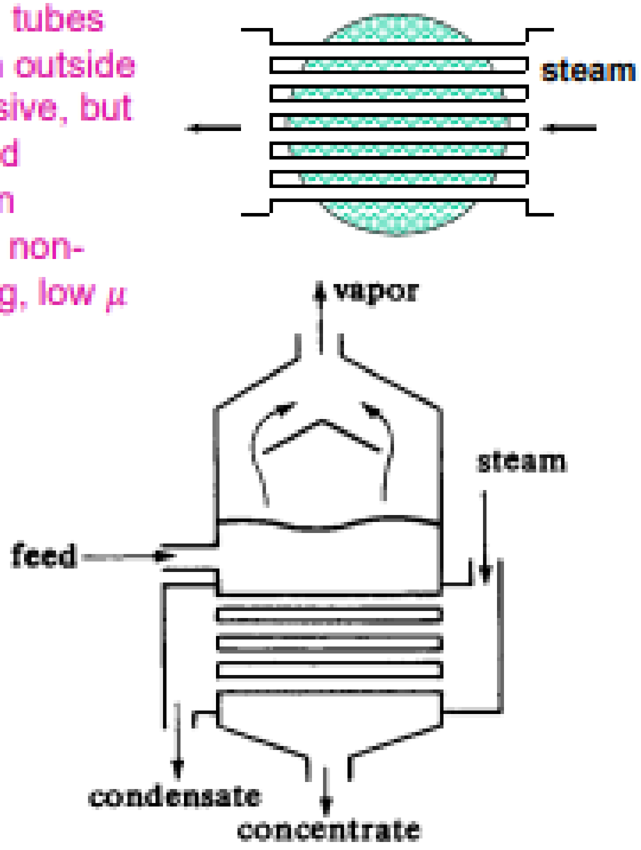
Evaporators



Issues:

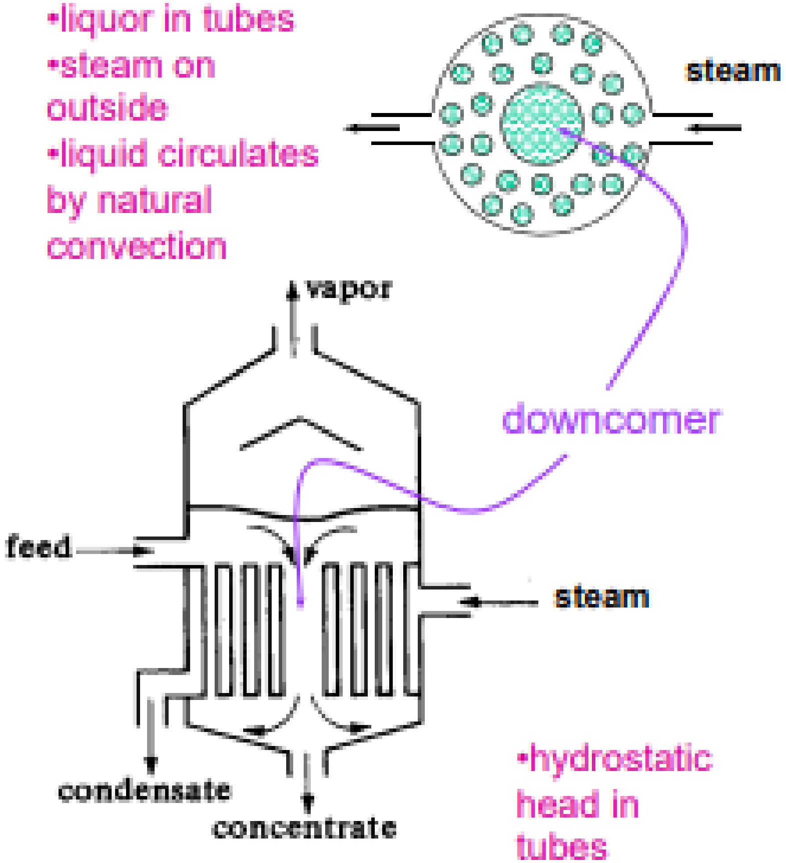
- viscosity, m
- scale formation
- liquor velocity
- time in evaporator

- steam in tubes
- liquor on outside
- inexpensive, but poor liquid circulation
- good for non-depositing, low μ fluids



horizontal-tube evaporator

- liquor in tubes
- steam on outside
- liquid circulates by natural convection

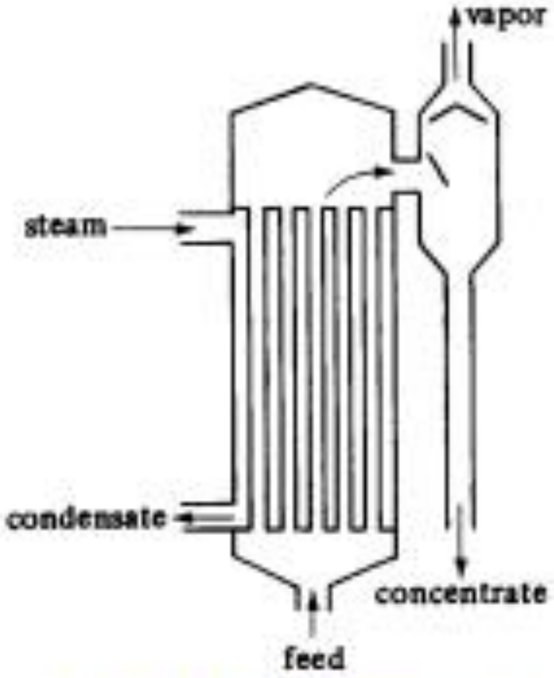


downcomer

vertical-tube evaporator

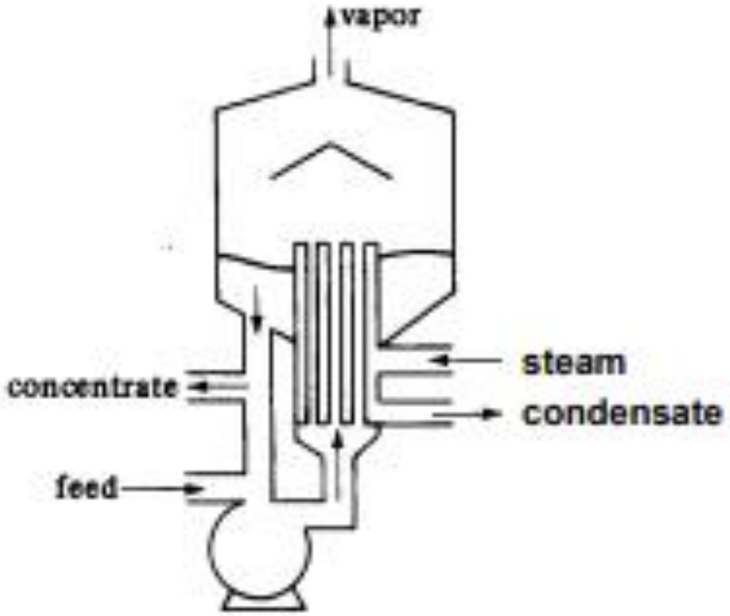
- hydrostatic head in tubes prevents boiling in tubes

- liquor in tubes
- steam on outside
- liquid circulates by natural convection
- single pass
- high liquid velocities



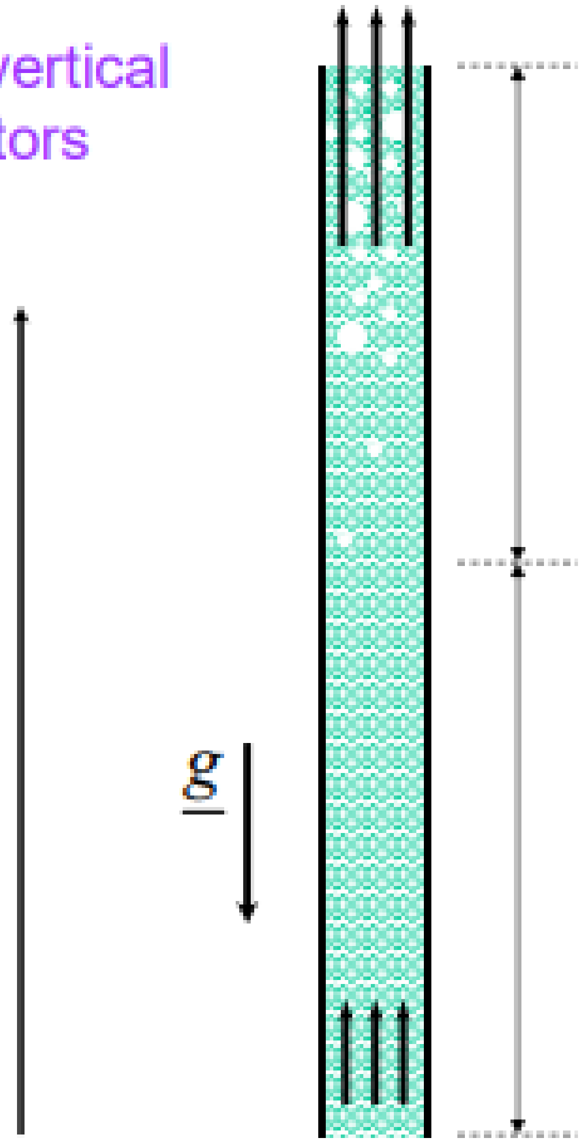
long-tube vertical evaporator

- liquor in tubes
- steam on outside
- liquid circulates by forced convection
- good for high μ fluids



forced-circulation evaporator

Long-tube vertical evaporators



Decreasing $\bar{\rho}$

Increasing $\bar{v}_z$

g

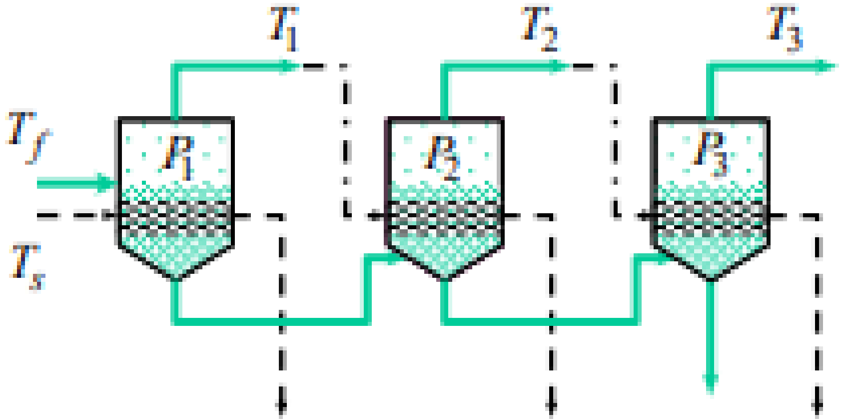
boiling, 2-phase zone

non-boiling zone

For discussion of how to estimate U, see Geankoplis 4th edition, p533

Greater efficiency may be obtained by operating several evaporators in series:

Multiple-Effect Evaporation



Norbert Rillieux: Inventor of Multiple-Effect Evaporation

Norbert Rillieux

From Wikipedia, the free encyclopedia

Norbert Rillieux (March 17, 1806 – October 8, 1894), a Creole American inventor and engineer, is most noted for his invention of the multiple-effect evaporator, an energy-efficient means of evaporating water. This invention was an important development in the growth of the sugar industry. Rillieux was a cousin of the painter Edgar Degas.

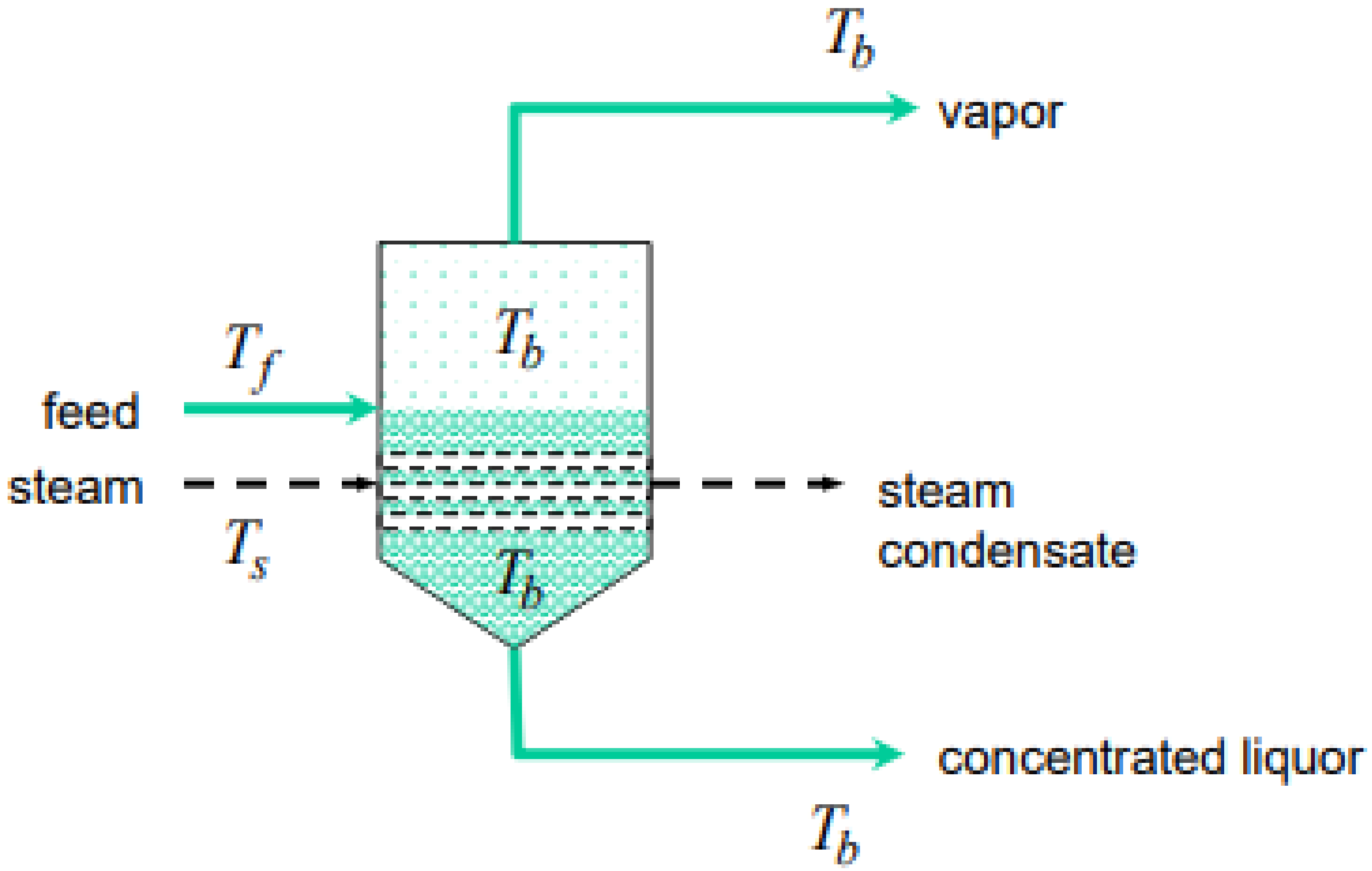
Contents [hide]

Norbert Rillieux in an undated photograph

Family [edit]

Norbert Rillieux was born into a prominent Creole family in New Orleans, Louisiana. He was the son of Vincent Rillieux, a white plantation owner, engineer and inventor, and his placée, Constance Vivant, a free person of

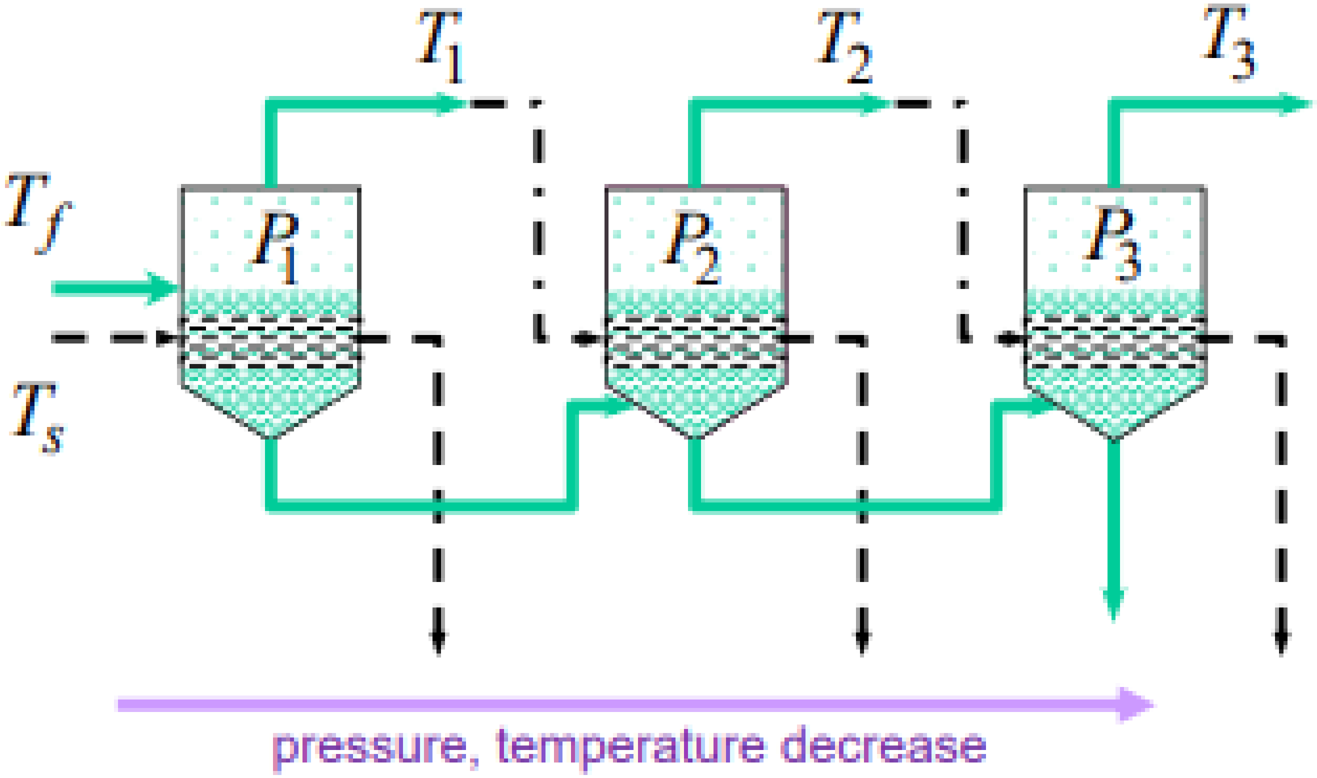
Single-Effect Evaporators



Multiple-Effect Evaporators

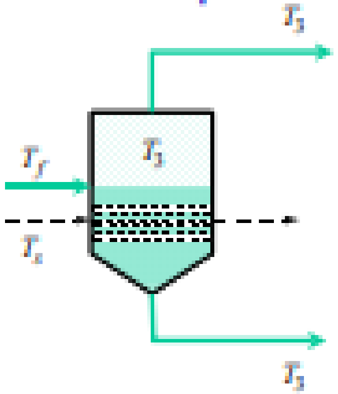
For each effect the vapor product becomes the source of heat for the subsequent effect

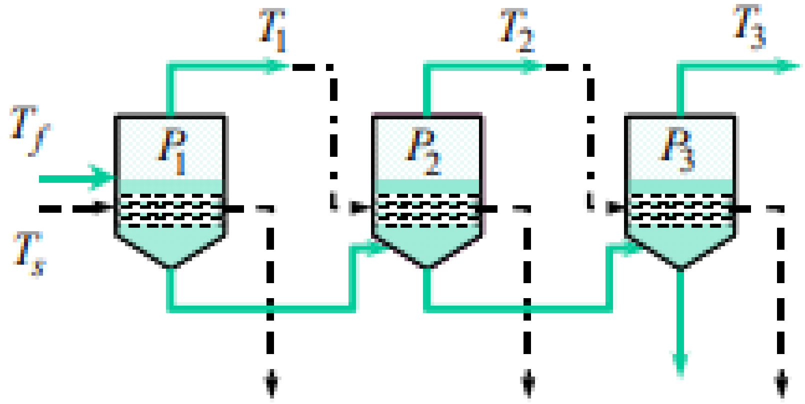
$$P_1 > P_2 > P_3$$
$$T_1 > T_2 > T_3$$



Compare Single- and Multiple-Effect Evaporators

$$Q = UA(T_s - T_3)$$





$$q_1 = UA(T_s - T_1)$$
$$q_2 = UA(T_1 - T_2)$$
$$q_3 = UA(T_2 - T_3)$$

$$Q = \sum q_i = UA(T_s - T_3)$$

same capacity = same amount of heat transferred
(but we did not have to pay for it all = more efficient)

Boiling/Evaporation

- Industrially we operate either in *nucleate* boiling or *film* boiling regimes
- There are different correlations for each regime and for different geometries
  - ✓ Nucleate boiling, horizontal surfaces
  - ✓ Nucleate boiling, vertical surfaces
  - ✓ Nucleate boiling, forced convection
  - ✓ Film boiling, horizontal tube

Condensation

- Industrially we operate in *film* condensation
- There are different correlations for different geometries
  - ✓ Vertical surfaces, laminar or turbulent
  - ✓ Outside stack of horizontal cylinders

Evaporators – designed with the boiling regimes in mind