Topic 2.2. Evaporation

Last lecture

- ✓ Describe the process of evaporation
- ✓ Industrial examples of evaporation processes
- ✓ Properties that affect evaporation processes
- ✓ Types of evaporation equipment
- ✓

This lecture

- ✓ Explain how the overall heat transfer coefficient is calculated for evaporation
- ✓ Perform heat and material balances on evaporation units and processes

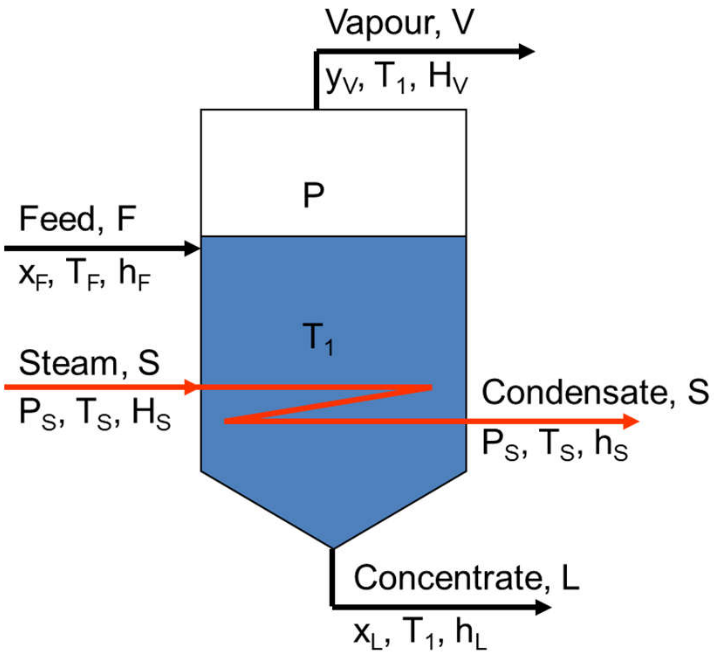
Methods of Evaporator Operations

1. Single-effect evaporators:

- The feed flowrate, F enters at T_F (K) and h_F. The concentrate flowrate, L leaves at solution boiling point, T_1 and h_L. The vapor leaves at the same temperature T_1 with saturated vapor enthalpy H_V

- The saturated vapor steam flowrate, S enters the heat exchanger at T_S and H_S and leaves at same temperature T_S with saturate liquid enthalpy h_S

- The evaporator pressure is P, which is the vapor pressure of the solution at T_1.

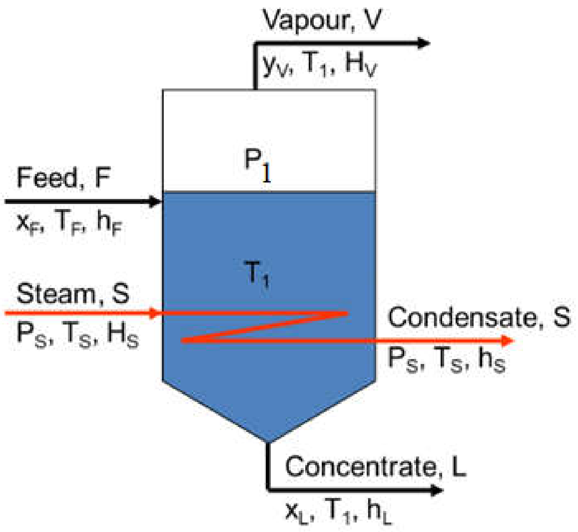


Used when the required capacity of operation is relatively small and/or the cost of steam is relatively cheap

The general design equation for the single-effect evaporator is

$$q = UA\,\Delta T = UA\,(T_S - T_1)$$

where q is the rate of heat transfer in W (btu/h), U is the overall heat-transfer coefficient in W/m^2 · K(btu/h · ft^2 · °F), A is the heat transfer area in m^2 (ft^2), T_S is the temperature of the condensing steam in K (°F), and T_1 is the boiling point of the liquid in K (°F).



Note that

- The steam provides only the latent heat, $\lambda = H_S - h_S$
- Vapor and liquid in evaporator are in equilibrium, the pressure P_1 is the saturation vapor pressure of the liquid of composition x_L at its boiling point T_1

Single-effect evaporators

- The total material balance across the evaporator

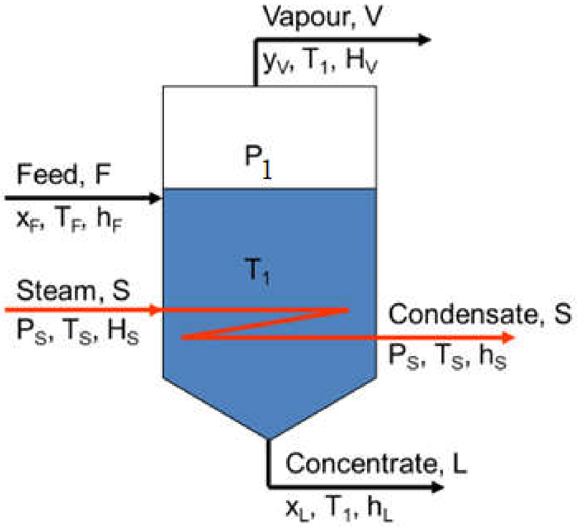
$$\boxed{F = L + V}$$

- The solute (solid) component balance

$$F\,x_F = L\,x_L + V y_V$$

Generally, there is no flow of solute with vapor

$$F\,x_F = L\,x_L + V y_V \quad \Rightarrow \quad \boxed{F\,x_F = L\,x_L}$$



- The heat balance across the evaporator

$$F\,h_F + S\,H_S = L\,h_L + V H_V + S\,h_S$$

Consider $\lambda = H_S - h_S$ and rearrange $\Rightarrow$ $\boxed{F\,h_F + S\,\lambda = L\,h_L + V H_V}$

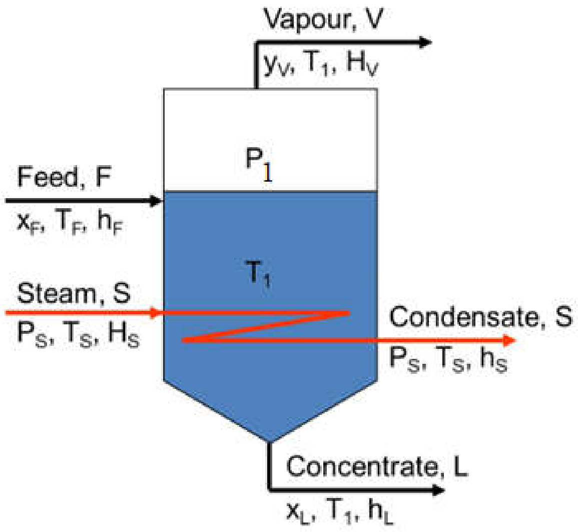
Single-effect evaporators

- The heat q transferred in the evaporator is

$$\boxed{q = S\,(H_S - h_S) = S\lambda}$$

The enthalpy of the feed, h_F can be approximated (assuming neglected heat of dilution) by

$$h_F = C_{PF}\left(T_F - T_{Ref.}\right)$$

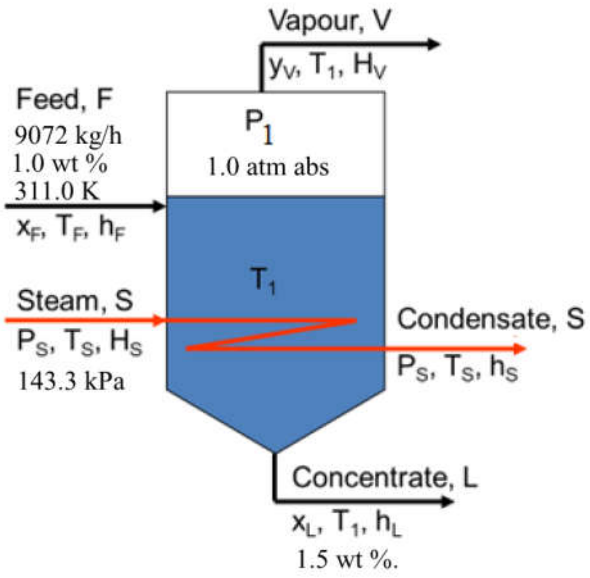


$$\text{Capacity} = \frac{\text{kg of vapor evaporated}}{\text{Time}} = m_V$$

$$\text{Economy} = \frac{\text{kg of vapor evaporated}}{\text{kg of steam used}} = \frac{m_V}{m_S}$$

Example 2.1 Heat-Transfer Area in a Single-Effect Evaporator

A continuous single-effect evaporator concentrates 9072 kg/h of a 1.0 wt % salt solution entering at 311.0 K (37.8°C) to a final concentration of 1.5 wt %. The vapor space of the evaporator is at 101.325 kPa (1.0 atm abs) and the steam supplied is saturated at 143.3 kPa. The overall coefficient $U = 1704$ W/m2 · K. Calculate the amounts of vapor and liquid product and the heat-transfer area required. Assume that the solution, since it is dilute, has the same boiling point as water.



Solution

$$F = L + V \quad \Rightarrow \quad 9072 = L + V$$

$$F\,x_F = L\,x_L \quad \Rightarrow \quad 9072\,(0.01) = L\,(0.015)$$

$$L = 6048 \;\; kg/h$$

$$9072 = 6048 + V$$

$$V = 3024 \;\; kg/h$$

○ For feeds of inorganic salts in water, the C_P can be assumed to be approximately that of water alone. Therefore, the specific heat of this feed is assumed to be $C_{PF} = 4.14 \frac{kj}{kg.K}$

○ Assume a reference temperature of *T*1 = 373.2 K (100°C), as the datum temperature. This temperature is the boiling point of water at 101.32 kPa.

Therefore, $h_L = 0 \frac{kj}{kg}$ as $h_L = C_{PL}(T_1 - T_{Ref.}) = C_{PL}(T_{Ref.} - T_{Ref.})$

○ The saturated vapor of the leaving water from top of the evaporator, H_V is the latent heat of vaporization according:

$$\lambda = H_V - h_L$$

○ The latent heat of vaporization is obtained from steam table at T1 = 373.2 K (100°C) and 101.32 kPa to be

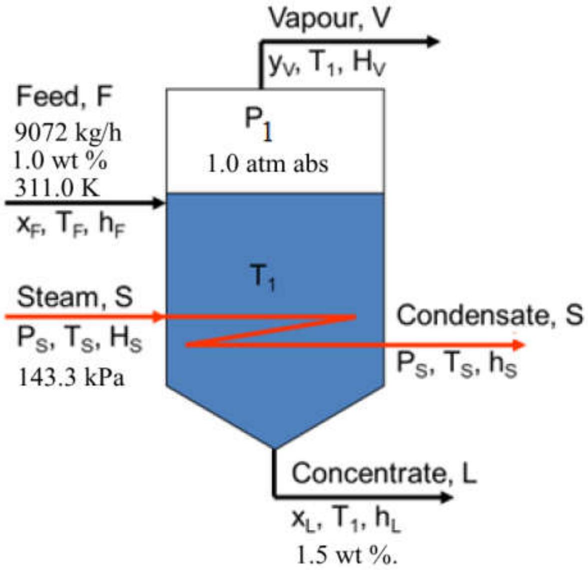
$$H_V = \lambda = 2257\ kJ/kg$$

- The latent heat λ of the steam at 143.3 kPa [saturation temperature TS = 383.2 K] is 2230 kJ/kg
- The enthalpy of the feed can be calculated from

$$h_F = C_{PF}\left(T_F - T_{Ref.}\right)$$

Then, the energy equation becomes:

$$\boxed{F\ h_F + S\ \lambda = L\ h_L + V H_V}$$



$$F C_{PF}\left(T_F - T_{Ref.}\right) + S\ \lambda = L(0) + V H_V$$

$$9072(4.14)(311 - 373.2) + S\ (2230) = L(0) + 3024\ (2257)$$

$$S = 4108\ kg/h$$

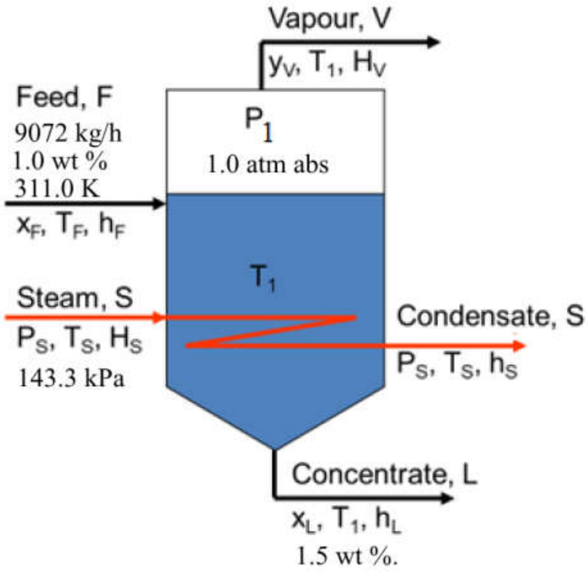
$$\boxed{q = S\ (H_S - h_S) = S\lambda = 4108\ (2230)\frac{1000}{3600} = 2{,}544{,}000\ W}$$

- Then, the required area is

$$q = UA\,\Delta T = UA\,(T_S - T_1)$$

$$2{,}544{,}000\ W = 1704\ W/m2{\cdot}K\ A\ (383.2\text{–}373.2)\ K$$

$$A = 149.3\ m^2$$



Steam economy = V / S = **3024/4108 = 0.73**

Example 2.2 Effect of feed temperature in a Single-Effect Evaporator

A continuous single-effect evaporator concentrates 9072 kg/h of a 1.0 wt % salt solution entering at 60ºC to a final concentration of 1.5 wt %. The vapor space of the evaporator is at 101.325 kPa and the steam supplied is saturated at 143.3 kPa. The overall coefficient U = 1704 W/m2.K.

Calculate the amounts of vapor and liquid products.

Data provided:

F = 9072 kg/h

x_F = 1 wt % = 0.01 kg solute / kg feed

T_F = 60 ºC

x_L = 1.5 wt % = 0.015 kg solute / kg liquid product

P = 101.325 kPa (1.0 atm abs)

P_S = 143.3 kPa

U = 1704 W/m^2.K

Solution

T_1 = saturated temperature at P (= 101.325 kPa) = 100ºC

T_S = saturated temperature at 143.3 kPa = 110 ºC

Data provided:

$F = 9072$ kg/h

$x_F = 0.01$ kg solute / kg feed

$T_F = 38°C$

$x_L = 0.015$ kg solute / kg liquid product

$P = 101.325$ kPa; $T_1 = 100°C$

$P_S = 143.3$ kPa; $T_S = 110$ °C

$U = 1704$ W/m^2.K

Available equations:

Overall material balance:

$F = L + V$

Solute balance:

$F\ x_F = L\ x_L$ (no solute in the vapor)

Heat balance:

$F\ h_F + S\ \lambda = L\ h_L + V\ H_V$

where $\lambda = H_S - h_S$

$q = S\ \lambda = U\ A\ \Delta T = U\ A\ (T_S - T_1)$

Overall material balance:

$F = L + V$ (1)

Solute mass balance:

$F\ x_F = L\ x_L$ (no solute in the vapor) (2)

Solve Eqns. (1) and (2) to have :

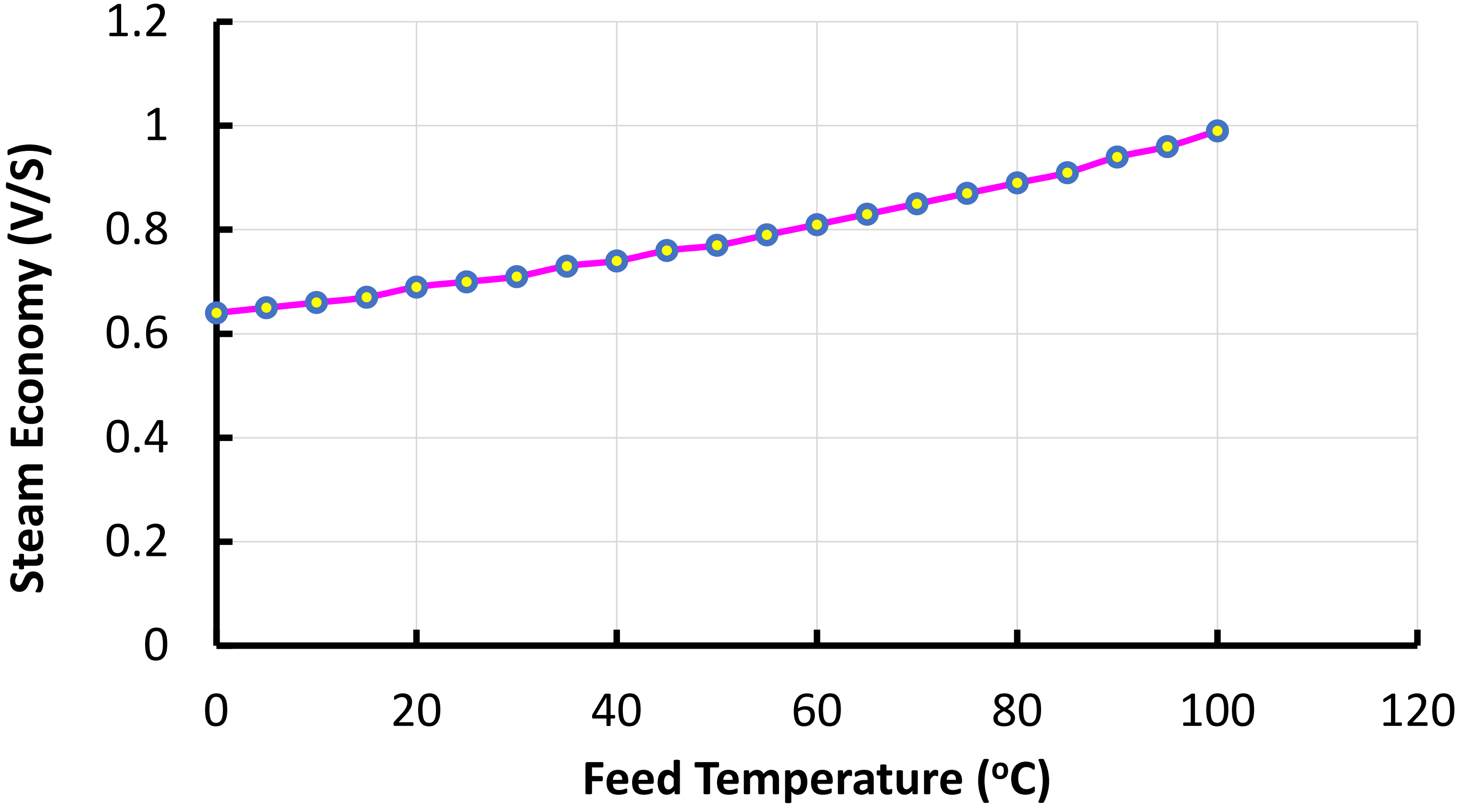
L = 6048 kg/h

V = 3024 kg/h

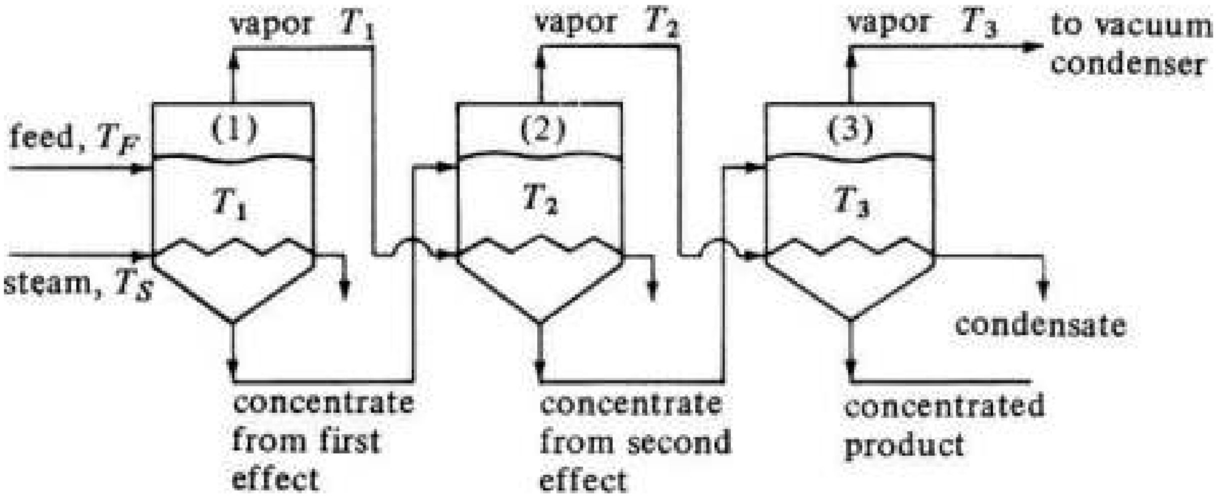
$$\boldsymbol{S = 3734\ kg/h}$$

Steam economy = V / S = **3024/3734 = 0.81**

Effect of feed temperature on the steam economy in Single-effect evaporators:

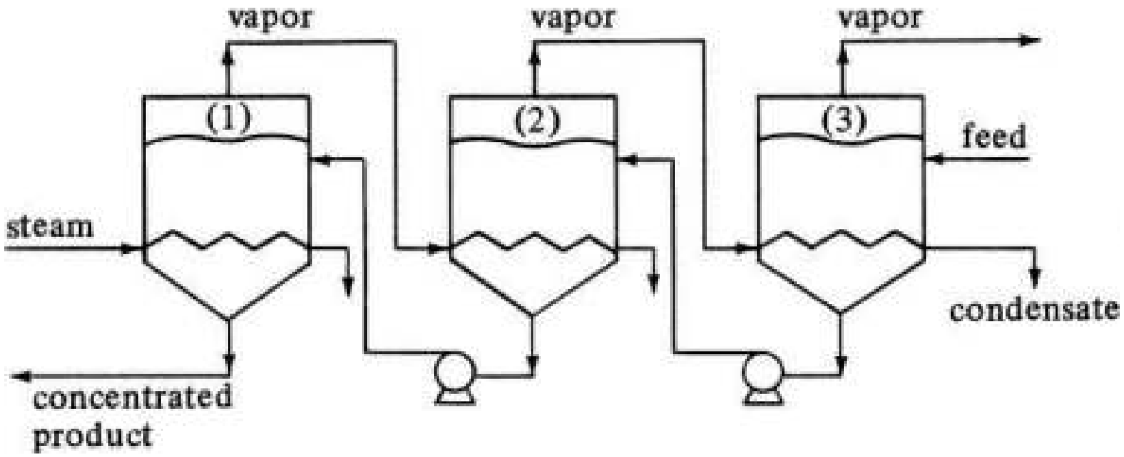


2. Forward-feed multiple-effect evaporators:



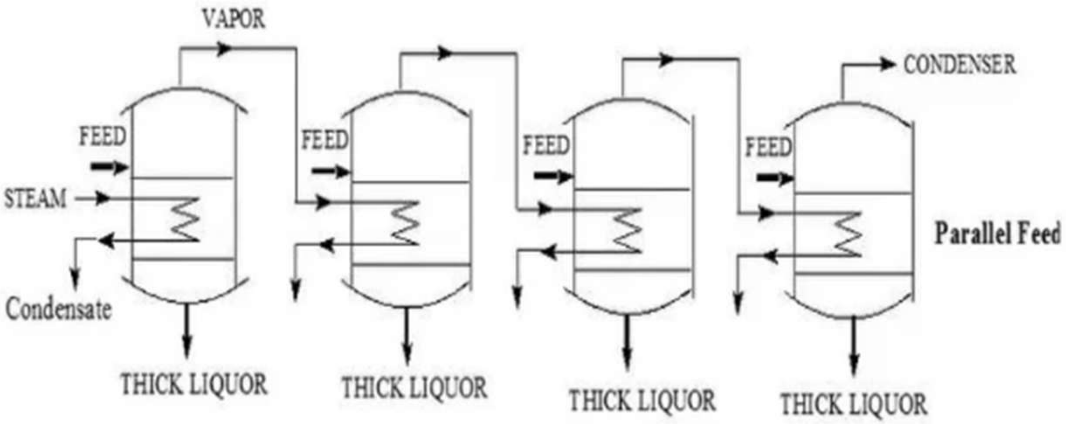
- Latent heat is recovered and reused by employing a multiple-effect evaporator
- The first effect operates at a temperature high enough so that the evaporated water serves as the heating medium to the second effect
- Almost 3 kg of water will be evaporated for 1 kg of steam for system of 3 evaporators. the steam economy is increased

2. Backward-feed multiple-effect evaporators:



- This method of reverse feed is advantageous when the fresh feed is cold
- liquid pumps must be used in each effect, since the flow is from low to high pressure
- Used when the concentrated product is highly viscous

3. Parallel-feed multiple-effect evaporators:



- The addition of fresh feed and the withdrawal of the concentrated product from each effect.
- The vapor from each effect is still used to heat the next effect.
- This method of operation is mainly used when the feed is almost saturated and solid crystals are the product, as in the evaporation of brine to make salt.

Overall Heat-Transfer Coefficients in Evaporators

The overall heat-transfer coefficient U in an evaporator is a function of the following:

1. The steam-side condensing coefficient outside tubes, which has a value of about 5700 W/m^2
2. The metal wall thermal resistance
3. The resistance of the scale on the liquid side
4. The liquid film coefficient inside tubes

Based on *"inside tubes flow"* $U_i = \dfrac{1}{\dfrac{1}{h_i}+\dfrac{1}{h_{di}}+\dfrac{d_i \ln(d_o/d_i)}{2k_w}+\dfrac{d_i}{d_o h_{do}}+\dfrac{d_i}{d_o h_o}}$

Or based on *"outside tubes flow"* $U_o = \dfrac{1}{\dfrac{1}{h_o}+\dfrac{1}{h_{do}}+\dfrac{d_o \ln(d_o/d_i)}{2k_w}+\dfrac{d_o}{d_i h_i}+\dfrac{d_o}{d_i h_{di}}}$

1. The steam-side condensing heat transfer coefficient:

- For vertical surfaces in laminar flow (Re < 1800)

$$N_{Re} = \frac{4m}{\pi D \mu_l}$$

m is the total mass of condensate a tube (kg)

$$N_{Nu} = \frac{hD}{k_l} = 0.725\left(\frac{\rho_l(\rho_l - \rho_v) g h_{fg} D^3}{N \mu_l k_l \Delta T}\right)^{1/4}$$

ρ_l is the density of liquid in kg/m^3 and ρ_v, that of the vapor, g is 9.8066 m/s^2
L is the vertical height of the surface or tube in m, μ_l is the viscosity of liquid in Pa·s
k_l is the liquid thermal conductivity in W/m·K, $\Delta T = T_{sat} - T_w$ in K
h_{fg} is the latent heat of condensation in J/kg at T_{sat}.
N is the number of horizontal tubes

All physical properties of the liquid except h_{fg} are evaluated at the film temperature $T_f = (T_{sat} + T_w)/2$

Overall Heat-Transfer Coefficients in Evaporators

1. The steam-side condensing heat transfer coefficient:

- For horizontal surfaces in laminar flow (Re < 1800)

$$N_{Re} = \frac{4m}{A\,\mu_l}$$

m is the total mass of condensate a tube (kg)
A is the area of horizontal surface

$$Nu = \frac{h\,L}{k_L} = 1.13\left[\frac{\rho_L(\rho_L - \rho_V)\,g\,\lambda\,L^3}{\mu_L\,k_L\,\Delta T}\right]^{0.25}$$

ρ_l is the density of liquid in kg/m^3 and ρ_v, that of the vapor, g is 9.8066 m/s^2
L is the vertical height of the surface or tube in m, μ_l is the viscosity of liquid in Pa·s
k_l is the liquid thermal conductivity in W/m·K, $\Delta T = T_{sat} - T_w$ in K
h_{fg} is the latent heat of condensation in J/kg at T_{sat}.

All physical properties of the liquid except h_{fg} are evaluated at the film temperature $T_f = (T_{sat} + T_w)/2$

Overall Heat-Transfer Coefficients in Evaporators

1. **The steam-side condensing heat transfer coefficient:**

- For vertical surfaces in Turbulent flow (Re > 1800)

$$N_{Nu} = \frac{hL}{k_l} = 0.0077 \left(\frac{g\rho_l^2 L^3}{\mu_l^2}\right)^{1/3} (N_{Re})^{0.4}$$

$$N_{Re} = \frac{4m}{\pi D \mu_l}$$

m is the total mass of condensate a tube (kg)

The solution of this equation is by trial and error since a value of N_{Re} must first be assumed in order to calculate h

ρ_l is the density of liquid in kg/m^3 and ρ_v, that of the vapor, g is 9.8066 m/s^2

L is the vertical height of the surface or tube in m, μ_l is the viscosity of liquid in Pa·s

k_l is the liquid thermal conductivity in W/m·K, $\Delta T = T_{sat} - T_w$ in K

h_{fg} is the latent heat of condensation in J/kg at T_{sat}.

All physical properties of the liquid except h_{fg} are evaluated at the film temperature $T_f = (T_{sat} + T_w)/2$

2. The solution-side heat transfer coefficient:

- For forced-circulation evaporators
- For short-tube vertical natural-circulation evaporators
- For long-tube vertical natural-circulation evaporators

$$\mathrm{Nu} = 0.028\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3}\left(\frac{\mu_m}{\mu_w}\right)^{0.14} \qquad 0.7 \le \mathrm{Pr} \le 16,700, \qquad \mathrm{Re} \ge 10^4, \qquad L/d_w \ge 60$$

- For the agitated-film evaporator

$$\frac{hd_v}{k} = c_1\left(\frac{C_p\mu}{k}\right)^{c_2}\left(\frac{(d_v - d_r)u\rho}{\mu}\right)\left(\frac{d_vN}{u}\right)^{0.82}\left(\frac{d_r}{d_v}\right)^{0.55}(n_B)^{0.53}$$

for cooling viscous liquids $c_1 = 0.014$ and $c_2 = 0.96$,

for thin mobile liquids $c_1 = 0.039$ and $c_2 = 0.70$.

d_v is the diameter of the vessel

d_r is the diameter of the rotor

u is the average axial velocity

N is the agitator speed

n_B is number of blades on the agitator

TABLE 8.3-1. *Typical Heat-Transfer Coefficients for Various Evaporators** *(B3, B4, L1, P2)*

Type of Evaporator	Overall U	
	$W/m^2 \cdot K$	$Btu/h \cdot ft^2 \cdot °F$
Short-tube vertical, natural circulation	1100–2800	200–500
Horizontal-tube, natural circulation	1100–2800	200–500
Long-tube vertical, natural circulation	1100–4000	200–700
Long-tube vertical, forced circulation	2300–11 000	400–2000
Agitated film	680–2300	120–400
Agitated-film evaporator, newtonian liquid, viscosity		
1 cP	2000	400
1 P	1500	300
100 P	600	120

* Generally, nonviscous liquids have the higher coefficients and viscous liquids the lower coefficients in the ranges given.

Effects of processing variables on evaporator operation

Effect of feed temperature:

- The inlet temperature of the feed has a large effect on the evaporator operation.
- When feed is not at its boiling point, steam is needed first to heat the feed to its boiling point and then to evaporate it.
- Preheating the feed can reduce the size of evaporator heat-transfer area.

Effect of steam pressure:

- High pressure provides high Ts values, and hence TS – T1 will increase.
- High pressure steam is however more costly.
- Therefore, overall cost analysis must be considered to determine the optimum steam pressure.

Effects of processing variables on evaporator operation

Effect of pressure:

- Pressure in the evaporator sets the boiling point of the solution (T1).
- Steam pressure determines the steam temperature (Ts)
- Since $q = U A (TS - T1)$, larger values of $(TS - T1)$ will help reduce the heat-transfer area needed and hence the cost of evaporator.
- Vacuum can be maintained in the solution side using a vacuum pump.

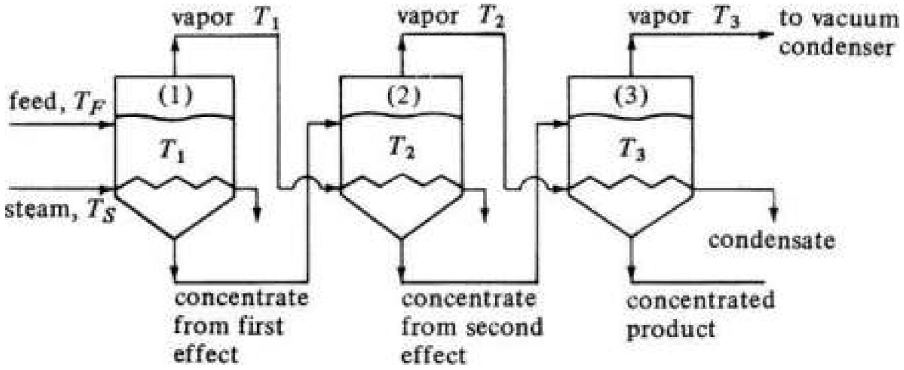
Temperature Drops and Capacity of Multiple-Effect Evaporators

The general design equation for the multi-effect forward evaporator is

$$q_1 = U_1 A_1 \Delta T_1 \qquad q_2 = U_2 A_2 \Delta T_2 \qquad q_3 = U_3 A_3 \Delta T_3$$

Assumption

- The Assuming that the solutions have no boiling point rise and no heat of solution, and neglecting the sensible heat necessary to heat the feed to the boiling point.
- Approximately all the latent heat of the condensing steam appears as latent heat in the vapor.
- This vapor then condenses in the second effect, giving up approximately the same amount of heat:



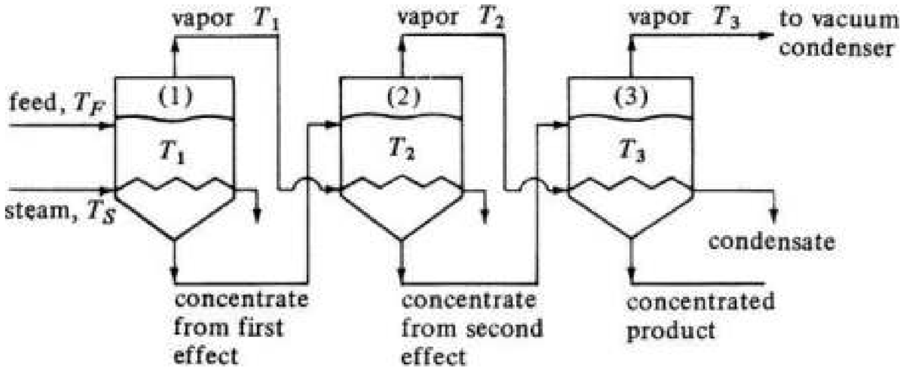
Forward-feed multiple-effect evaporators

Then, the heat transfer into the 1st evaporator equals to that of other evaporators

$$q_1 = q_2 = q_3 \quad \Rightarrow \quad U_1\, A_1\, \Delta T_1 = U_2\, A_2\, \Delta T_2 = U_3\, A_3\, \Delta T_3$$

Assuming all areas are equal

$$\Rightarrow \quad \frac{q}{A} = U_1\, \Delta T_1 = U_2\, \Delta T_2 = U_3\, \Delta T_3$$



For no boiling-point rise

$$\sum \Delta T = \Delta T_1 + \Delta T_2 + \Delta T_3 = T_S - T_3$$

Since ΔT_1 is proportional to $\frac{1}{U_1}$, then

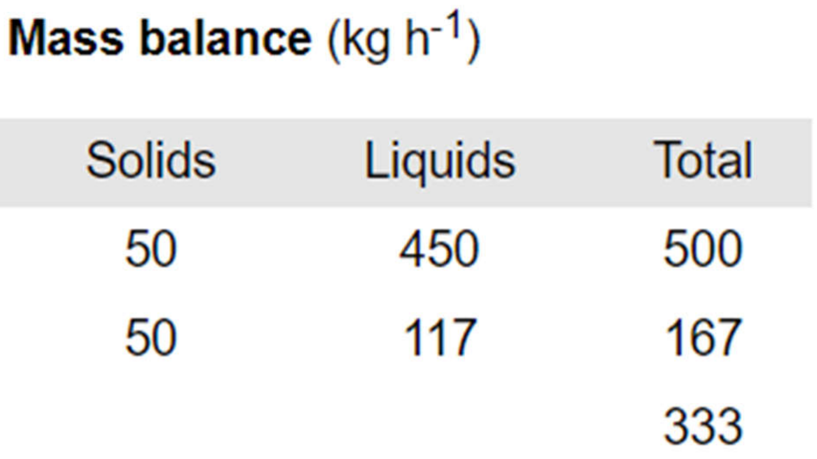
$$\Delta T_1 = \sum \Delta T \frac{1/U_1}{1/U_1 + 1/U_2 + 1/U_3}$$

Similar equations can be written for ΔT_2 and ΔT_3

Example 2.3 Triple effect evaporators: steam usage and heat transfer surface

Estimate the evaporating temperatures in each effect, for a triple effect evaporator evaporating 500 kg/h of a 10% solution up to a 30% solution. Steam is available at 200 kPa gauge and the pressure in the evaporation space in the final effect is 60 kPa absolute. Assume that the overall heat transfer coefficients are 2270, 2000 and 1420 $J/m^2 \cdot s.°C$ in the first, second and third effects respectively. Neglect sensible heat effects and assume no boiling-point elevation, and assume equal heat transfer in each effect.

Solution



Mass balance ($kg\ h^{-1}$)

	Solids	Liquids	Total
Feed	50	450	500
Product	50	117	167
Evaporation			333

Heat balance

From steam tables, the condensing temperature of steam at 200 kPa (g) is 134°C and the latent heat is 2164 kJ kg $^{-1}$. Evaporating temperature in final effect under pressure of 60 kPa (abs.) is 86°C, as there is no boiling-point rise and latent heat is 2294 kJ kg^{-1}.

$$q_1 = q_2 = q_3$$

$$U_1\ A_1\ \Delta T_1 = U_2\ A_2\ \Delta T_2 = U_3\ A_3\ \Delta T_3$$

$$\sum \Delta T = \Delta T_1 + \Delta T_2 + \Delta T_3 = T_S - T_3$$

⇨

Equating the heat transfer in each effect:

$$q_1 = q_2 = q_3$$

$$U_1A_1\Delta T_1 = U_2A_2\ \Delta T_2 = U_3A_3\Delta T_3$$

And $\Delta T_1 + \Delta T_2 + \Delta T_3 = (134 - 86) = 48$°C.

Now, if $A_1 = A_2 = A_3$

then $\Delta T_2 = U_1\Delta T_1 / U_2$ and $\Delta T_3 = U_1\Delta T_1 / U_3$

so that $\Delta T_1(1 + U_1/U_2 + U_1/U_3) = 48$,

⇨

$$\Delta T_1 \times [1 + (2270/2000) + (2270/1420)] = 48$$

$$3.73\Delta T_1 = 48$$

$$\Delta T_1 = 12.9°\text{C},$$

$$\Delta T_2 = \Delta T_1 \times (2270/2000) = 14.6°\text{C}$$

$$\Delta T_3 = \Delta T_1 \times (2270/1420) = 20.6°\text{C}$$

And so the evaporating temperature:

- in first effect is (134 - 12.9) = 121°C; latent heat (from Steam Tables) 2200 kJ kg^{-1}.
- in second effect is (121 - 14.6) = 106.5°C; latent heat 2240 kJ kg^{-1}
- in the third effect is (106.5 - 20.6) = 86°C, latent heat 2294 kJ kg^{-1}

Boiling-Point Rise of Solutions

The solutions inside the evaporator are not diluted, hence their thermal properties differ considerably from those of water, and change with the amount of water being removed.

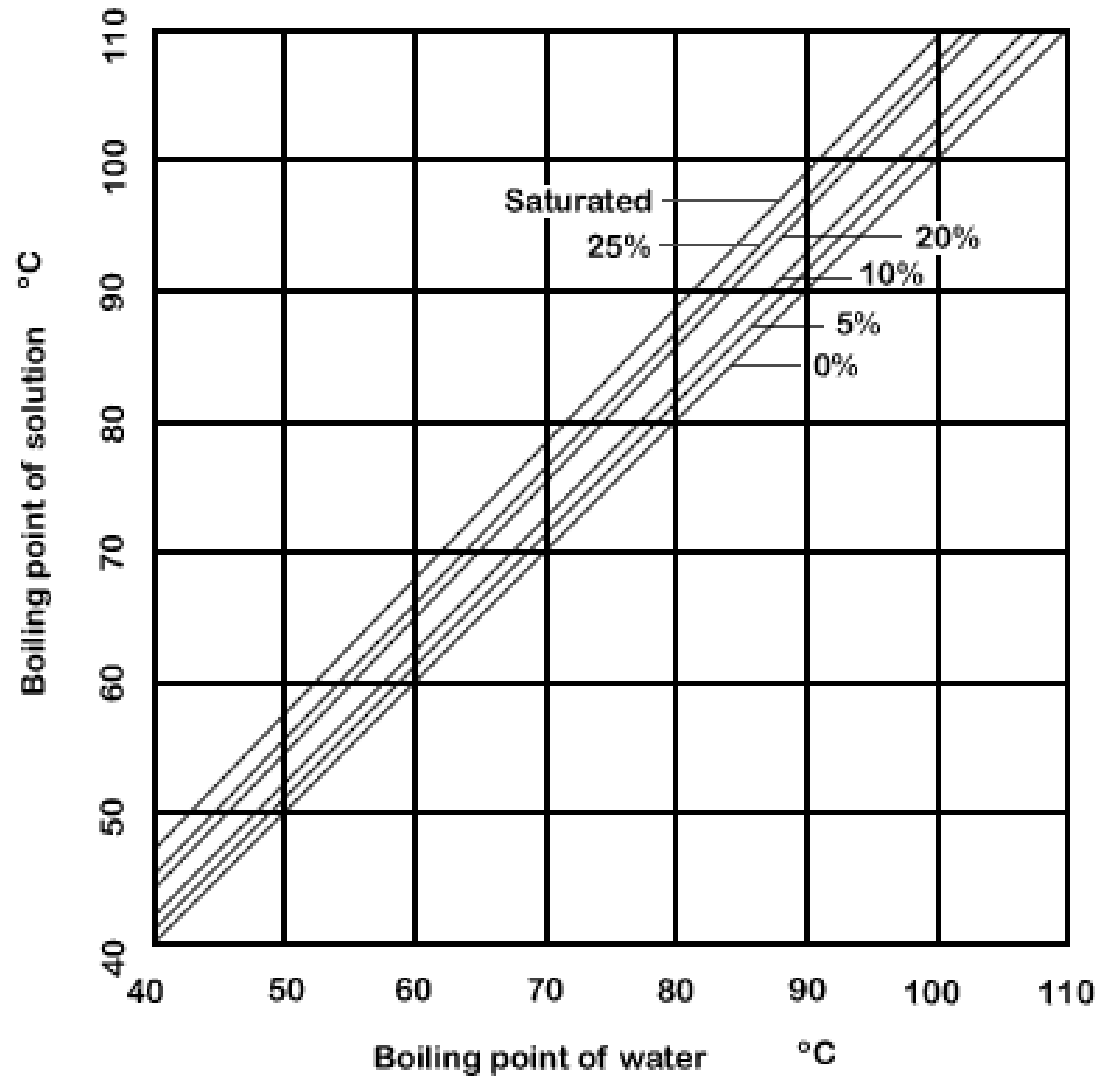
⇨ Solution heat capacity and boiling point are quite different from those of water

For strong solutions of dissolved solutes, the boiling-point rise due to the solutes in the solution usually cannot be predicted.

⇨ Dühring’s rule can be applied

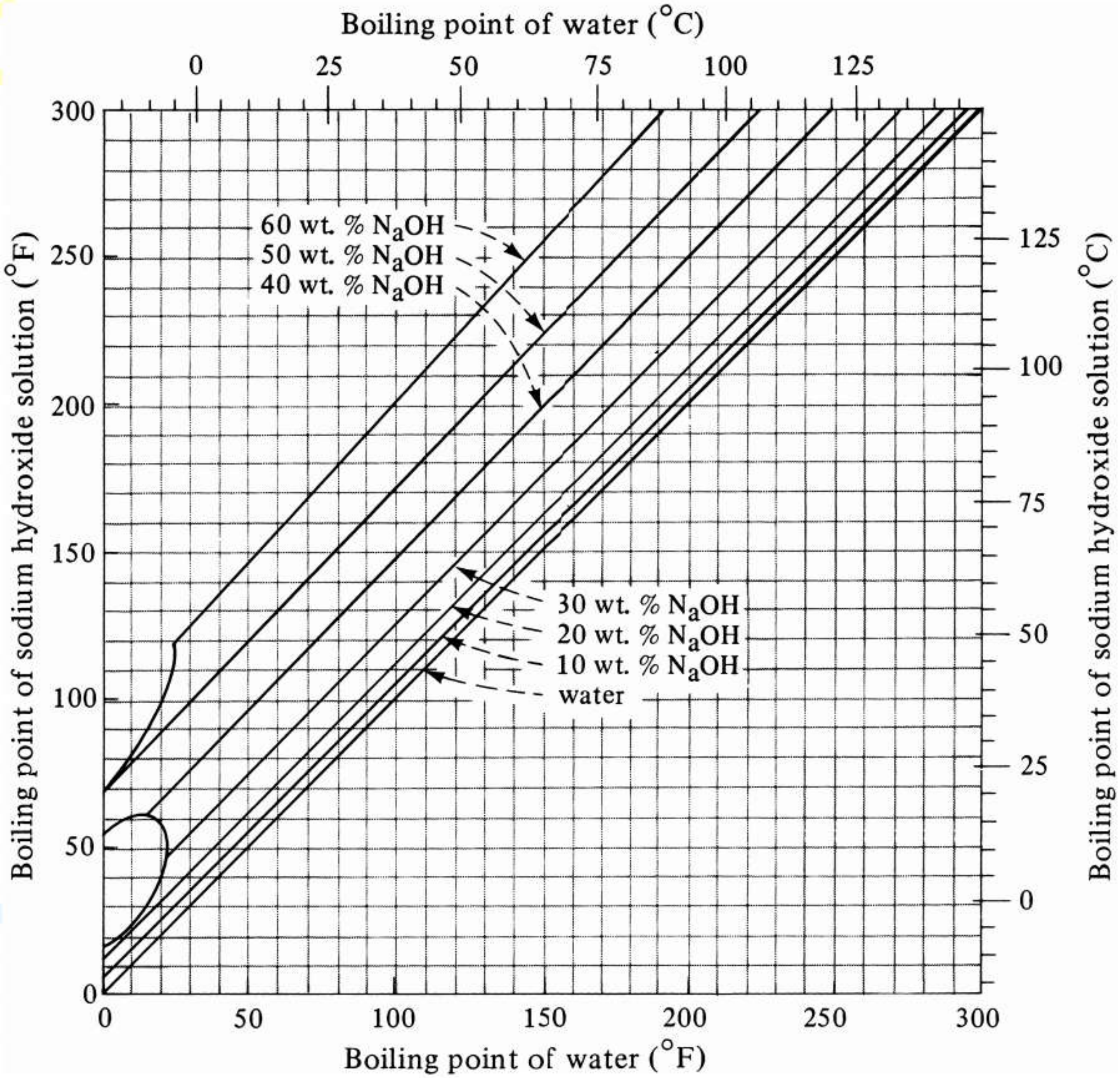
A straight line is obtained if the boiling point of a solution is plotted against the boiling point of pure water at the same pressure for a given concentration at different pressures

Dühring lines for aqueous solutions of sodium chloride



For each solution there will be a specific chart

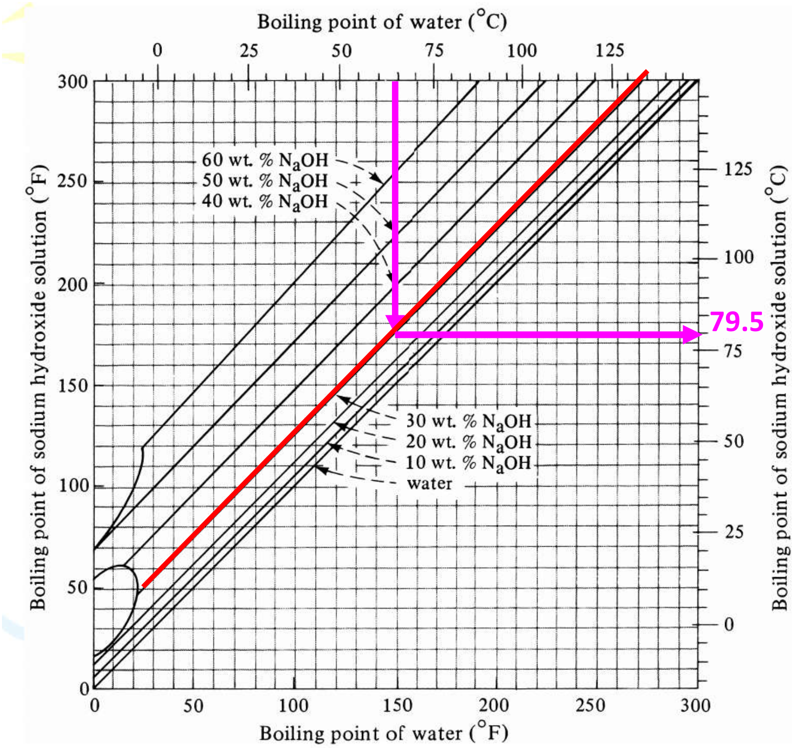
Dühring lines for aqueous solutions of sodium hydroxide



For each solution there will be a specific chart

Example 2.4. Use of a Dühring Chart for Boiling-Point Rise

If an evaporator operates at a pressure of 25.6 kPa and a solution of 30% NaOH is being boiled. Determine the boiling temperature of the NaOH solution and the boiling-point rise (BPR) of the solution over that of water at the same pressure



Solution

From the steam tables: the boiling point of water at 25.6 kPa is 65.6°C

From Figure aside: for 65.6°C and 30% NaOH, the boiling point of the NaOH solution is 79.5°C.

The boiling-point rise;

(BPR) is 79.5 – 65.6 = 13.9°C

Enthalpy–Concentration Charts of Solutions

The heat-of-solution phenomenon is added or evolved when a solution gets concentrated or diluted, respectively. A considerable temperature rise/drop occurs.

⇨ The amount of heat evolved depends on the type of substance and the amount of water used.

For some solutions, heat capacities can't be easily used to calculate enthalpies

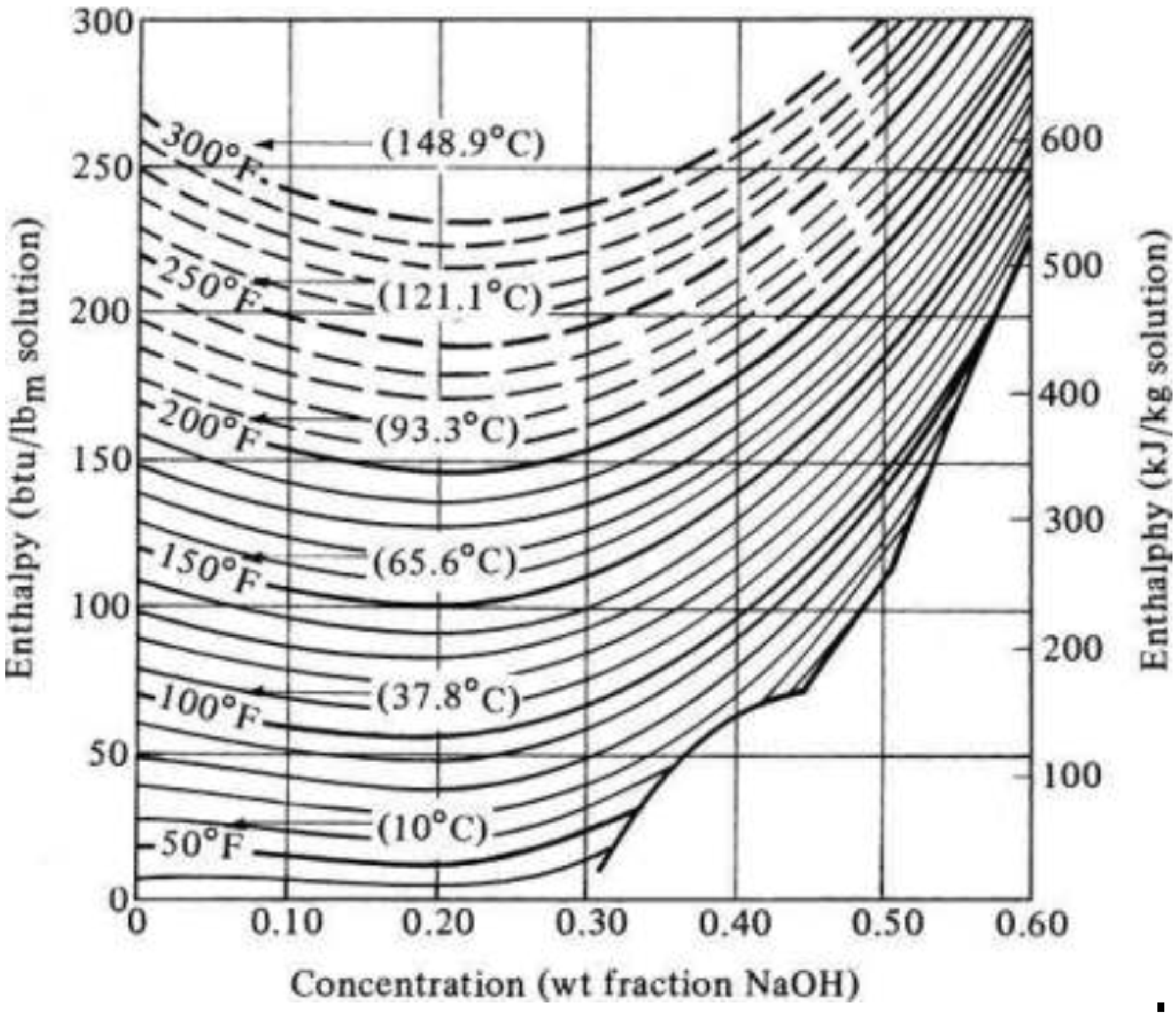
⇨ Enthalpy- concentration Chart can be used

Enthalpies from the figure can be used with those in the steam tables.

values for h_F *and* h_L *can be taken from the chart and values for* λ *and* H_V *from the steam tables*

Enthalpy–Concentration Charts of NaOH solution

For each solution there will be a specific chart



Example 2.5. Use of Enthalpy–Concentration Charts of Solutions

An evaporator is used to concentrate 4536 kg/h of a 20% solution of NaOH in water entering at 60°C to a product of 50% solids. The pressure of the saturated steam used is 172.4 kPa and the pressure in the vapor space of the evaporator is 11.7 kPa. The overall heat-transfer coefficient is 1560 W/m²·K. Calculate the steam used, the steam economy in kg vaporized/kg steam used, and the heating surface area in m².

Solution

Given information:

$F = 4536$ kg/h
$x_F = 0.20$
$T_F = 60°\text{C}$
$P_1 = 11.7$ kPa
steam pressure = 172.4 kPa,
$x_L = 0.50$

$F = L + V$ ⇨ $4536 = L + V$

$F\ x_F = L\ x_L$ ⇨ $4536\ (0.2) = L\ (0.5)$

$$L = 1814\ \ kg/h$$

$$4536 = 1418 + V$$

$$V = 2722\ \ kg/h$$

To determine the boiling point $\boldsymbol{T_1}$ of the 50% concentrated solution, we need to get the boiling point of water at $\boldsymbol{P_1} = 11.7\ kPa$ from steam table

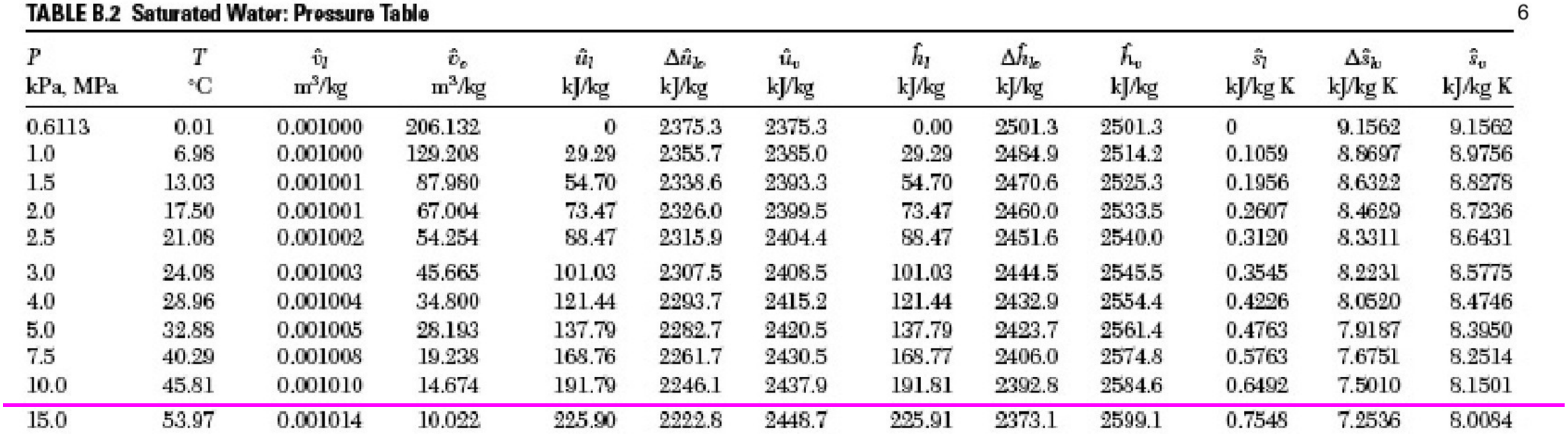


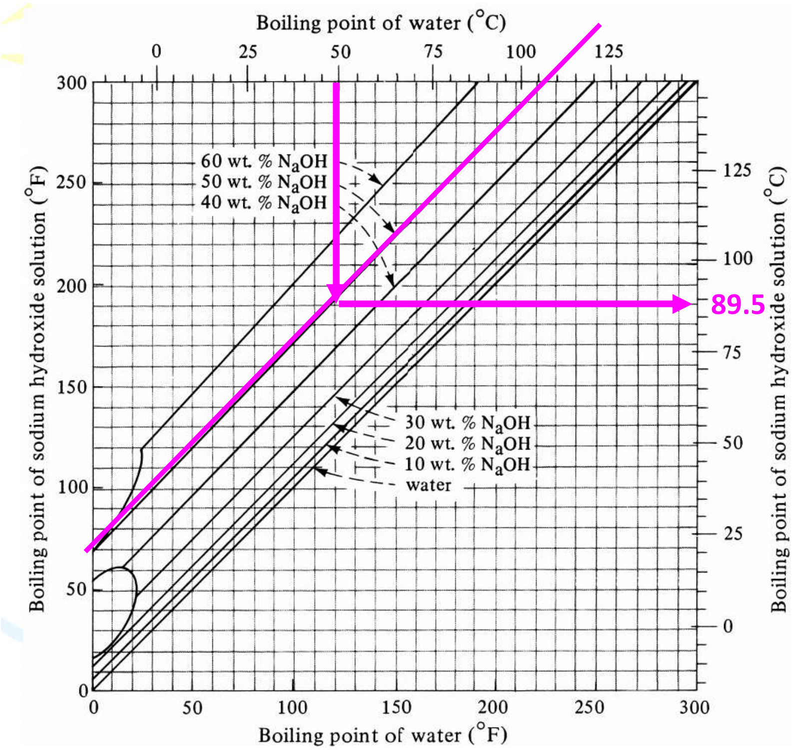
TABLE B.2 Saturated Water: Pressure Table

P kPa, MPa	T °C	$\hat{v}_l$ m³/kg	$\hat{v}_v$ m³/kg	$\hat{u}_l$ kJ/kg	$\Delta\hat{u}_{lv}$ kJ/kg	$\hat{u}_v$ kJ/kg	$\hat{h}_l$ kJ/kg	$\Delta\hat{h}_{lv}$ kJ/kg	$\hat{h}_v$ kJ/kg	$\hat{s}_l$ kJ/kg K	$\Delta\hat{s}_{lv}$ kJ/kg K	$\hat{s}_v$ kJ/kg K
0.6113	0.01	0.001000	206.132	0	2375.3	2375.3	0.00	2501.3	2501.3	0	9.1562	9.1562
1.0	6.98	0.001000	129.208	29.29	2355.7	2385.0	29.29	2484.9	2514.2	0.1059	8.8697	8.9756
1.5	13.03	0.001001	87.980	54.70	2338.6	2393.3	54.70	2470.6	2525.3	0.1956	8.6322	8.8278
2.0	17.50	0.001001	67.004	73.47	2326.0	2399.5	73.47	2460.0	2533.5	0.2607	8.4629	8.7236
2.5	21.08	0.001002	54.254	88.47	2315.9	2404.4	88.47	2451.6	2540.0	0.3120	8.3311	8.6431
3.0	24.08	0.001003	45.665	101.03	2307.5	2408.5	101.03	2444.5	2545.5	0.3545	8.2231	8.5775
4.0	28.96	0.001004	34.800	121.44	2293.7	2415.2	121.44	2432.9	2554.4	0.4226	8.0520	8.4746
5.0	32.88	0.001005	28.193	137.79	2282.7	2420.5	137.79	2423.7	2561.4	0.4763	7.9187	8.3950
7.5	40.29	0.001008	19.238	168.76	2261.7	2430.5	168.77	2406.0	2574.8	0.5763	7.6751	8.2514
10.0	45.81	0.001010	14.674	191.79	2246.1	2437.9	191.81	2392.8	2584.6	0.6492	7.5010	8.1501
15.0	53.97	0.001014	10.022	225.90	2222.8	2448.7	225.91	2373.1	2599.1	0.7548	7.2536	8.0084

At $\boldsymbol{P_1} = 11.7\ kPa$ from steam table; $T_s = 48.9\ °\mathrm{C}$

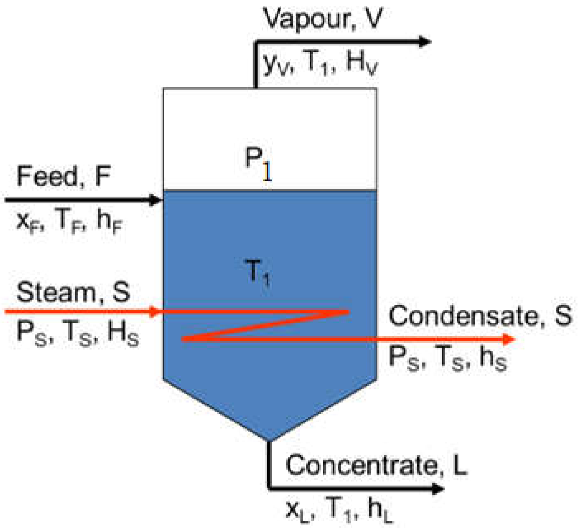
From **Dühring Chart**

For a boiling point of water of 48.9°C and 50% NaOH ⇨ $T_1 = 89.5\ ℃$



Boiling-point rise = $T_1 - T_s$

= 89.5 – 48.9 = 40.6°C



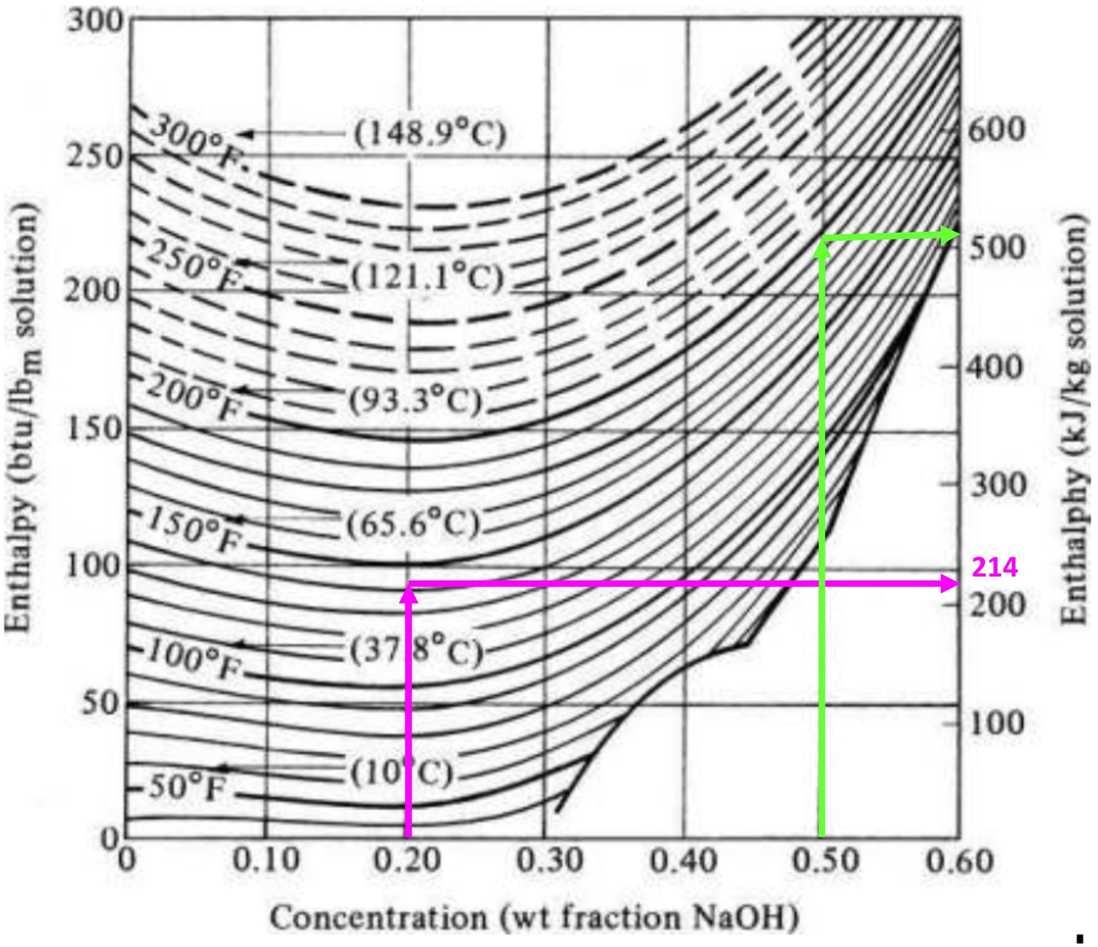
From **Enthalpy – concentration Chart**

At feed concentration of 20% NaOH and feed temperature $T_F = 60°C$

⇨ $h_f = 214 \text{ kJ/kg}$

At product concentration of 50% NaOH and solution temp. $T_1 = 89.5\ °C$

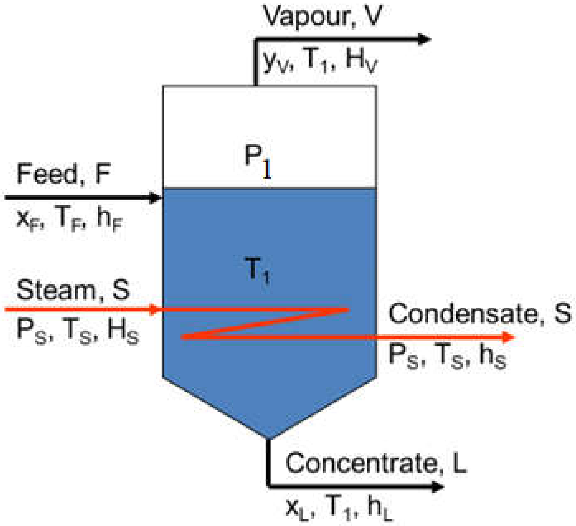
⇨ $h_L = 505 \text{ kJ/kg}$



Since the boiling point of water is 48.9°C and the evaporator temperature is calculated to be $T_1 = 89.5$ °C and its pressure $P_1 = 11.7\ kPa$, then the vapor V that is leaving the evaporator is in superheated state

From superheated team table at:

$T_1 = 89.5$ °C and
$P_1 = 11.7\ kPa$ ⇨ $H_V = 2667$ kJ/kg



For the saturated steam at 172.4 kPa, the saturation temperature from the steam tables is 115.6°C and the latent heat is λ = 2214 kJ/kg

$$\boxed{F\ h_F + S\ \lambda = L\ h_L + V H_V}$$

$$4535\ (214) + S\ (2214) = 1814\ (505) + 2722\ (2667)$$

$$S = 3255\ kg/h$$

$$\boxed{q = S\,(H_S - h_S) = S\lambda = 3255\,(2214)\,\frac{1000}{3600} = 2{,}002{,}000\ W}$$

$$q = UA\,\Delta T = UA\,(T_S - T_1)$$

$$2{,}002{,}000\ W = 1560\ W/m2{\cdot}K\ A\ (115.6 - 89.5)\ K$$

$$A = 49.2\ m^2$$

Steam economy = V / S

= 2722/3255 = 0.836