Heat Transfer with Phase Change

So far we have discussed heat transfer due to a temperature gradient/difference

$$\frac{q_x}{A} = -k\frac{dT}{dx} \qquad \text{conduction}$$

$$\frac{q_x}{A} = h(T_b - T_w) \qquad \text{convection}$$

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

- Important in evaporation, distillation
- **LARGE** *h*

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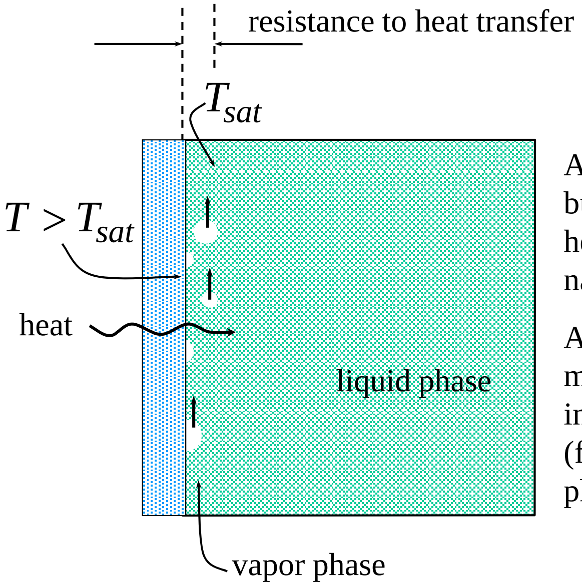
Boiling



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

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

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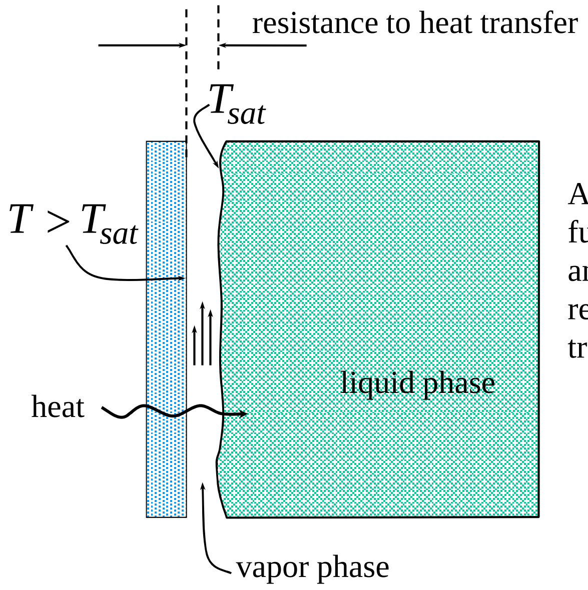
Film Boiling



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

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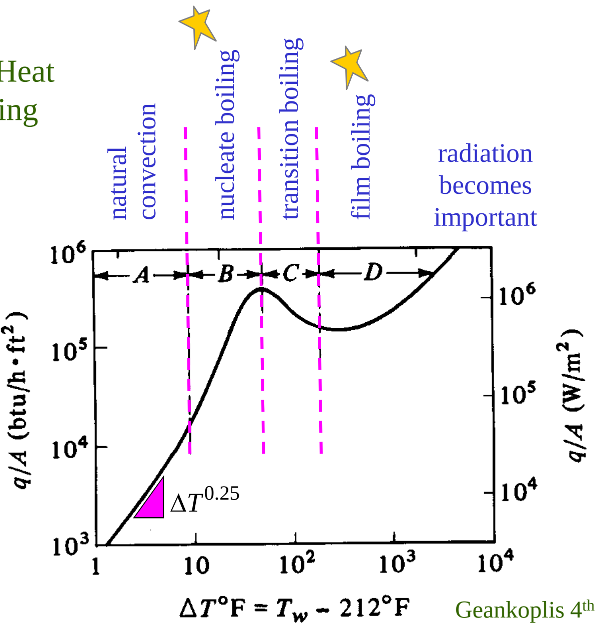
Regimes of Heat Transfer during Boiling



Geankoplis 4th ed, p284

There are correlations for *h* for each regime.

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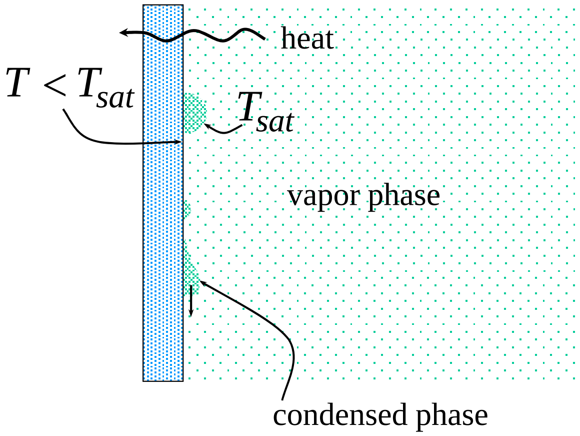
Dropwise Condensation

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



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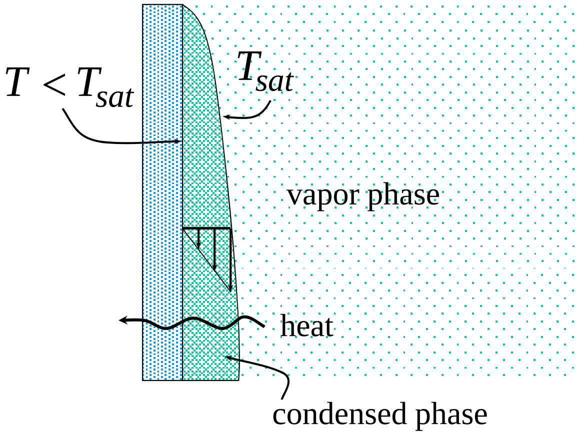
Film Condensation

- film reduces h
- very stable
- often used



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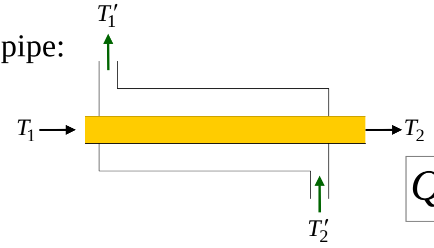
Heat Exchangers

double-pipe:



$$\boxed{Q = UA\Delta T_{lm}}$$

To increase Q appreciably, we must increase A, i.e. R_i

But:
- only small increases possible
- increasing R_i decreases h

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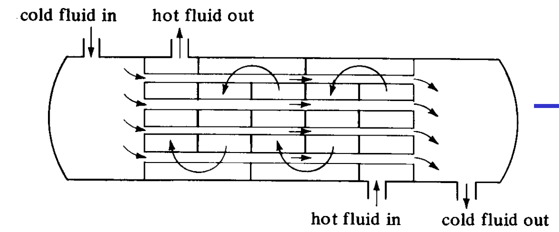
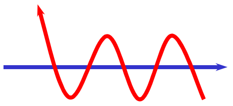
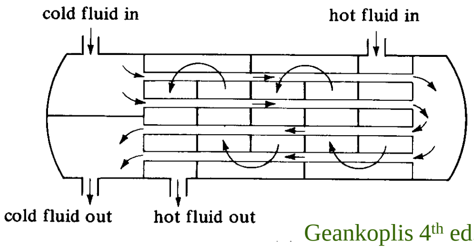
1-1 Shell and Tube Heat Exchanger

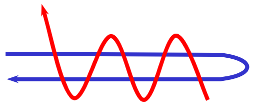




1 shell
1 tube

1-2 Shell and Tube Heat Exchanger





1 shell
2 tube

Geankoplis 4th ed., p292

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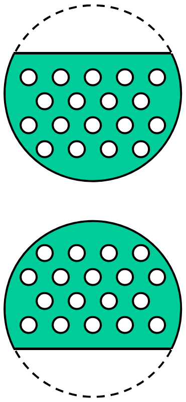
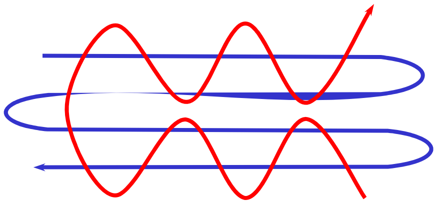
Cross Baffles in Shell-and-Tube Heat Exchangers



And other more complex arrangements:



2 shell
4 tube

For double-pipe heat exchanger:

$$\boxed{Q = UA\Delta T_{lm}}$$

For shell-and-tube heat exchangers:

$$Q = UA\underbrace{\left[\Delta T_{lm}(F_T)\right]}_{\equiv \Delta T_m}$$

calculated correction factor
(obtain from charts)

correct mean temperature difference for shell-and-tube heat exchangers

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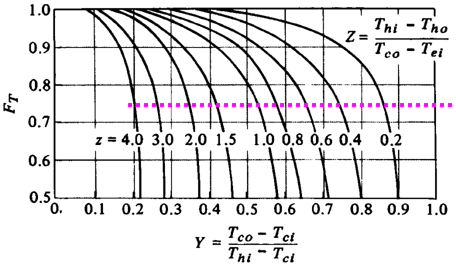
F_T
Shell-and-Tube Heat Exchangers

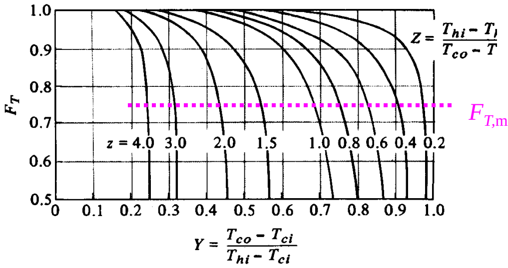
(1-1 exchanger, $F_T = 1$)

1-2



$F_{T,\min}$=0.75

2-4



$F_{T,\min}$=0.75

T_{hi} = hot, in
T_{ho} = hot, out
T_{ci} = cold, in
T_{co} = cold, out

Geankoplis 4th ed., p295

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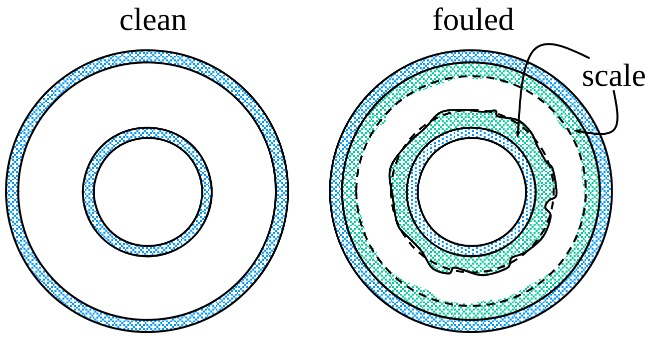
Heat Exchanger Fouling

- material deposits on hot surfaces
- rust, impurities
- strong effect when boiling occurs

scale adds an additional resistance to heat transfer



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Heat transfer resistances

$$U_{i\,or\,o} = \frac{\dfrac{1}{R_{i\,or\,o}}}{\dfrac{1}{h_iR_i} + \dfrac{1}{k}\ln\left(\dfrac{R_o}{R_i}\right) + \dfrac{1}{h_oR_o}}$$

resistance due to interface

resistance due to limited thermal conductivity

add effect of fouling

$$U_{i\,or\,o} = \frac{\dfrac{1}{R_{i\,or\,o}}}{\dfrac{1}{h_iR_i} + \dfrac{1}{h_{di}R_i} + \dfrac{1}{k}\ln\left(\dfrac{R_o}{R_i}\right) + \dfrac{1}{h_{do}R_o} + \dfrac{1}{h_oR_o}}$$

see Perry's Handbook, or Geankoplis 4th ed.
Table 4.9-1, page 300 for values of h_d

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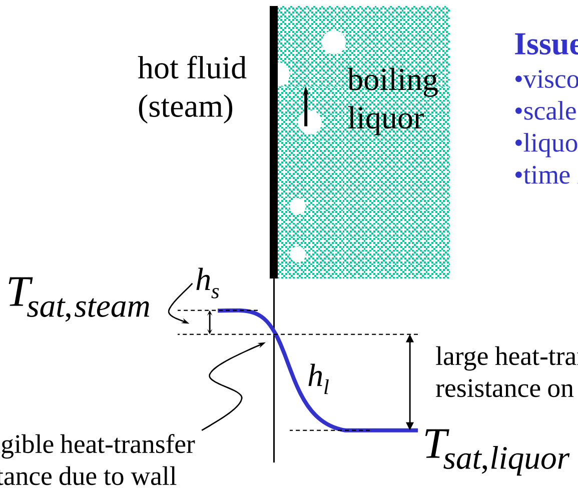
Evaporators



hot fluid (steam)

boiling liquor

$T_{sat,steam}$

h_s

h_l

large heat-transfer resistance on liquor-side

$T_{sat,liquor}$

negligible heat-transfer resistance due to wall

Issues:
- viscosity, μ
- scale formation
- liquor velocity
- time in evaporator

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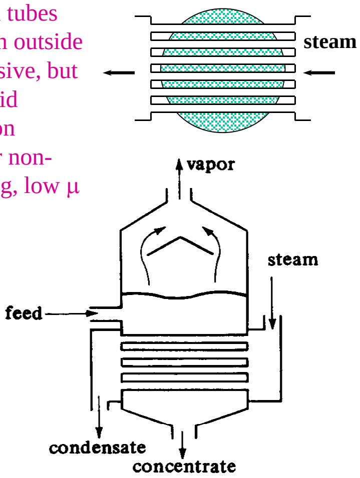
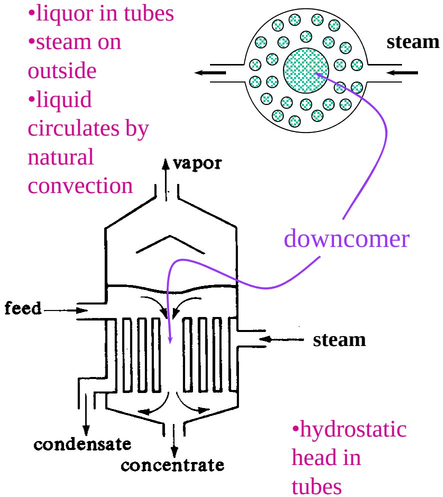
- steam in tubes
- liquor on outside
- inexpensive, but poor liquid circulation
- good for non-depositing, low μ fluids



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

Geankoplis, p492

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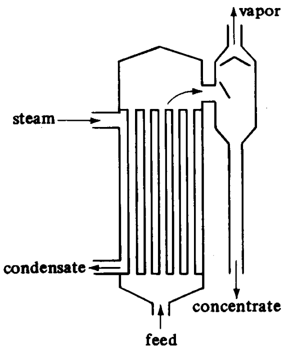
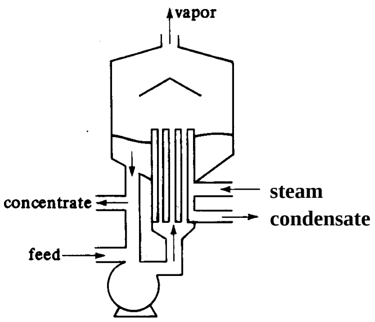
- liquor in tubes
- steam on outside
- liquid circulates by natural convection
- single pass
- high liquid velocities



long-tube vertical evaporator

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



forced-circulation evaporator

Geankoplis, p492

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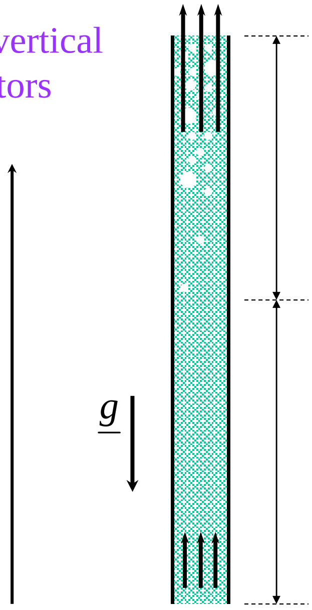
Long-tube vertical evaporators



decreasing $\bar{\rho}$
increasing $\bar{v}_z$

boiling, 2-phase zone

non-boiling zone

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Forced Convection

(turbulent; little or no vaporization)

Natural convection

(non-boiling zone)

$$\boxed{\mathrm{Nu} = 0.028\,\mathrm{Pr}^{\frac{1}{3}}\,\mathrm{Re}^{0.8}\left(\frac{\mu_{\mathrm{b}}}{\mu_{\mathrm{w}}}\right)^{0.14}}$$

$$\mathrm{Nu} = \frac{hD}{k} \qquad \mathrm{Re} = \frac{DV\rho}{\mu} \qquad \mathrm{Pr} = \frac{\hat{C}_p\mu}{k}$$

$$\mu^{0.33}\mu^{-0.8} = \mu.^{-0.47}$$

μ goes up, *h* goes down,

h does not depend on ΔT

Geankoplis, p495

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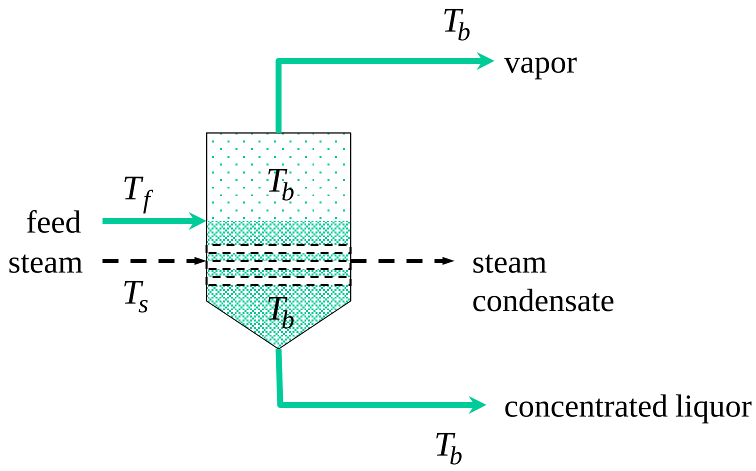
Single-Effect Evaporators


T_b

vapor

T_f

feed

steam

T_s

T_b

T_b

steam

condensate

concentrated liquor

T_b

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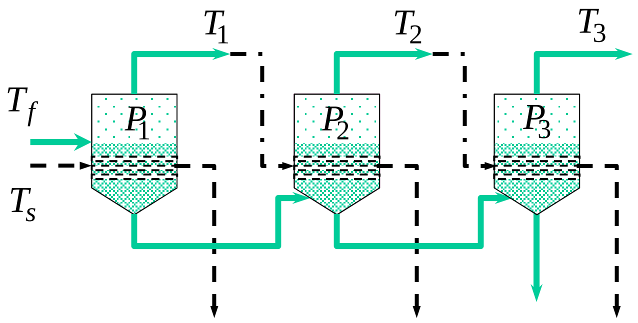
Multiple-Effect Evaporators

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

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



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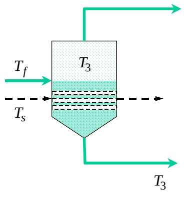
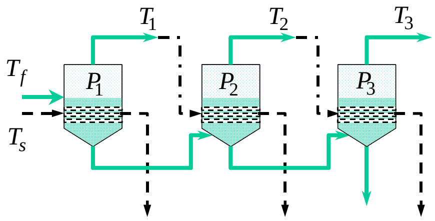
Compare Single- and Multiple-Effect Evaporators

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





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

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

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

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