Evaporators

Tubular evaporators

- Boilers: Fuel directly fires tubular apparatus
- Vaporizing exchangers: Convert latent or sensible heat of one fluid to latent heat of another (also known as vaporizer) used for evaporation of water or aqueous solution ⇒ evaporator

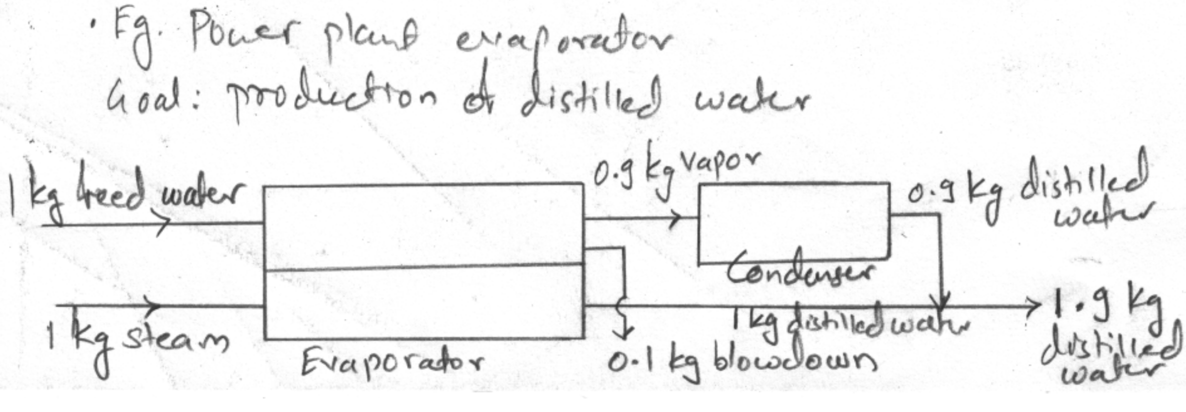
· Reboiler: exchanger used at the bottom of a distillation column to form vapor

· Evaporators

- Power plant evaporators
  goal: generate pure water from raw/pre-treated water
- chemical evaporators
  goal: Water removal for concentrating a solution

Multiple Effect Evaporation (in parallel)

· Eg. Power plant evaporator
Goal: production of distilled water

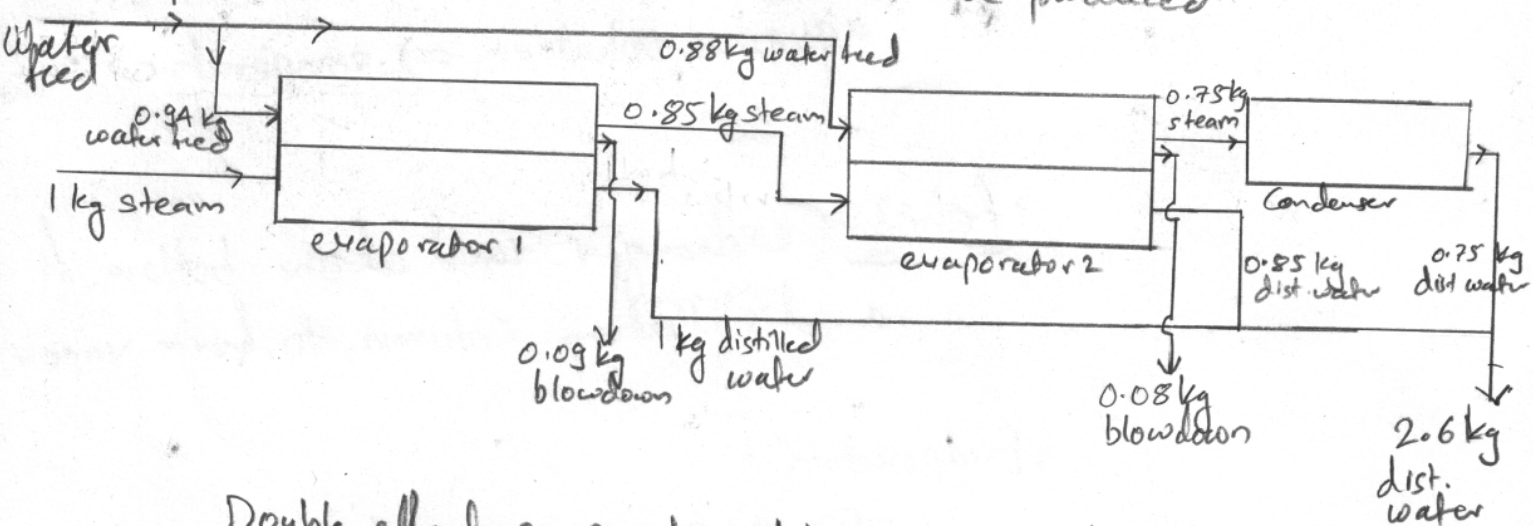


Blowdown: water drained from evaporator to reduce fouling (scale-formation)

Single effect evaporator: 1 kg steam produces 1.9 kg distilled water.

Note: Condensing can be used to partially pre-heat the feed to the evaporator or in other parts of the plant.

Instead, if it is used as a heat source in a second evaporator, more distilled water can be produced



Double effect evaporator: 1 kg steam produces 2.6 kg distilled water

Note: To maintain temperature difference between vapor and liquid in subsequent effects, pressure on succeeding effects must be decreasing

Blowdown quantity wastes sensible heat, but is necessary to prevent scale formation.

$\Rightarrow$ Limit on justifyable number of effects (fixed cost increase)

Chemical Evaporators

- No blowdown
- Can be operated as forward feed or backward feed with multiple-effect systems in series
  - forward-feed: liquid and vapor flow in same direction
  - backward-feed: liquid and vapor flow in opposite direction
  - forward is preferred, unless other considerations such as a viscous liquid is present

- Concentrated aqueous solutions undergo a boiling point rise.
  $\Rightarrow$ Boiling point is above that for pure water, at a given pressure.

For solutions with significant boiling point rise (~2°C and above, their latent heat of vaporization also differs from the pure water latent heat.

Two relations are available (valid for dilute solutions only)

with $T_{sat,sol}$ ≡ boiling point of the solution ⎫ in absolute scale
$T_{sat,wat}$ ≡ boiling point of pure water ⎭ at a given pressure

and ΔT_{sol} ≡ rate of change of boiling curve for solution over a pressure range

ΔT_{wat} ≡ rate of change of solution's boiling curve over the same pressure range

P_{sol}, P_{wat} ≡ absolute vapor pressures of solution, water at same T.

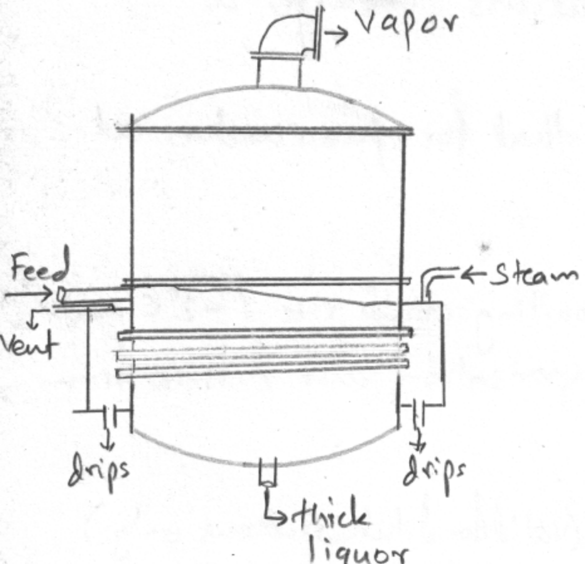
$$\frac{h_{fg,wat}}{h_{fg,sol}} = \frac{\Delta T_{wat}}{\Delta T_{sol}}\left(\frac{T_{sat,wat}}{T_{sat,sol}}\right)^2$$ — Duhring's rule

or

$$\frac{h_{fg,sol}}{h_{fg,wat}} = \frac{d\log P_s}{d\log P_w},$$ — Othmer's method

Types of Chemical Evaporators

- Either natural circulation based or forced circulation based
- Forced are typically used for scale forming, or viscous solutions
- Natural: Horizontal tube, Calandria vertical tube, Basket vertical tube, Long tube vertical



Horizontal tube evaporator

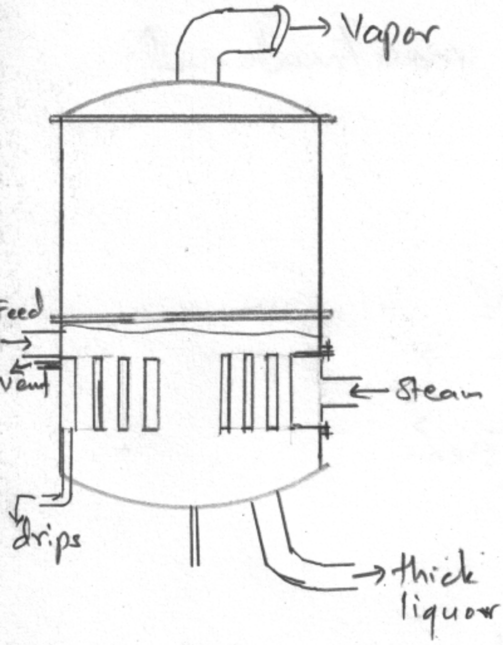
Notes:

- Used to make thick liquor (not solids/crystals)
- Tube length ≤ evaporator size

Horizontal Tube Evaporator

- Oldest design
- Do not take advantage of natural flow currents (convection currents)
- Steam is in the tubes
- Advantages
  - Small headroom
  - Any air entering with steam does not reduce heat transfer area
- Disadvantage:
  - Scaling around (outside) tubes

Calandria Evaporator



Calandria evaporator

Notes:

- Common in industry
- Also known as "standard" evaporators

- Short vertical-tube bundle
- Steam flows outside tubes in the Steam chest
- Liquid rises through tubes and circulates back to the bottom through large space close to the centre (typically 0.5-1 times area of the tubes).

Advantages:

- Scaling occurs inside tubes
- Can be used for handling thick fluids, with optional propeller at the bottom

Disadvantages:

- Differential expansion between shell and tubes may result into stresses

- Basket type evaporators are similar, except that they have a removable bundle of tubes that can be cleaned easily and has no issues due to differential expansion. Used for scale forming liquids, but not for viscous liquids.

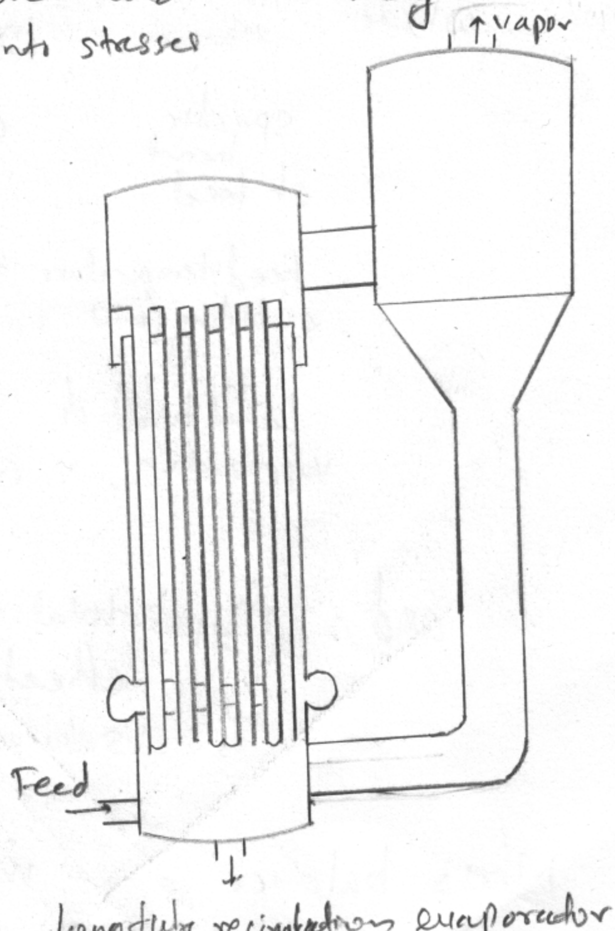
Long Tube Evaporator

- Long heating element
- Liquor passage through tubes (only once)
- Steam enters through a vapor belt

Advantages/Use

- Foamy and frothy liquids

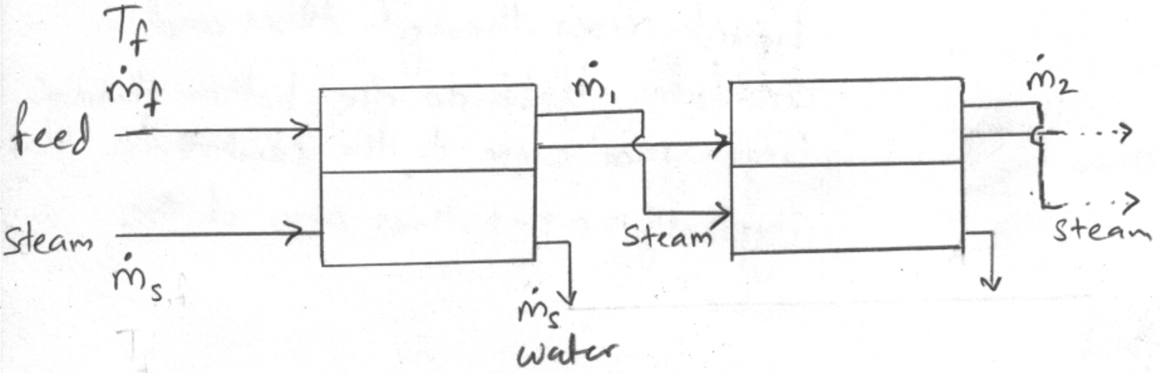
Disadvantage: - Not for scaling liquids



long tube recirculation evaporator

Analysis of Multiple Effect Evaporators

Simple analysis: Involves energy and mass/material balance



For a forward feed multiple-effect evaporator, energy balance

First effect: $\dot{m}_s h_{fg,s} + \dot{m}_f c_f (T_f - T_1) = \dot{m}_1 h_{fg,1}$

Second effect: $\dot{m}_1 h_{fg,1} + (\dot{m}_f - \dot{m}_1) c_1 (T_1 - T_2) = \dot{m}_2 h_{fg,2}$

Third effect: $\dot{m}_2 h_{fg,2} + (\dot{m}_f - \dot{m}_1 - \dot{m}_2) c_2 (T_2 - T_3) = \dot{m}_3 h_{fg,3}$

. . . .

where

	inlet	effect-1	effect-2 ....
specific heat of feed	c_f	c_1	c_2
Feed temperature or boiling point	T_f	T_1	T_2
Latent heat of vaporization	$h_{fg,s}$ (steam)	$h_{fg,1}$ (liquor)	$h_{fg,2}$ (liquor)

and $\dot{m}_{\Sigma i}$ ≡ total rate of water removed across all effects

T_s ≡ saturation temperature of inlet steam

Mass balance $\dot{m}_{\Sigma i} = \dot{m}_1 + \dot{m}_2 + \dot{m}_3 + \ldots$

Then, the surface area requirements are

$$A_1 = \frac{Q}{U\Delta T} = \frac{\dot{m}_s h_{fg,s}}{U_1(T_s - T_1)}$$

$$A_2 = \frac{\dot{m}_1 h_{fg,1}}{U_2(T_1 - T_2)}$$

$$A_3 = \frac{\dot{m}_2 h_{fg,2}}{U_3(T_2 - T_3)} \quad \cdots$$

Similar balance can be performed for backward feed.

Example: Triple effect evaporator

It is desired to concentrate 22679 kg/hr of a chemical solution at 37.77°C and 10% solids to a product that contains 50% solids. Steam is available at 184062 Pa (12 psig) and the last effect of a triple-effect evaporator with equal heat transfer surface in each effect will be assumed to operate at a vacuum with pressure at 13445 Pa (1.95 psia). Water is available at 29.44°C for use in a barometric condenser. Calculate steam consumption, heating surface requirement and condenser water required.

Given

$\dot{m}_f = 22679$ kg/hr

total solids in feed $= 0.1 \times 22679 = 2267.9$ kg/hr

$$\text{total product} = \frac{2267.9}{0.5} = 4535.8 \text{ kg/hr}$$

$$\sum_{i=1}^{3} \dot{m}_i = \dot{m}_1 + \dot{m}_2 + \dot{m}_3 = \dot{m}_f - \text{total product} = 18143.2 \text{ kg/hr}$$

Assuming:

$$C_f = C_1 = C_2 = C_3 = 4.1868 \text{ kJ/kg K}$$

Also given,

$U_1 = 1.23\times10^7$ J/m²·K $\quad U_2 = 5.11\times10^6$ J/m²·K; $U_3 = 2.55\times10^6$ J/m²·K

Using energy balance and material balance above, with

$T_f = 37.77°C$

T_s at 12 psig $= 117.78°C$

T_3 at 1.95 psia $= 51.67°C$

Total temperature difference $= 66.1°C$

Assuming pressure difference to be nearly equal across each effect (due to area being equal), as a first approximation,

Average pressure difference (per effect) $= 8.25$ psi

1st effect	$T_s = 117.78°C$	$h_{fg,s} = 2207.37$ kJ/kg
2nd effect	$T_1 = 106.67°C$	$h_{fg,1} = 2235.28$ kJ/kg
3rd effect	$T_2 = 90°C$	$h_{fg,2} = 2281.80$ kJ/kg
vapor to condenser	$T_3 = 51.67°C$	$h_{fg,3} = 2377.17$ kJ/kg

Substituting in energy and material balance,

$$3973.27\,\dot{m}_s + 22679 \times 1 \times (37.77 - 106.67) = 4023.51\,\dot{m}_1$$

$$4023.51\,\dot{m}_1 + (22679 - \dot{m}_1) \times (106.67 - 90) = 4107.25\,\dot{m}_2$$

$$4107.25\,\dot{m}_2 + (22679 - \dot{m}_1 - \dot{m}_2) \times (90 - 51.67) = 4278.91\,\dot{m}_3$$

$$\sum_{i=1}^{3} \dot{m}_i = \dot{m}_1 + \dot{m}_2 + \dot{m}_3 = 18143.2 \text{ kg/hr}$$

Solving the above equations simultaneously,

$\dot{m}_1 = 5607.5$ kg/hr

$\dot{m}_2 = 6015.3$ kg/hr

$\dot{m}_3 = 6520.4$ kg/hr

$\dot{m}_s = 8642.2$ kg/hr

$$A_1 = \frac{\dot{m}_s h_{fg,s}}{U_1(T_s - T_1)} = 140\,m^2$$

$$A_2 = \frac{\dot{m}_1 h_{fg,1}}{U_2(T_1 - T_2)} = 147\,m^2$$

$$A_3 = \frac{\dot{m}_2 h_{fg,2}}{U_3(T_2 - T_3)} = 140\,m^2$$

Heat transferred to condenser $= \dot{m}_3 h_{fg,3} = 1.55 \times 10^{10}$ J/hr

Water requirement 1.55×10^{10} J/hr $= \dot{m}_w \times C_{P,w} \times \Delta T_{water}$

assuming $\Delta T_{water} = 19.5\,°C$

$\dot{m}_w = 1.8985 \times 10^5$ kg/hr

Notes:

- Assumption of equal pressure drop across subsequent effects may not be valid.
  eg: due to scale formation (uneven)

- Thus, the evaporator calculations above might need to be adjusted for the new pressure profile.

- Similar calculation for backward-feed evaporator reveals that the total steam requirement is lower for backward-feed evaporator.

- Practical issues arise, however, in using backward feed evaporators. Also, pump requirements could add up substantially to the operating costs.