CM3110
Transport I
Part II: Heat Transfer

Heat Transfer with Phase Change

Evaporators and Condensers

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

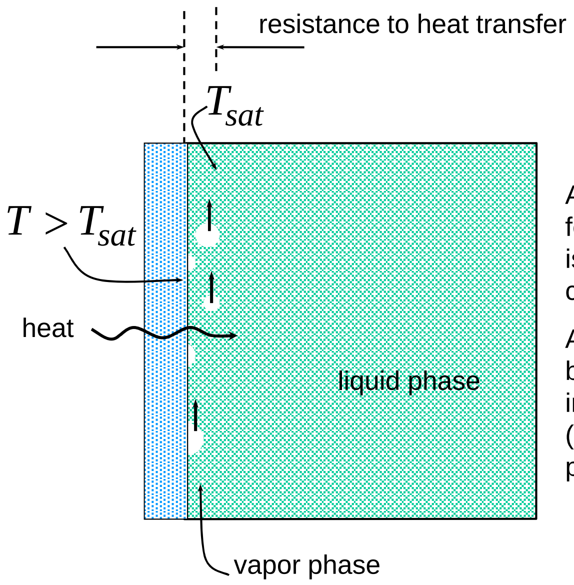
Newton's law of cooling

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.

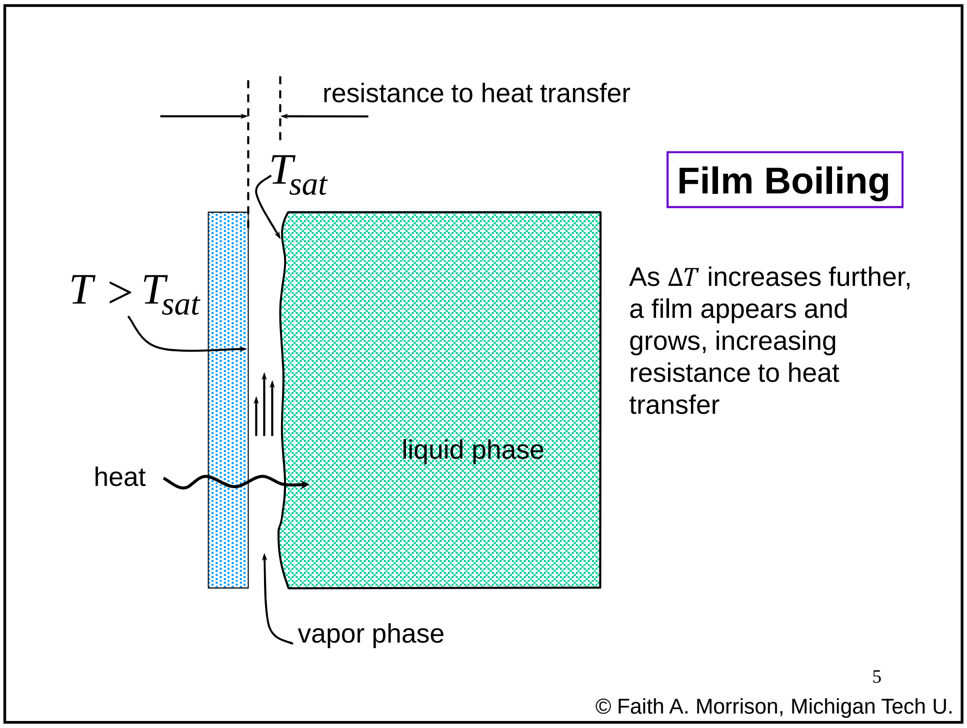
- Important in evaporation, distillation
- **LARGE** *h*
- It's important to know in which **regime** you operate
- Each regime has different correlations

Boiling



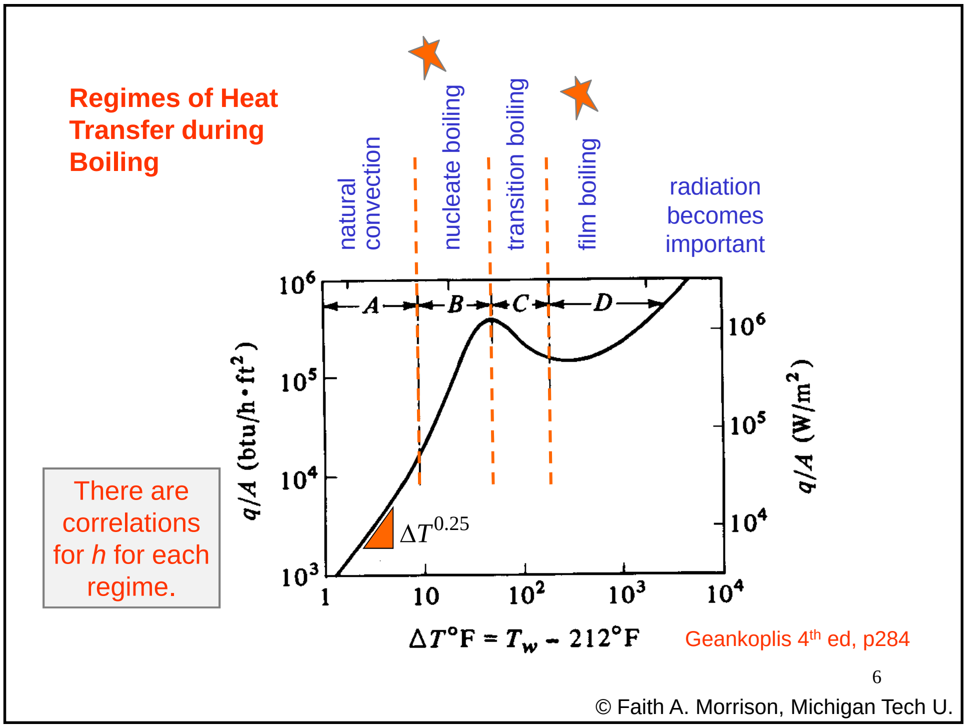
At low D*T*, few bubbles form, and heat transfer is by natural convection.

As D*T* 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

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

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

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

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

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

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:

$$\Delta T[=]K$$
$$\frac{q}{A}[=]\frac{kW}{m^2}$$
$$h[=]\frac{W}{m^2K}$$
$$p[=]kPa$$

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

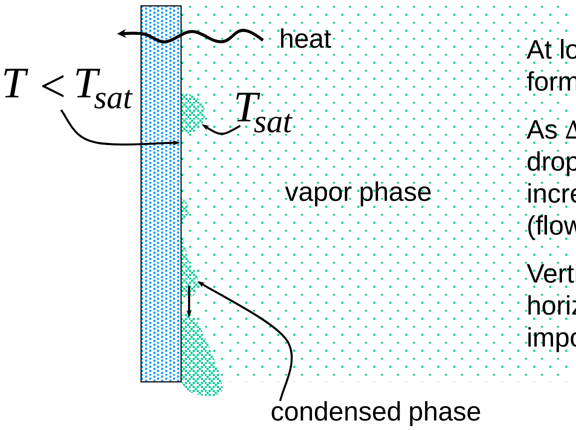
$$h = 0.62\left[\frac{\left(k_v^3\rho_v(\rho_l-\rho_v)g\left[\Delta H(T_{sat})+0.4\hat{C}_{p,v}\Delta T\right]\right)}{D\mu_v\Delta T}\right]^{\frac{1}{4}}$$

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



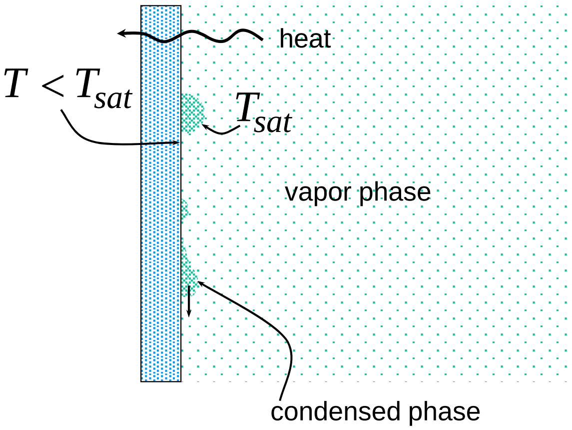
At low ΔT, few droplets form,

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

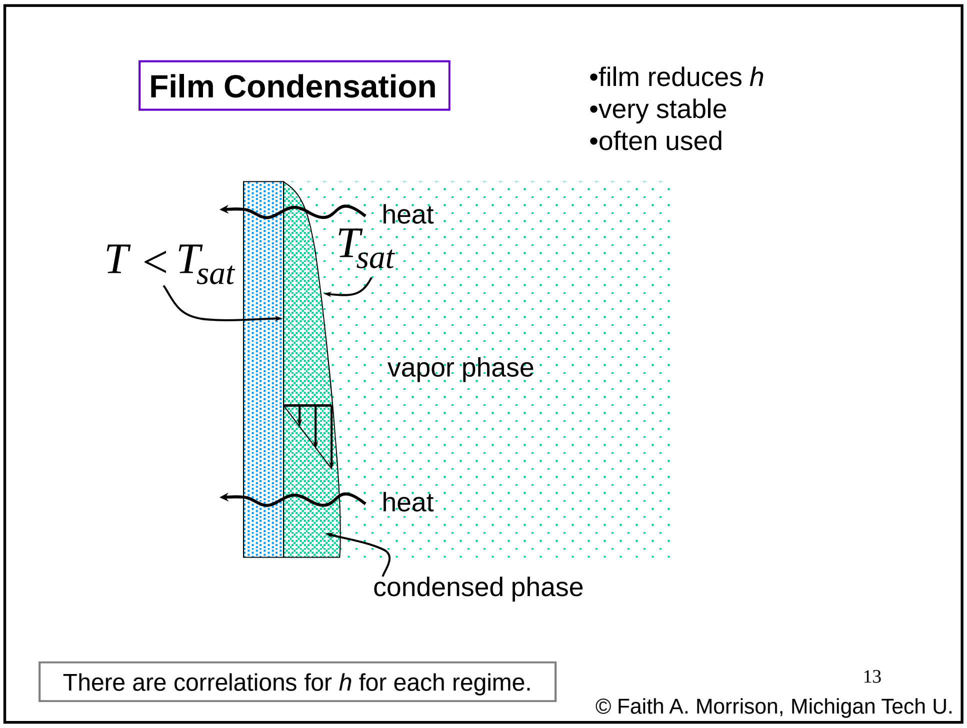
Vertical plates; horizontal tubes important

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:

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

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

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

$L[=]m$

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

$\mu_l[=]Pa\ s$

$g[=]m/s^2$

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

(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:

$\Delta T[=]K$

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

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

$T_{sat}[=]K$

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

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

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

$D[=]m$

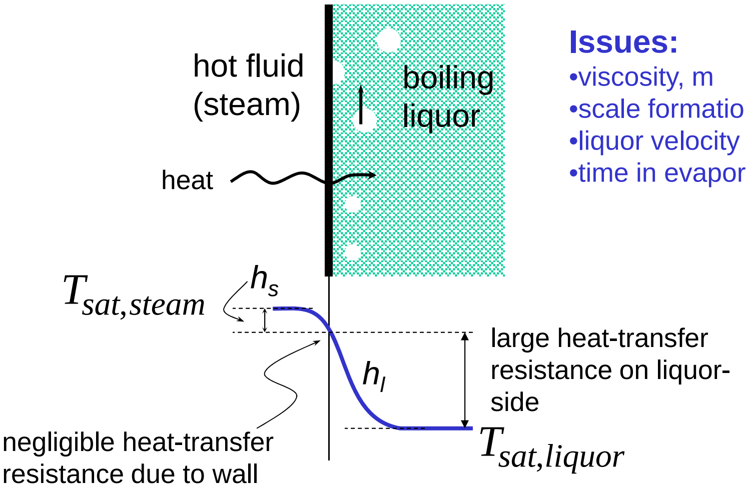
$\mu_l[=]Pa\ s$

$g[=]m/s^2$

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

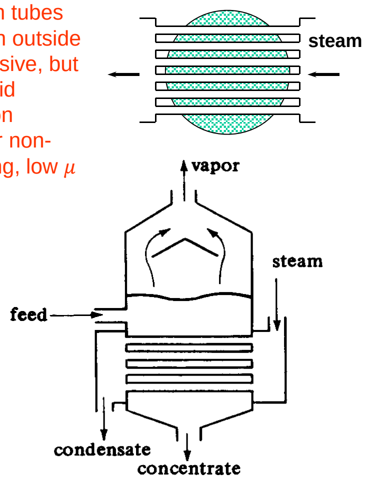
(All material properties at the film temperature)

Evaporators



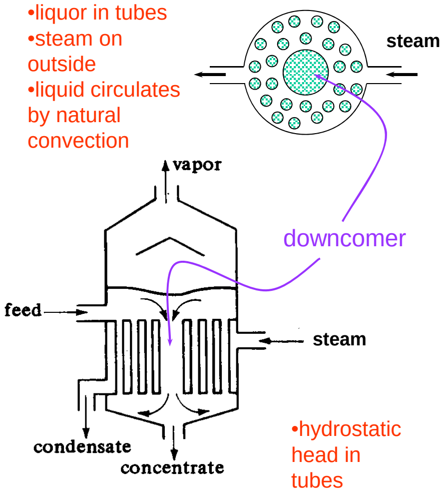
Issues:
- •viscosity, m
- •scale formation
- •liquor velocity
- •time in evaporator

- •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



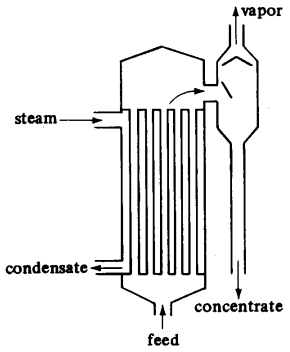
vertical-tube evaporator

- •hydrostatic head in tubes prevents boiling in tubes

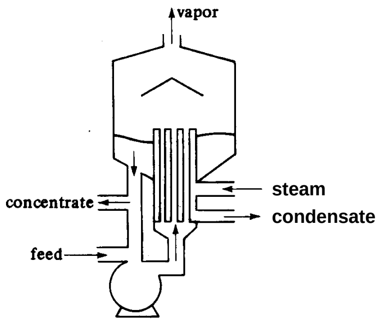
Geankoplis, p492

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

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



long-tube vertical evaporator



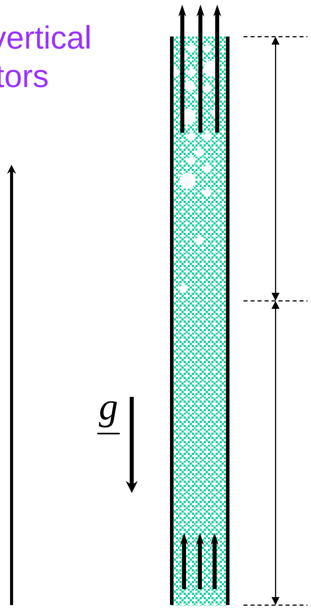
forced-circulation evaporator

Geankoplis, p492

Long-tube vertical evaporators

Decreasing $\bar{\rho}$

Increasing $\bar{v}_z$



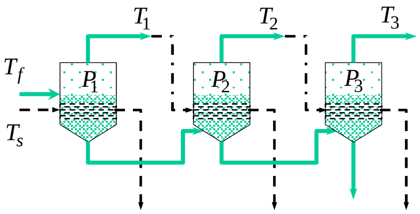
boiling, 2-phase zone

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

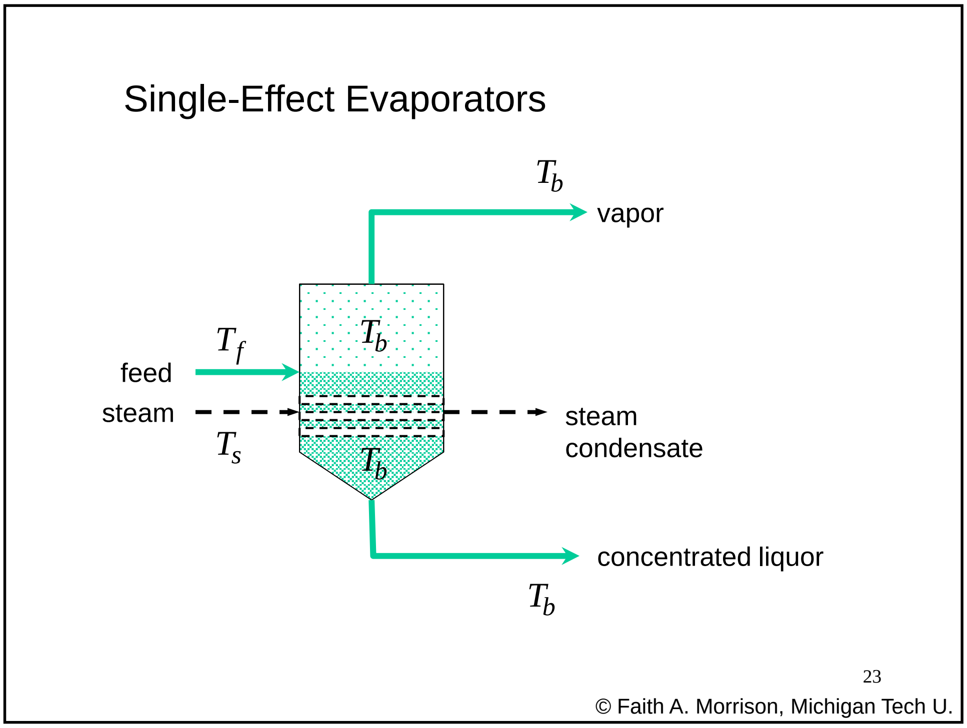
Norbert Rillieux (March 17, 1806 – October 8, 1894), a Creole American inventor and engineer, is most noted for his invention of the multiple-effect evaporator, an energy-efficient means of evaporating water. This invention was an important development in the growth of the sugar industry. Rillieux was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

Contents [hide]

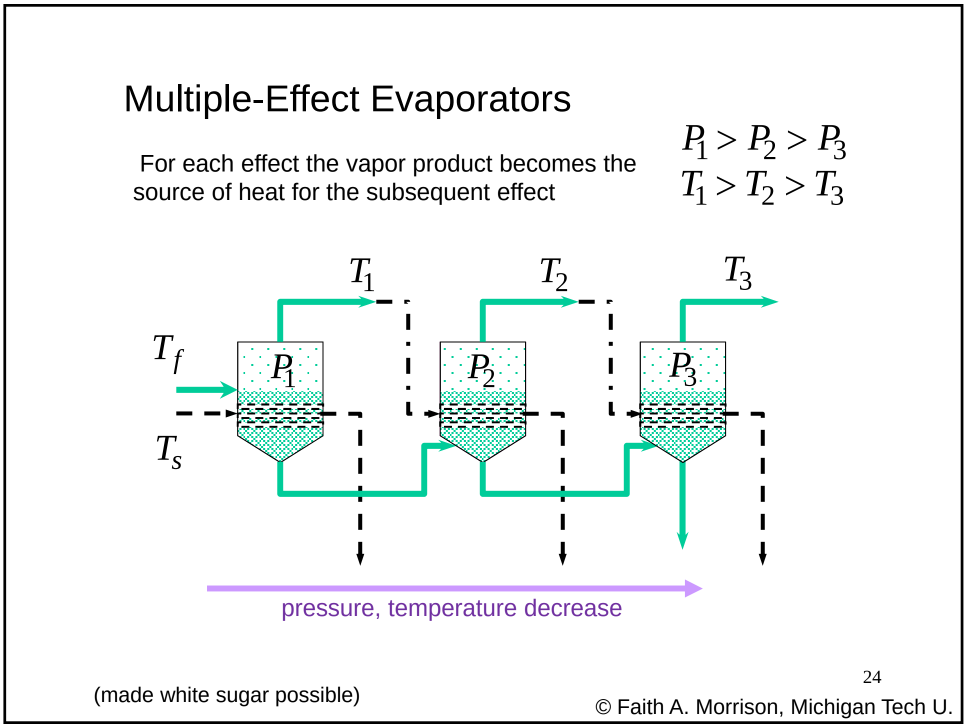
Norbert Rillieux in an undated photograph

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

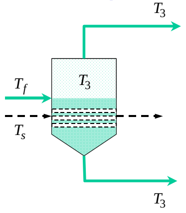
$P_1 > P_2 > P_3$

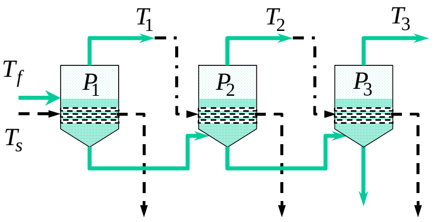
$T_1 > T_2 > T_3$

(made white sugar possible)

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)

(used in sugar production, for example)

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Summary

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

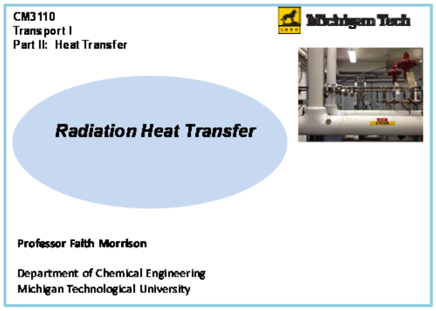
Condensation

- 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

Next:

- ~~Heat transfer with phase change~~
- ~~Evaporators~~
- Radiation
- *DONE*



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Radiation Heat Transfer

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