

CM3110
Transport I
Part II: Heat Transfer

MichiganTech

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

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

Newton's law of cooling

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

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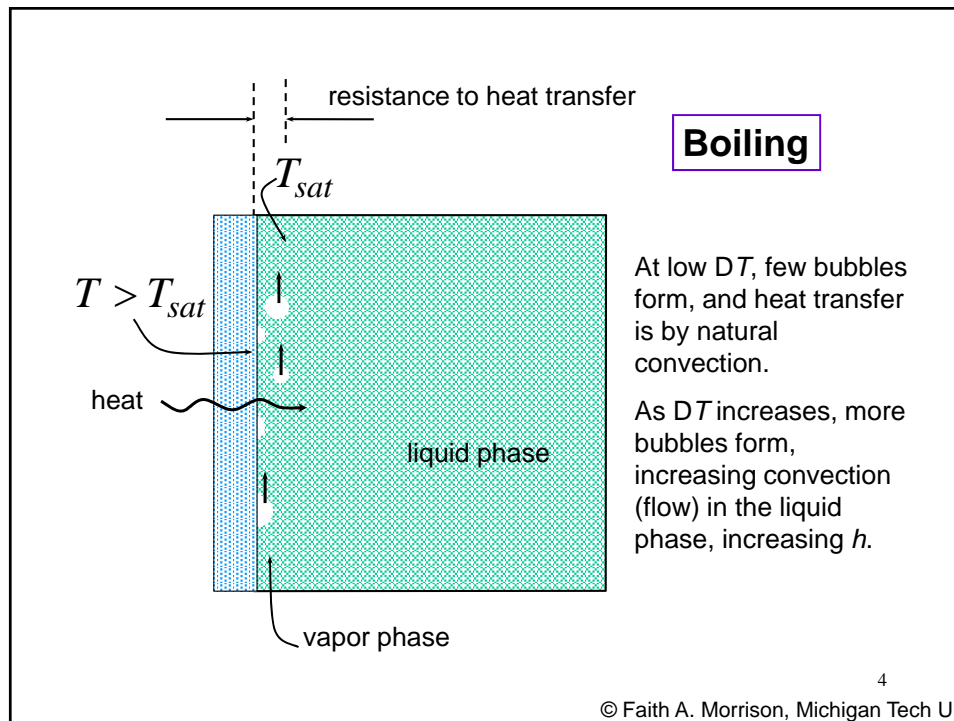
1. forced convection
 - laminar
 - turbulent
2. natural convection
3. phase change

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

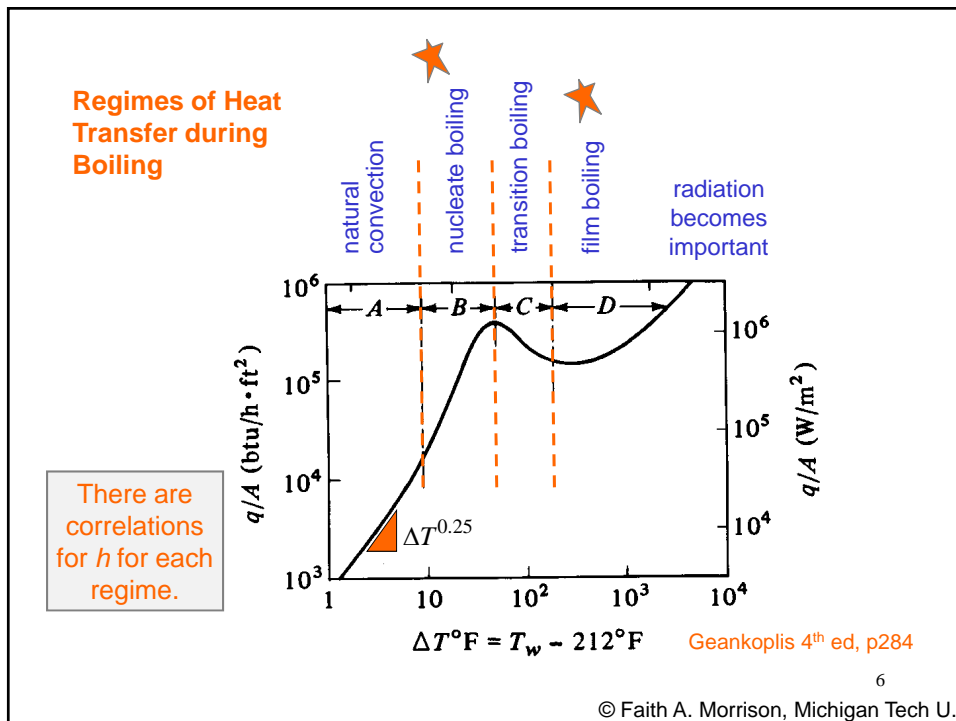
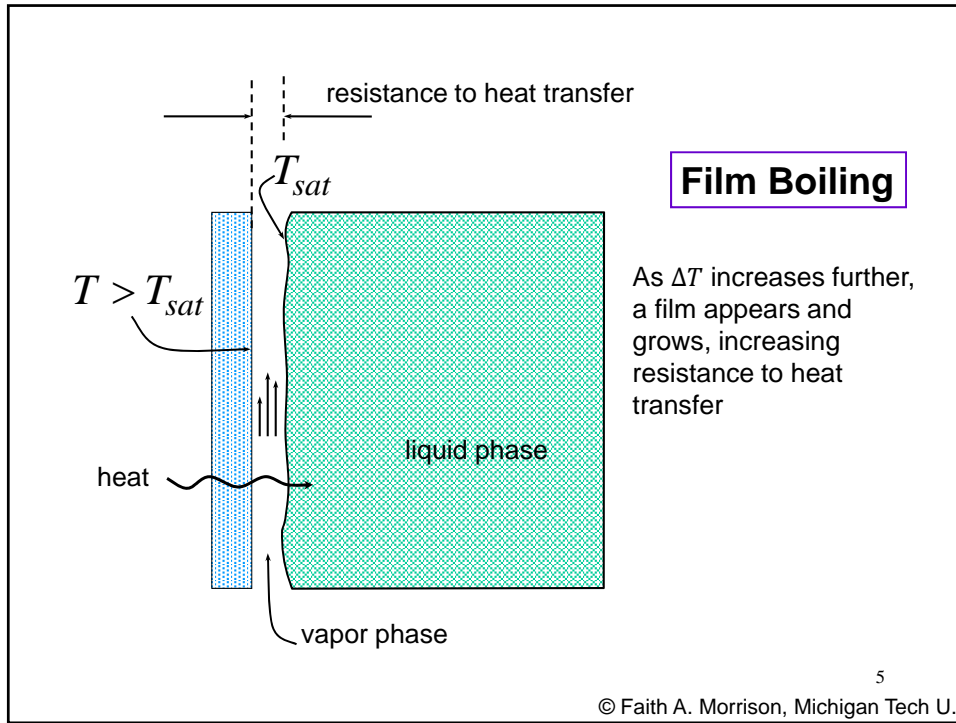
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Regimes of Heat Transfer during Boiling

There are correlations for h for each regime.

For example:
Nucleate boiling, horizontal surfaces

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

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

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
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Regimes of Heat Transfer during Boiling

There are correlations for h for each regime.

For example:
Nucleate boiling, vertical surfaces

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

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

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
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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

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Regimes of Heat Transfer during Boiling

There are correlations for h for each regime.

For example:
Film boiling, horizontal tubes

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

Equations good for these units:

$$\Delta T [=] K$$

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

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

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

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

$$D [=] m$$

$$\mu_v [=] Pa s$$

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

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

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

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Condensation

At low ΔT , few droplets form,

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

Vertical plates; horizontal tubes important

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Dropwise Condensation

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

There are correlations for h for each regime.

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Film Condensation

- film reduces h
- very stable
- often used

There are correlations for h for each regime.

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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

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

Equations good for these units:

$\Delta T [=] K$	$k_l [=] \frac{W}{mK}$	$\mu_l [=] Pa \cdot s$
$h [=] \frac{W}{m^2K}$	$\rho_v, \rho_l [=] \frac{kg}{m^3}$	$g [=] m/s^2$
$m [=] \frac{kg}{s}$	$\Delta H [=] \frac{J}{kg}$	$T_{film} = \frac{T_{wall} + T_{sat}}{2}$
	$L [=] m$	(All material properties at the film temperature)

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Regimes of Heat Transfer during Condensation

There are correlations for h for each regime.

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For example:

Film condensation, vertical surfaces, turbulent flow

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

Equations good for these units:

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

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

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

$$L [=] m$$

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

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

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

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

(All material properties at the film temperature)

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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

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

Equations good for these units:

$$\Delta T [=] K$$

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

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

$$T_{sat} [=] K$$

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

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

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

$$D [=] m$$

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

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

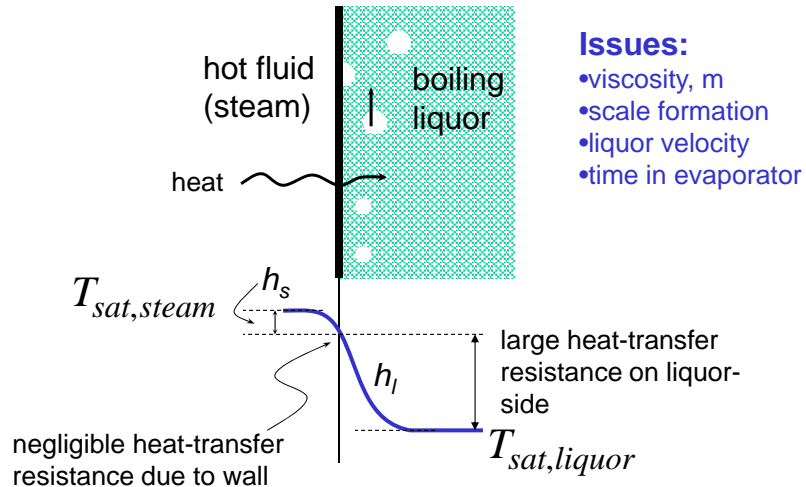
$$T_{film} = \frac{T_{wall} + T_{sat}}{2}$$

(All material properties at the film temperature)

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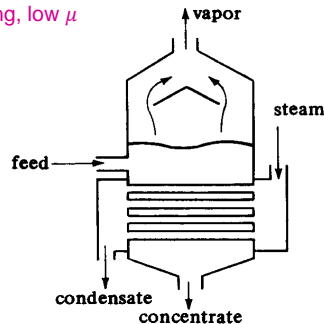
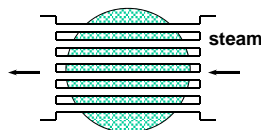
Evaporators



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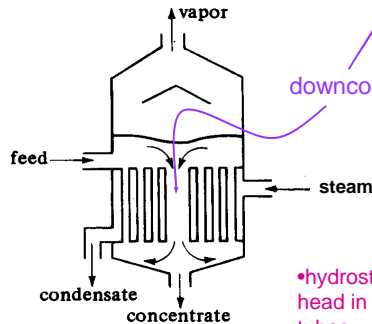
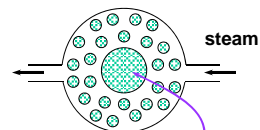
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- steam in tubes
- liquor on outside
- inexpensive, but poor liquid circulation
- good for non-depositing, low μ fluids



horizontal-tube evaporator

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



- hydrostatic head in tubes prevents boiling in tubes

vertical-tube evaporator

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 19

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Long-tube vertical evaporators

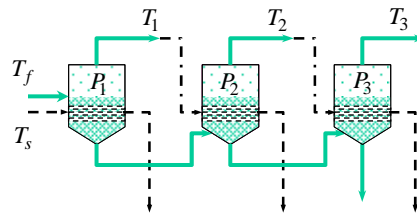
For discussion of how to estimate U , see Geankoplis 4th edition, p533

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

Multiple-Effect Evaporation

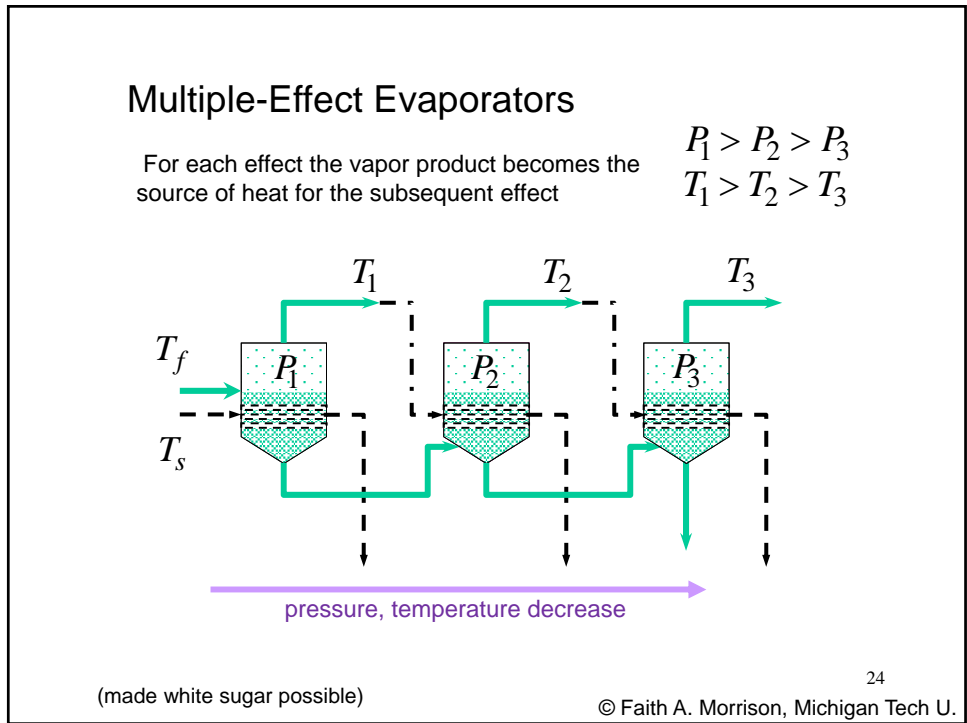
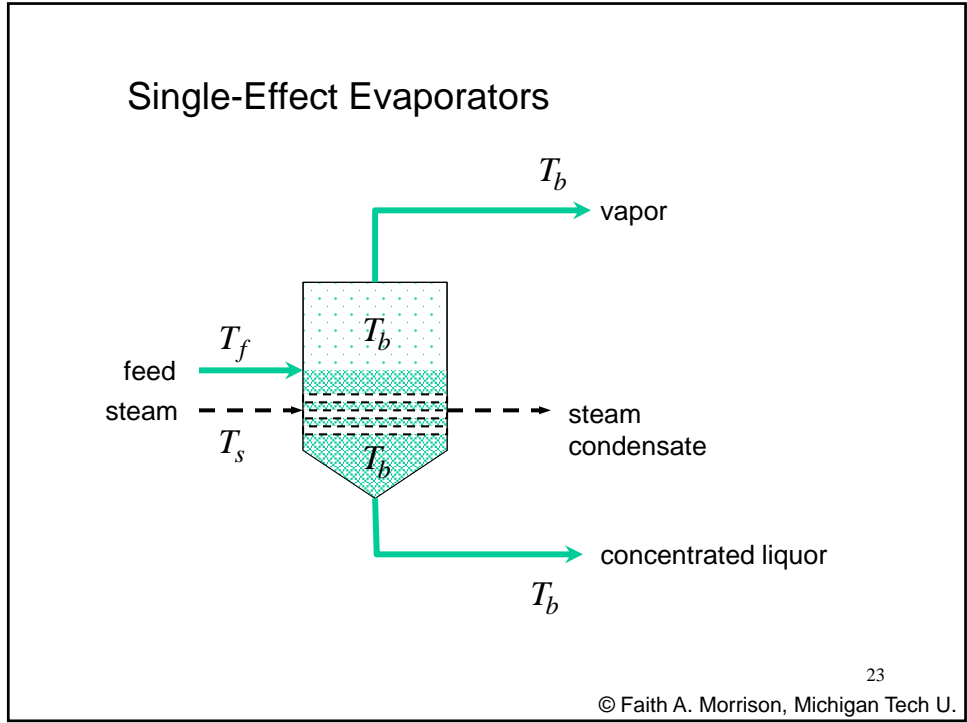


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Norbert Rillieux: Inventor of Multiple-Effect Evaporation

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(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


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Next:

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

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Radiation Heat Transfer

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