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280.371 Process Engineering Operations

Evaporation Lecture 4

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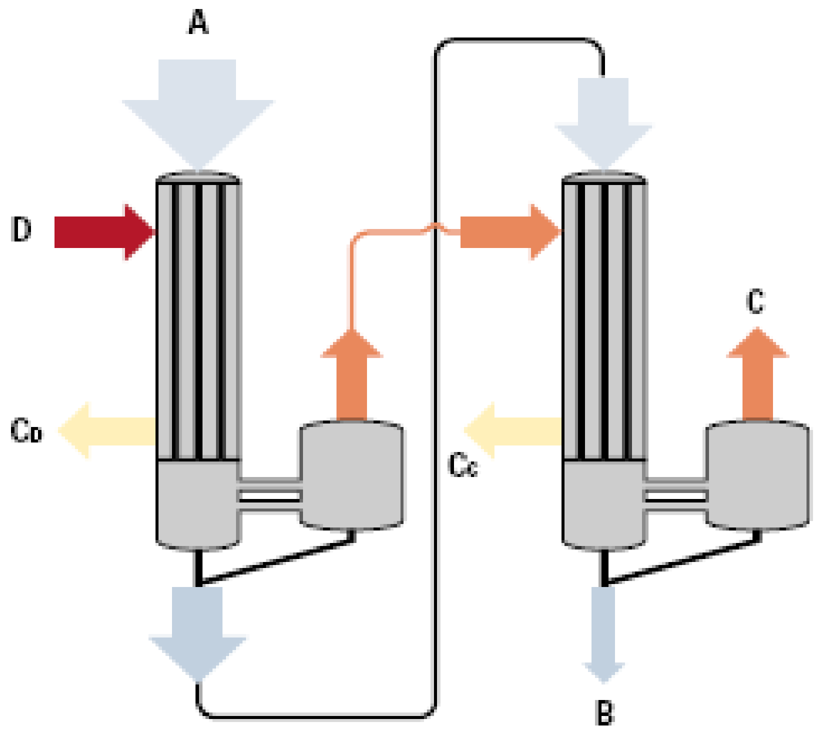
Multiple-effect evaporators

Rationale

- Steam economy of single-effect < 1 (<100%)
- In multiple-effect operation, evaporated vapour from one stage is used as the steam (heat) supply in the next stage
  - For n stages, steam economy ~ n $kg.kg^{-1}$

    → efficiency increases n times
  - Capital cost increases ~ n times; but commonly energy cost savings are greater

Example – 2 stage

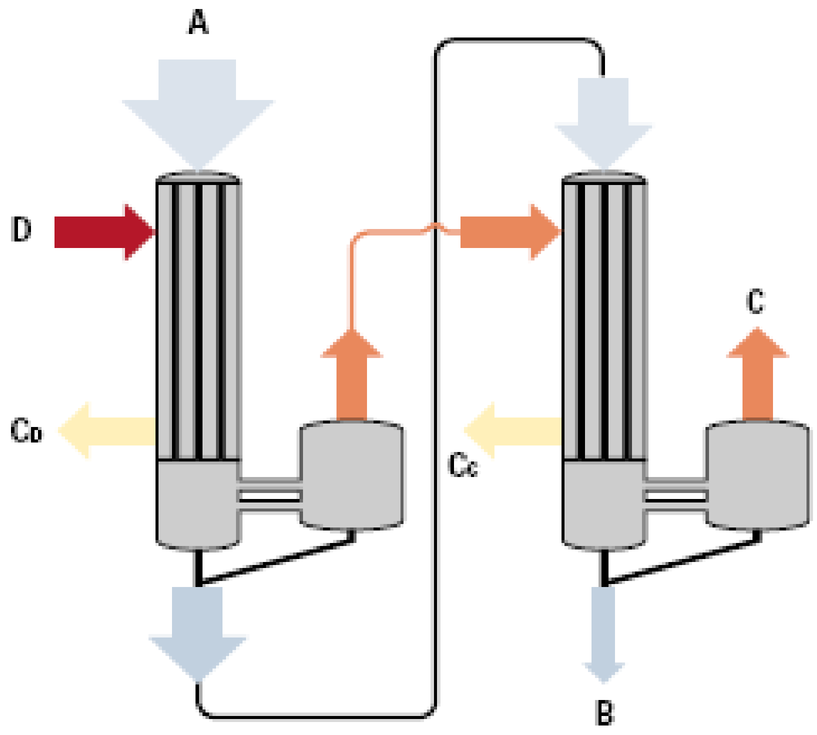


A *Product*
B *Concentrate*
C *Condensate*
Cᴄ *Vapour condensate*
Cᴅ *Heating steam condensate*
D *Heating steam*
E *Electrical energy*

Multiple-effect evaporators - operation

- As vapours from primary effect passed on to heat next effect
  - Each subsequent effect operates at a lower pressure than previous
  - Next boiling temperature reduced
- Maximum pressure difference between primary steam heat source and condensing pressure in the final stage
- High degree of flexibility in the design of multiple-effect evaporators.
- High capital costs as **n** increases

Example – 2 stage

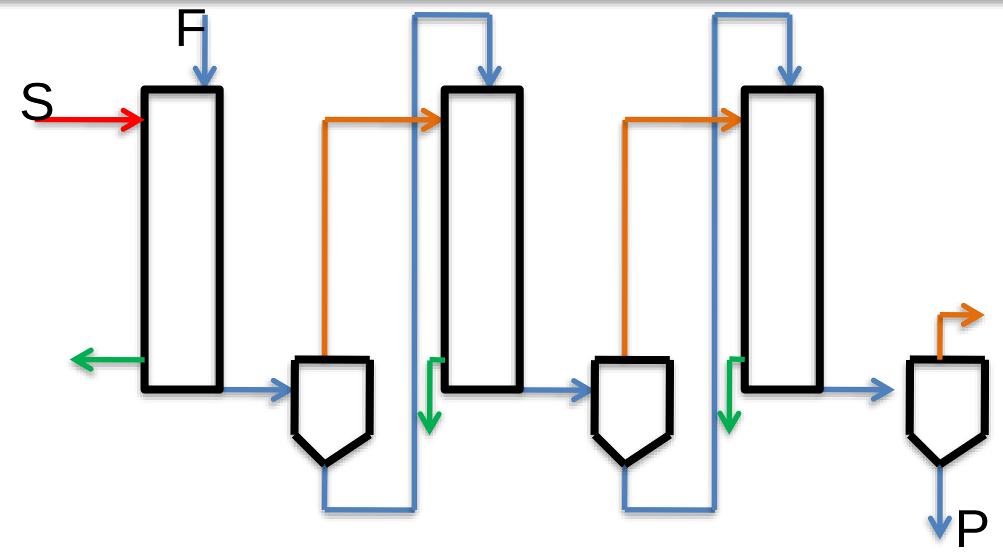


A Product
B Concentrate
C Condensate
CC Vapour condensate
CD Heating steam condensate
D Heating steam
E Electrical energy

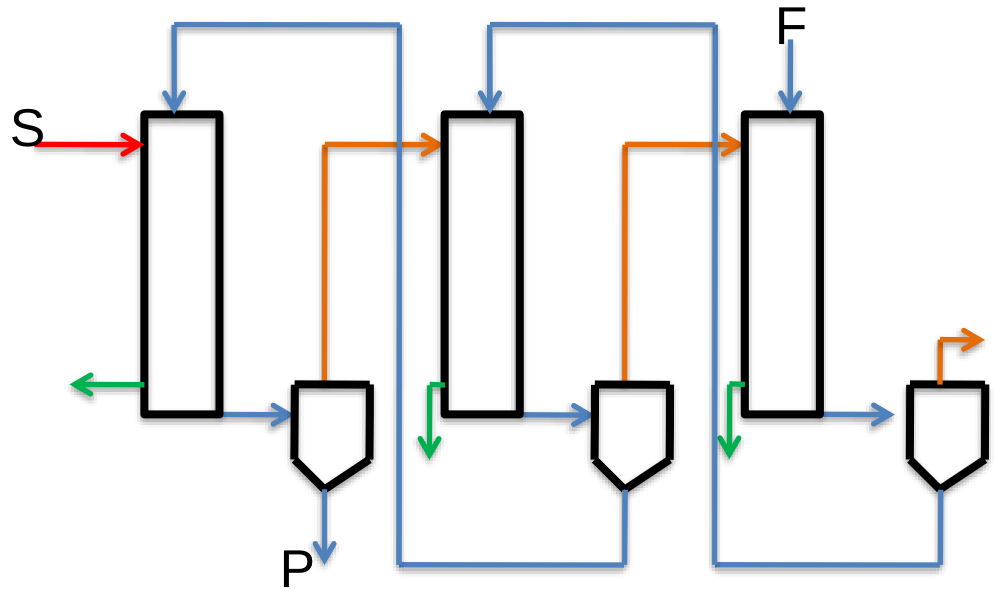
Multiple-effect evaporator - operation 2

- Different flow strategies used
  - Feed-forward
  - Feed-back
  - Mixed-flow
- Conventionally, to establish $\Delta\theta$ must operate with a pressure gradient
- Limit to number of stages for conventional operation depends on
  - Available ΔP and/or $\Delta\theta$
  - f(vacuum, set-up, thermal sensitivity)

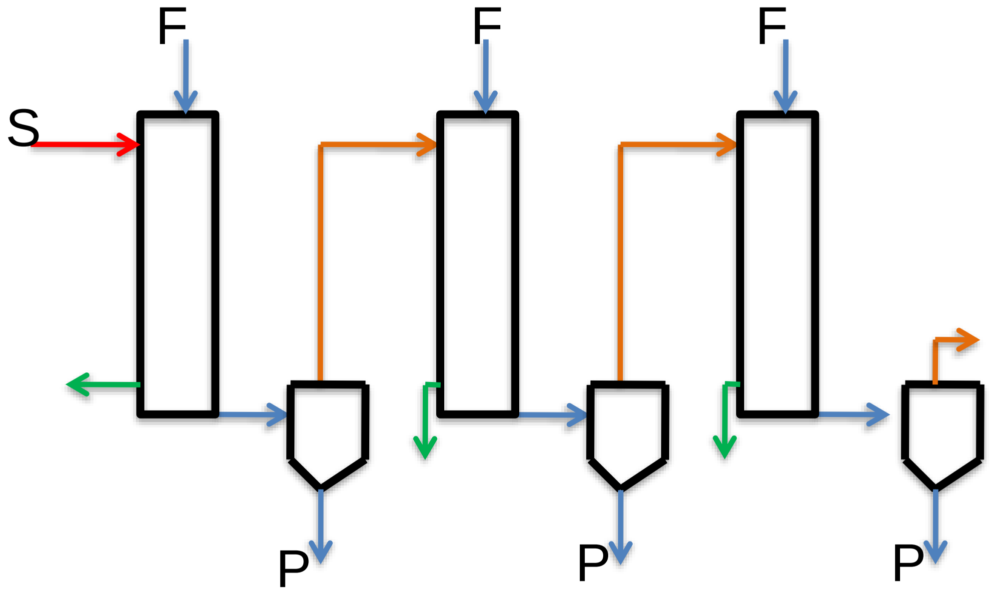
Flow strategies



Feed forward



Feed backward



Parallel flow

Vapour recompression

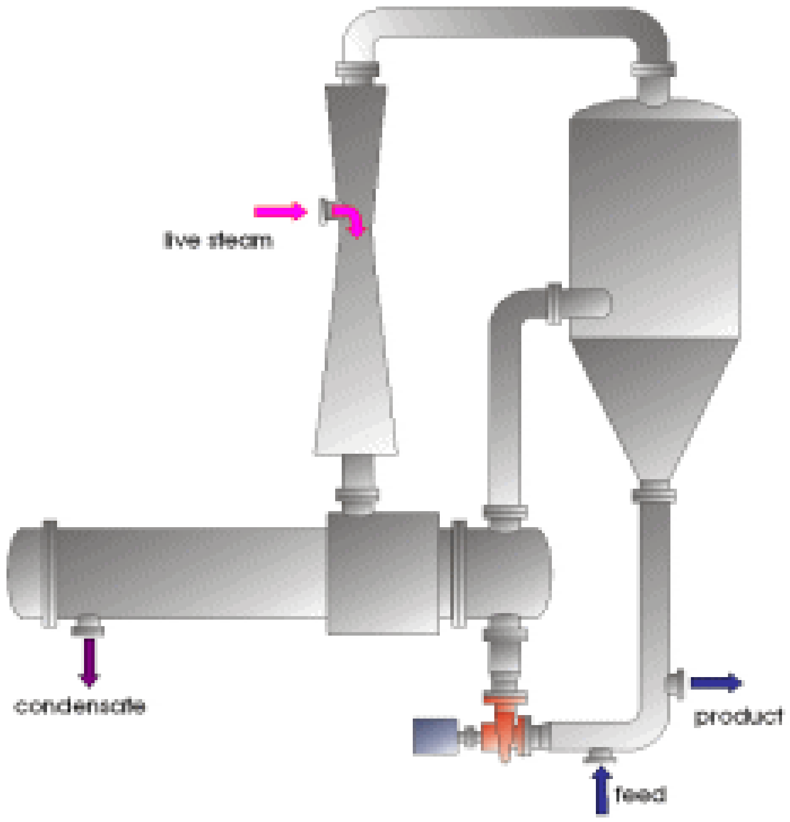
- Can increase steam pressure prior to reuse to recover latent heat

- Two options for vapour recompression
  - Thermal (TVR) - using a steam ejector (venturi)
  - Mechanical (MVR) - using a compressor

- Demand for fresh steam is reduced
- Reduced installation costs with TVR

Thermal vapour recompression – steam ejector

- Raises the pressure and hence the temperature of the re-used vapour
- Evaporation load in the effect is effectively doubled
- *n* effect evaporator becomes an evaporator with capability of *n+1* effects – efficient use of energy in evaporator vapours.
- Widely used in multi-effect evaporators – most common
- 2 types - nozzle or regulating spindle



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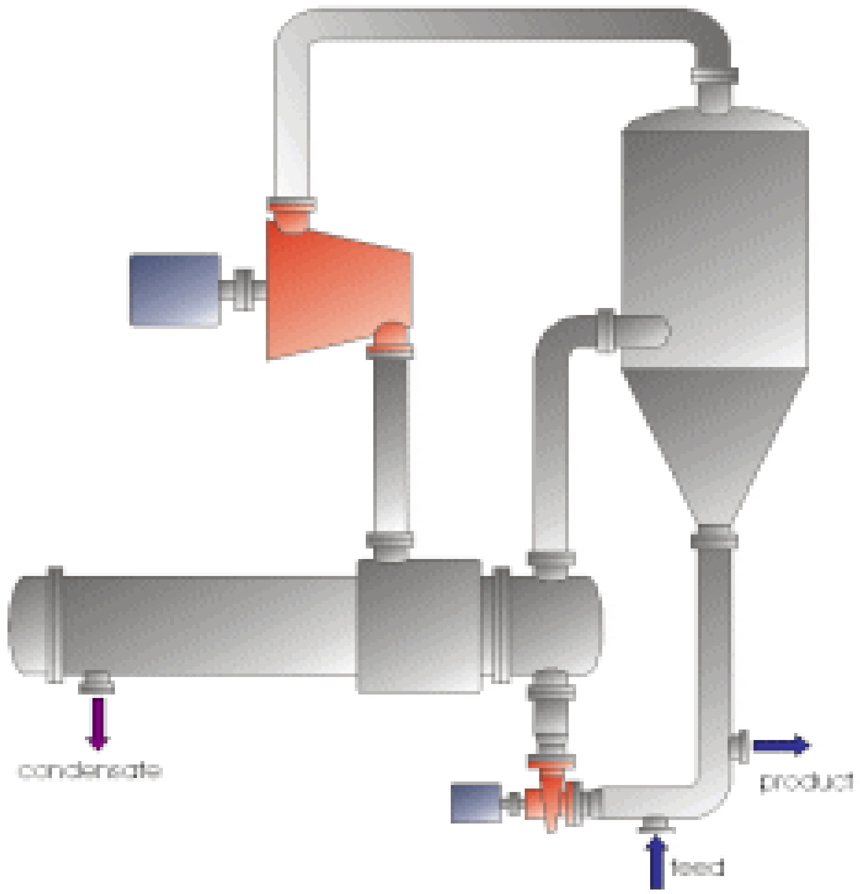
Mechanical vapour recompression

- a compressor increases the pressure of the vapour
- expensive
- widespread use in the food industry
- positive displacement compressors, axial or radial flow compressors (fan compressors)



TVR / MVR – falling film

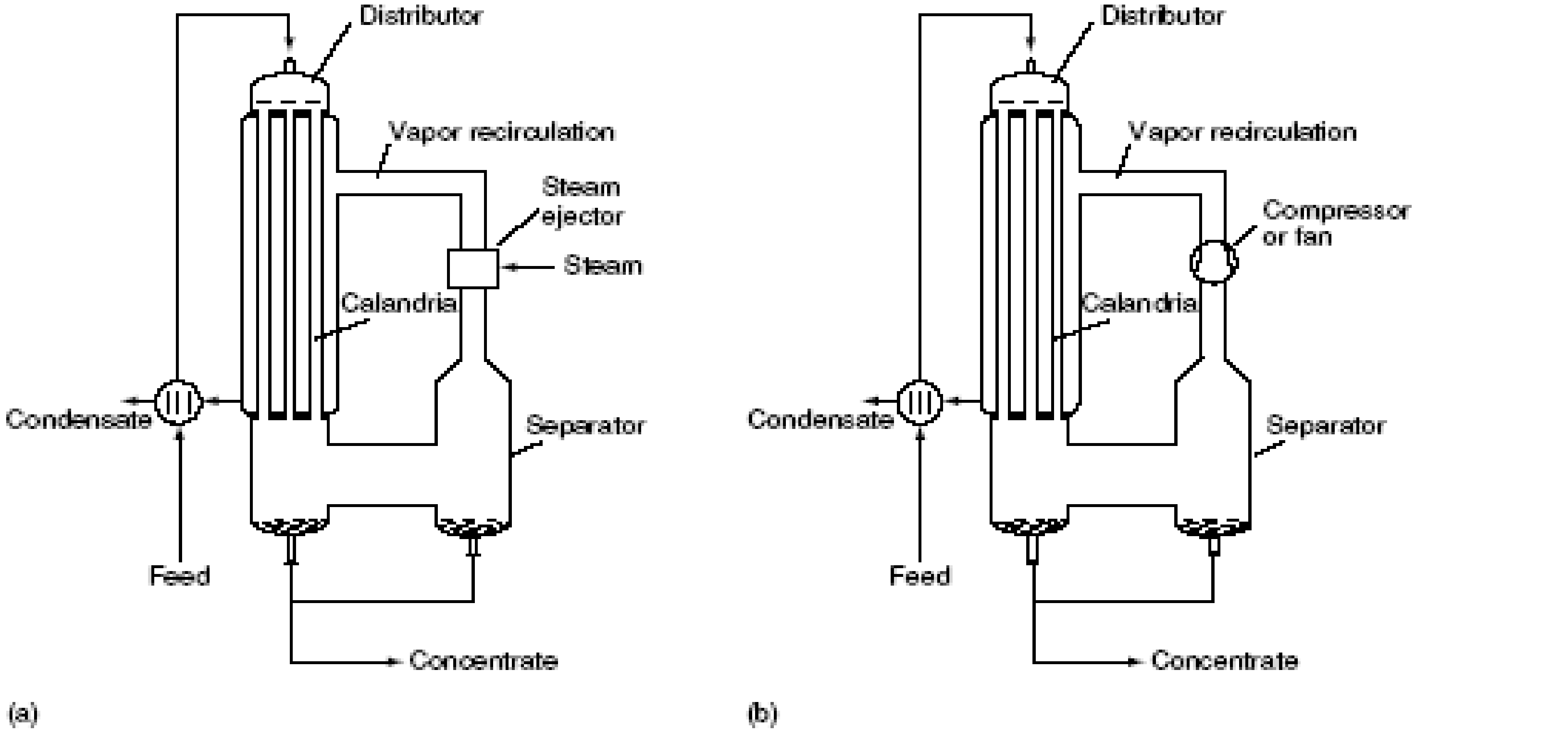


Figure 4 Main components of vapor recompression evaporators: (a) TVR and (b) MVR. Reproduced from Evaporation: Uses in the Food Industry, *Encyclopaedia of Food Science, Food Technology and Nutrition*, Macrae R, Robinson RK and Sadler MJ (eds), 1993, Academic Press.

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Mass and energy balances- multiple-effect

- Mass balances over each stage or overall e.g. 3-stage system

- ***Solute mass balance***

$$m_F x_F = m_L x_L \qquad (1)$$

- ***Overall mass balance***

$$m_F = \left(m_{V1} + m_{V2} + m_{V3}\right) + m_L \qquad (2)$$

m_{Vi} - mass flow rate of vapour from ***i*** th stage

Energy balance – multiple-effect

Assuming constant evaporation rate

$$\phi = m_{V1}h_{fg1} = m_{V2}h_{fg2} = m_{V3}h_{fg3} \qquad (3)$$

Then

$$m_{Vi} = \frac{\dfrac{1}{h_{fgi}}}{\left(\dfrac{1}{h_{fg1}} + \dfrac{1}{h_{fg2}} + \dfrac{1}{h_{fg3}}\right)}\left[m_{V1} + m_{V2} + m_{V3}\right] \qquad (4)$$

If $h_{fg1} \approx h_{fg2} \approx h_{fg3}$
then

$$m_{Vi} \approx \frac{1}{3}\left[m_{V1} + m_{V2} + m_{V3}\right] \qquad (5)$$

- Heat transfer in each stage is assumed constant

Heat transfer rate equations

$$\phi = U_1 A_1 (\theta_S - \theta_1) = U_2 A_2 (\theta_1 - \theta_2) = U_3 A_3 (\theta_2 - \theta_3)$$

$$\phi = U_1 A_1 \Delta\theta_1 = U_2 A_2 \Delta\theta_2 = U_3 A_3 \Delta\theta_3 \qquad (6)$$

The temperature difference driving force (and pressure) in each stage must be determined.

Assuming:

(a)Constant $\Delta\theta$ - less common

$$\left(\theta_S-\theta_1\right)=\left(\theta_1-\theta_2\right)=\left(\theta_2-\theta_3\right)=\frac{1}{3}\left(\theta_S-\theta_3\right) \qquad \textbf{\textit{(7)}}$$

(b) Constant area (A) – most common

$$U_1A_1\Delta\theta_1=U_2A_2\Delta\theta_2=U_3A_3\Delta\theta_3 \qquad \textbf{\textit{(8)}}$$

(b) Constant area (A) – most common

$$\emptyset_1 = \emptyset_2 = \emptyset_3$$

$$U_1 A_1 \Delta\theta_1 = U_2 A_2 \Delta\theta_2 = U_3 A_3 \Delta\theta_3 \quad \textbf{(9)}$$

$$\left(\theta_i - \theta_{i+1}\right) = \frac{\dfrac{1}{U_{i+1}}}{\dfrac{1}{U_1} + \dfrac{1}{U_2} + \dfrac{1}{U_3}} \left(\theta_S - \theta_3\right) \qquad \textbf{(10)}$$

General Solution Procedure

1. Solve equations (1) and (2) to determine the amount of water evaporated ($m_{V1}+m_{V2}+m_{V3}$) and the missing solution flow rate or composition.
2. Determine the steam heat source temperature (θ_s) and allowable last stage condensate temperature and pressure.
3. Determine the boiling point elevation in the last stage and hence determine the last stage solution temperature (θ_3).
4. Use Equation (7) or (8) to determine the temperature difference across the heat exchanger for each stage.
5. Use Equation (4) or (5) to determine the amount of water evaporated in each stage.
6. Use Equation 6 to determine the area of the heat exchanger.

Multi-stage evaporator - General Solution Procedure

Step 1 Solve equations mass balance equations to determine the amount of water evaporated $(m_{V1} + m_{V2} + m_{V3})$ and the missing solution flow rate or composition.

Step 2 Determine the steam heat source temperature (θ_s) and allowable last stage condensate temperature and pressure.

Step 3 Determine the boiling point elevation in the last stage and hence determine the last stage solution temperature (θ_3)

Step 3 Determine the temperature difference across the heat exchanger for each stage

Step 5 Determine the amount of water evaporated in each stage

Step 6 Determine the area of the heat exchanger

Question 6: Three stage feed forward evaporator

Ten kg/s of 2 wt% NaCl is being concentrated to 20wt% NaCl in a three effect feed forward evaporator. Steam is available at 150 kPa abs and a vacuum of 500 mmHg (below atmospheric) is being pulled by the vacuum pump. The overall heat transfer coefficients for the first, second and third heat exchangers are 1000 W/m^2K, 900 W/m^2K and 800 W/m^2K respectively and the area of the three heat exchangers are identical.

(a) Determine the size of the heat exchangers.

(b) What increase in production would be expected if the steam pressure was increased to 200kPa.a?

Question 7: Three stage feed forward evaporator

A 5 wt% citric acid solution is concentrated in a triple effect feed forward evaporator to 60 wt% using steam at 20 kPa gauge. 10 kg/s of cooling water at 20°C is injected into the final stage condenser of operating at 10 kPa absolute.

(a) Calculate the amount of water evaporated in the final stage and hence the production rate of 60wt% citric acid.

(b) Both the overall heat transfer coefficient and the temperature difference across each heat exchanger is identical. Determine the size of each heat exchanger if the overall heat transfer coefficient is 1000 W/m^2K.