Chapter five – Evaporation

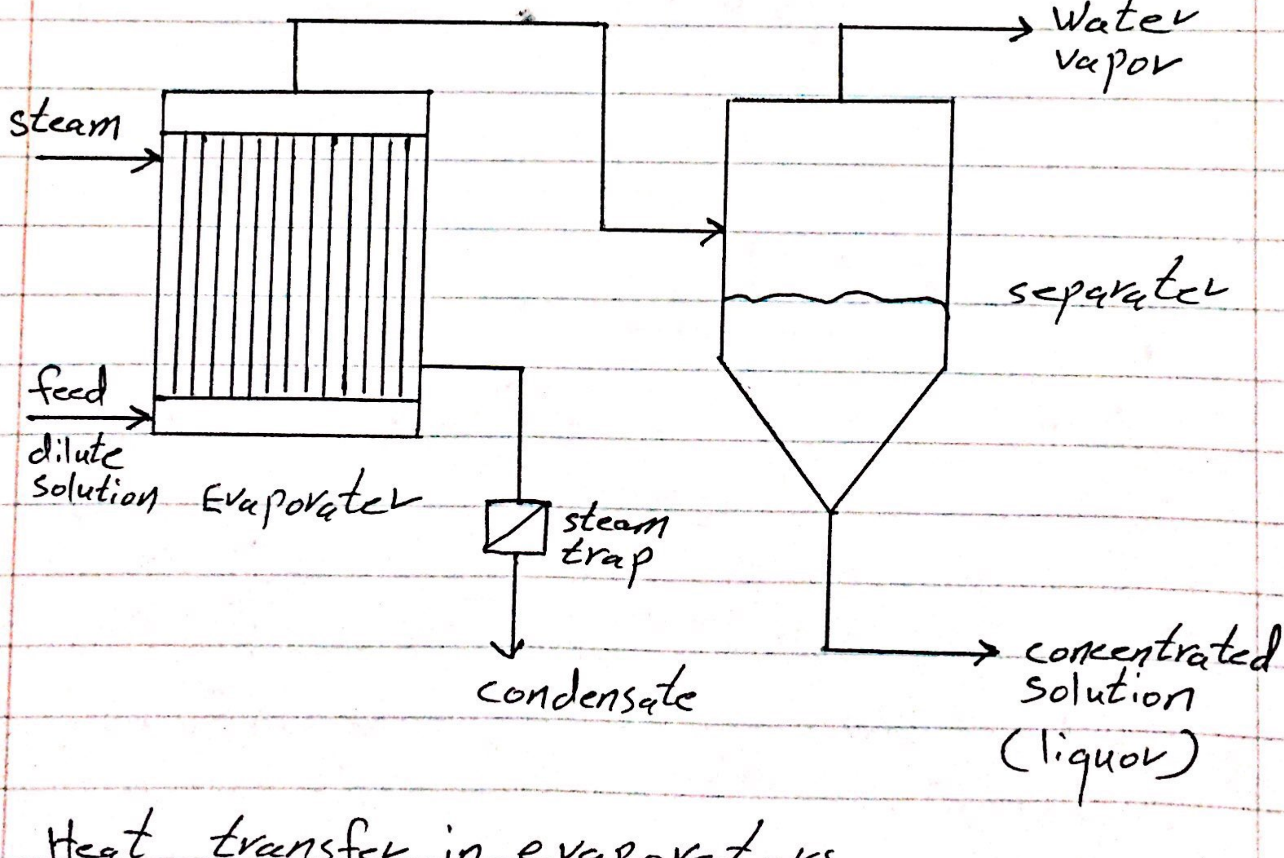
المحاليل المائية

Evaporation: concentration of aqueous solution

هو عملية تركيز المحاليل المائية بإستخدام البخار

* **Evaporation:** The removal of water from a solution by boiling the liquor in a suitable vessel and withdrawing the vapor. If the solution contains dissolved solids the resalting strong liquor may become saturated so that crystals are deposited.

Evaporation is carried out by adding heat to the solution, the heat is supplied principally to provide the latent heat of vaporisation.



Heat transfer in evaporators.

$$Q = U A \Delta T \quad \text{——} (1)$$

where Q = heat transfer per unit time (W)

U = overall heat transfer coefficient ($W/m^2 K$)

A = heat transfer surface area (m^2)
ΔT = the temperature difference between the two streams (steam & water vapor) $(T_s - T)$

$$Q = S\lambda \qquad (2)$$

where S = quantity of steam (kg)
λ = latent heat of vaporization
(الحرارة الكامنة للتبخر)

Notice:
At the same pressure a solution has a boiling point greater than that of water, and the difference between its boiling point and that of water is called the boiling point Rise. (B.P.R).

Types of evaporator

Multi Effect Evaporator:

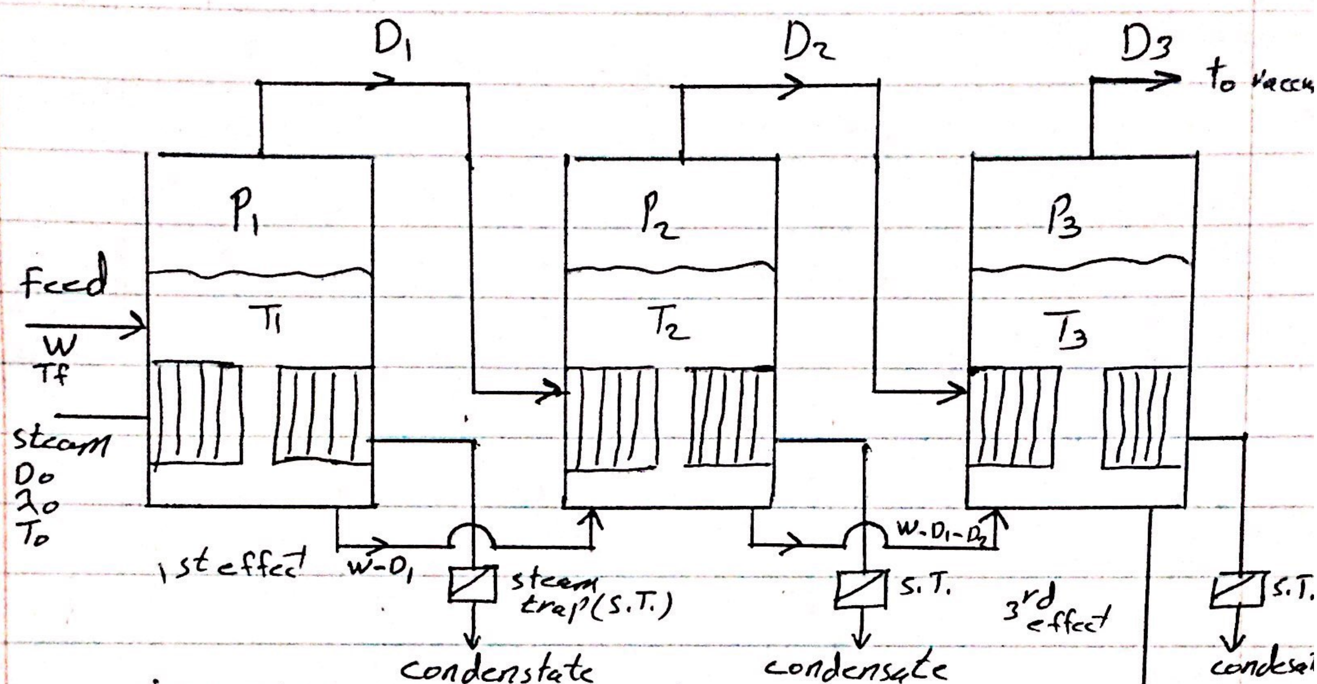
المبخر المتعدد المراحل: عادةً يستخدم مبخر متعدد المراحل سواء مرحلتين أو ثلاث مراحل وذلك للاستفادة من بخار الماء المتكون نتيجة رفع درجة حرارة السائل أو المحلول المائي المطلوب تركيزه، حيث يمرر بخار الماء إلى المرحلة اللاحقة وبخار الماء فعله المؤثر مشابه للبخار أو (steam).

$$\text{steam economy} = \frac{\text{amount of vapor evaporated}}{\text{amount of steam used.}}$$

③

1- Forward Feed system for Triple Effect:

ويكون السائل والبخار باتجاه واحد.



$D_0 =$ كمية البخار المستخدم

$\lambda_0 =$ الحرارة الكامنة للتبخر

$T_0 =$ درجة حرارة البخار

$W =$ كمية السائل الداخل

$T_f =$ درجة حرارة السائل

$$\text{Steam economy} = \frac{D_1 + D_2 + D_3}{D_0}$$

$$\text{condenser load} = D_3$$

$$Q_1 = U_1 A_1 \Delta T_1 \quad \text{—— (3)}$$

$$\Delta T_1 = T_0 - T_1$$

$$Q_2 = U_2 A_2 \Delta T_2 \quad \text{—— (4)}$$

$$\Delta T_2 = T_1 - T_2$$

$$Q_3 = U_3 A_3 \Delta T_3 \quad \text{—— (5)}$$

$$\Delta T_3 = T_2 - T_3$$

ملاحظة مهمة:
دائمًا يتم استخدام vaccume في المبخرات ومن النقطة التي تسحب من D_3 وذلك لخفض درجة غليان السائل الداخل ومقاومة بالنسبة للمواد الغذائية لكي لا تتأثر بالحرارة.

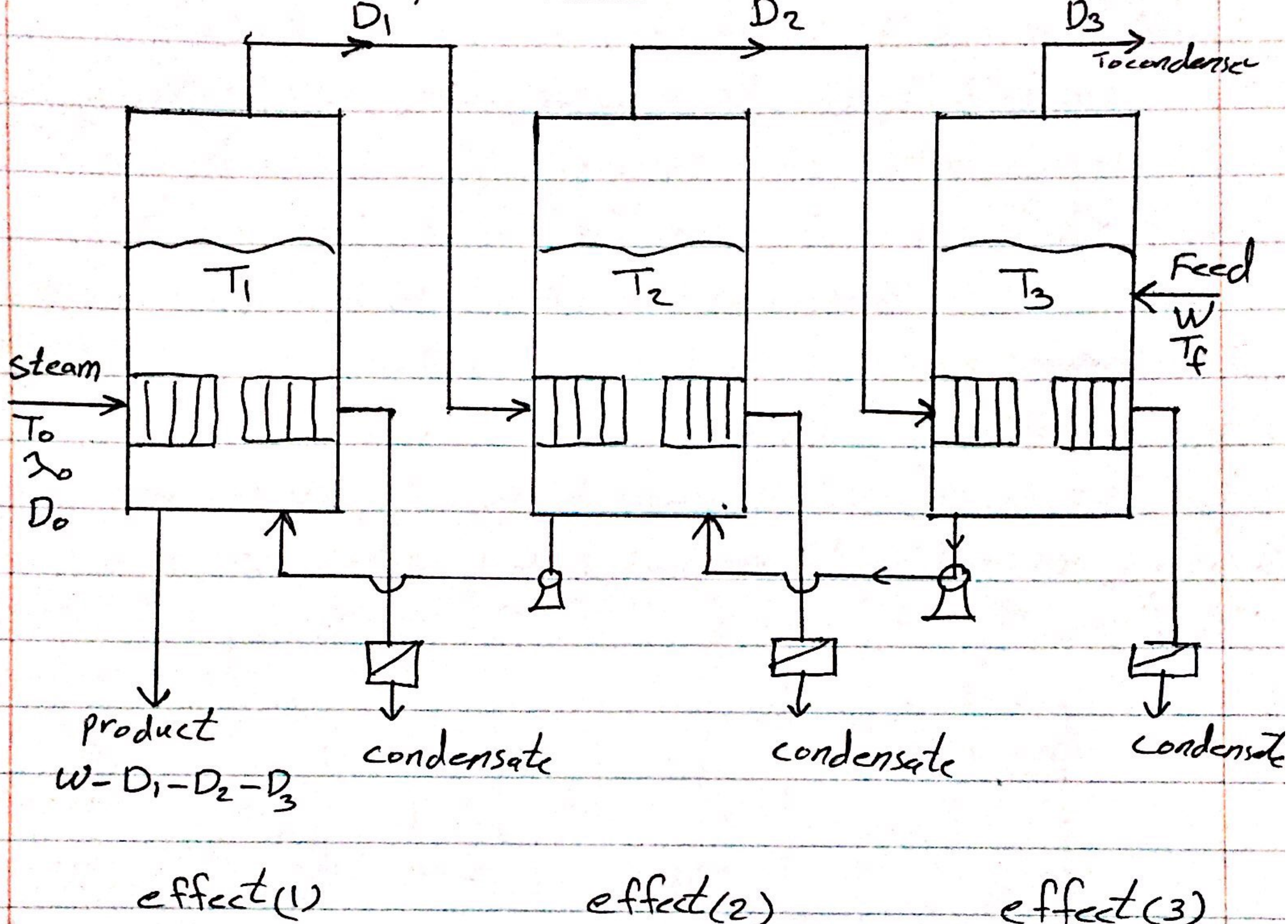
neglect the heat required to heat the feed from T_f to T_1, the heat Q_1 trasferred across A_1 appeare as latent heat in vapor D_1 and is used as steam in the second effect

Hence $Q_1 = Q_2 = Q_3$ —— (6)

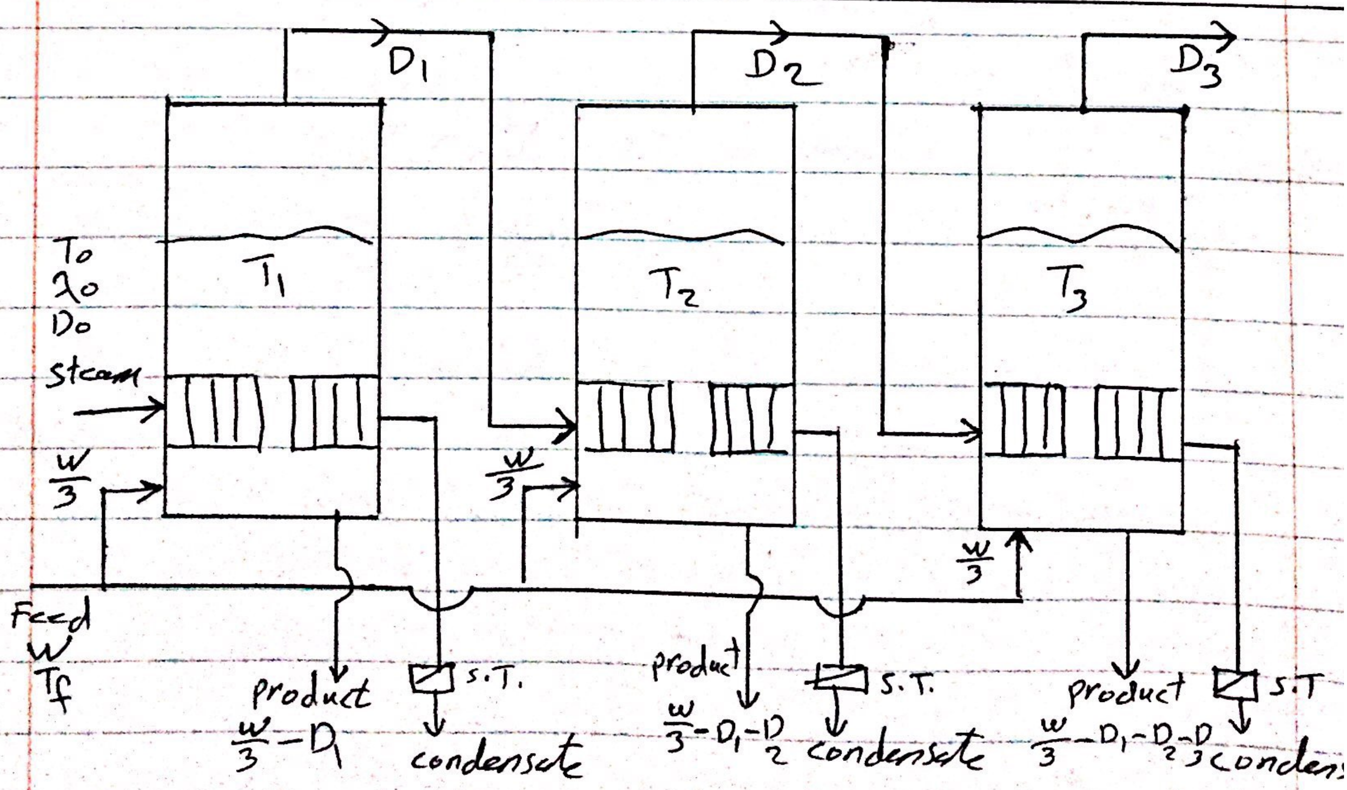
if $A_1 = A_2 = A_3$

$$U_1 \Delta T_1 = U_2 \Delta T_2 = U_3 \Delta T_3 \quad \text{—— (7)}$$

2) Back word feed arrangement for triple effect evaporator.



3) Arrangement of triple effect evaporator for parallel feed

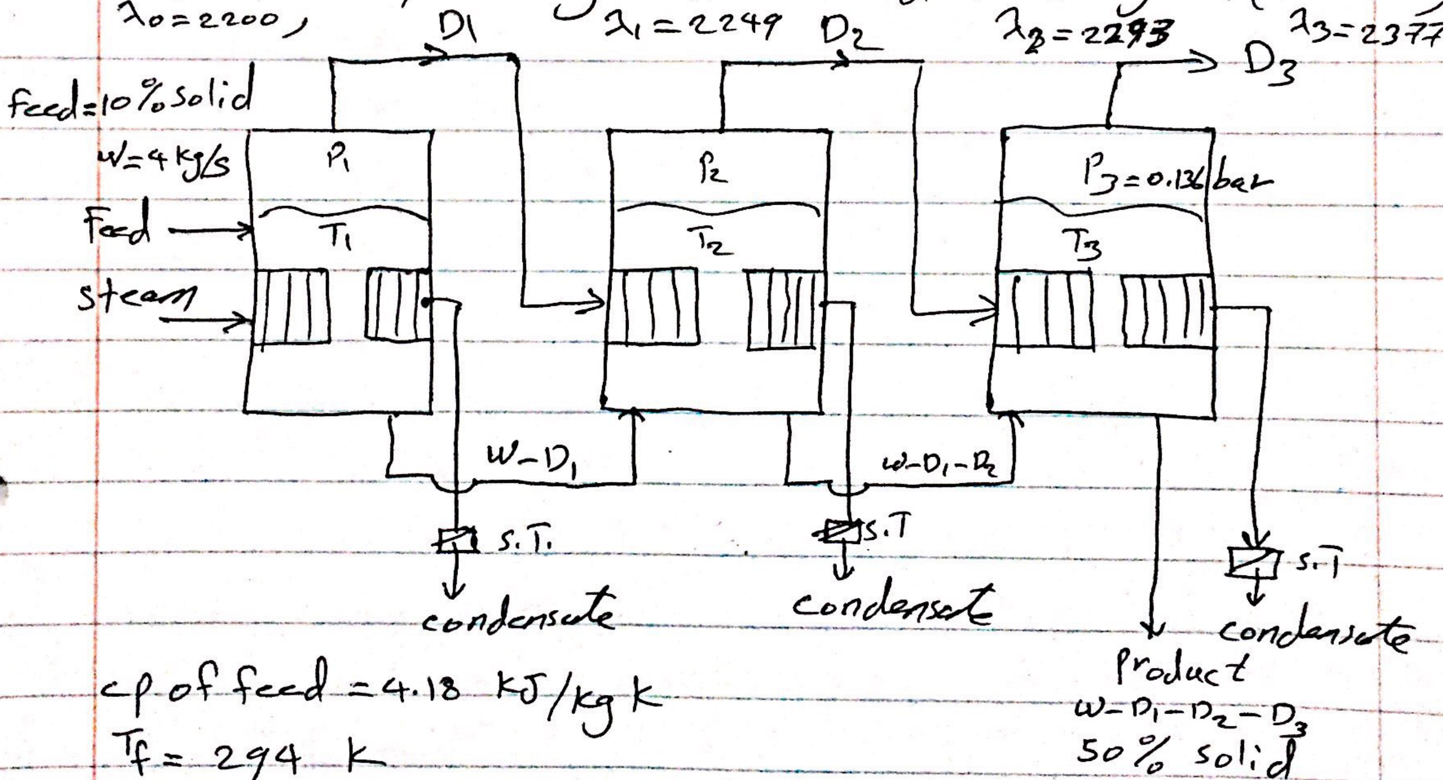


(5)

(1)

Example:

4 kg/s of liquor with 10% solid is feed at 294 K to first effect of triple effect unit. Liqour with 50% solid is to be with drawn from third effect which at pressure of 0.136 bar. The liquor will be assume to have a cp of 4.18 kJ/kg K) and have no B.P.R. Saturated dry steam at 205 kN/m^2 is feed to the heating element of the 1st effect and the condensate is removed at the steam temperature in each effect. If three unity are to have equal area. Find the steam consumption (D_o). Assume U_1, U_2, U_3 is 3.1, 2.0, 1 kW/m^2 K respectively. And Forward feed system (co-current)



cp of feed = 4.18 kJ/kg K

$T_f = 294$ K

steam used is saturated dry at pressure = 205 kN/m^2

from steam table $T_o = 394$ (درجة غليان)

P_3 of 3rd effect = 0.136, therefore the boiling point of water = 325 K

$$\Sigma \Delta T = T_o - T_3$$

$$= 394 - 325 = 69^\circ K$$

(6)

$$\Sigma \Delta T = \Delta T_1 + \Delta T_2 + \Delta T_3 = 69$$

$$U_1 \Delta T_1 = U_2 \Delta T_2 = U_3 \Delta T_3$$

$$3.1 \underset{\substack{\downarrow \\ 13}}{\Delta T_1} = 2 \underset{\substack{\downarrow \\ 20}}{\Delta T_2} = 1.0 \underset{\substack{\downarrow \\ 36}}{\Delta T_3}$$

Since the feed is cold it will be necessary to have greater value ΔT_1 than given by this analysis

$\Delta T_1 = 18$ K

$\Delta T_2 = 17$ K

$\Delta T_3 = 34$ K

69 K

$$\left.\begin{aligned} \Delta T_1 &= T_o - T_1 \\ 18 &= 394 - T_1 \end{aligned}\right\} \Rightarrow T_1 = 376 \text{ K}$$

$$\left.\begin{aligned} \Delta T_2 &= T_1 - T_2 \\ 17 &= 376 - T_2 \end{aligned}\right\} \Rightarrow T_2 = 359 \text{ K}$$

$$\left.\begin{aligned} \Delta T_3 &= T_2 - T_3 \\ &= 359 - T_3 \end{aligned}\right\} \Rightarrow T_3 = 325 \text{ K}$$

Energy balance for effect (1).

reference temp. $= T_1$

$$D_o \lambda_o + W c_p (T_f - T_1) = D_1 \lambda_1 + \cancel{(W - D_1) c_p (T_1 - T_1)}^{=0}$$

$$2200 D_o + 4 \times 4.18 (294 - 376) = 2249 D_1 \quad \text{—— (1)}$$

Energy balance on effect (2).

reference (T_2)

$$D_1 \lambda_1 + (W - D_1) c_p (T_1 - T_2) = D_2 \lambda_2 + \cancel{(W - D_1 - D_2) c_p (T_2 - T_2)}^{=0}$$

$$2249 D_1 + (4 - D_1) 4.18 (376 - 359) = 2293 D_2 \quad \text{—— (2)}$$

Energy balance on stage (3).

reference (T_3)

$$D_2 \lambda_2 + (W - D_1 - D_2) c_p (T_2 - T_3) = D_3 \lambda_3 + \cancel{(W - D_1 - D_2 - D_3) c_p (T_3 - T_3)}^{=0}$$

$$2293 D_2 + (4 - D_1 - D_2) 4.18 (359 - 325) = 2377 D_3 \quad \text{—— (3)}$$

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يوجد لدينا أربعة مجاهيل هما، D_0, D_1, D_2, D_3
∴ يجب أن نكون أربعة معادلات والآن عندنا ثلاثة معادلات
المعادلة الرابعة تشتق كما يلي :-

	solid	liquid	Total	% solid
Feed	0.4	3.6	4	10%
product	0.4	0.4	0.8	50%
evaporated		3.2	3.2	

$$\therefore D_1 + D_2 + D_3 = 3.2 \quad \text{——} \ (4)$$

kg/s amount of vapor evaporated from liquor

تكامل $D_1 = 0.99$ kg/s

$D_2 = 1.065$ kg/s

$D_3 = 1.635$ kg/s

$D_0 = 1.635$ amount of steam used

$$A_1 = \frac{D_0 \lambda_0}{U_1 \Delta T_1} = \frac{1.635 \times 2200}{3.1 \times 18} = 64.5 \ m^2$$

$$A_2 = \frac{D_1 \lambda_1}{U_2 \Delta T_2} = \frac{0.99 \times 2249}{2 \times 17} = 65.6 \ m^2$$

$$A_3 = \frac{D_2 \lambda_2}{U_3 \Delta T_3} = \frac{1.065 \times 2293}{1. \times 34} = 71.82 \ m^2$$

$$\text{steam economy} = \frac{\text{amount of vapor evaporated}}{\text{amount of steam used}}$$

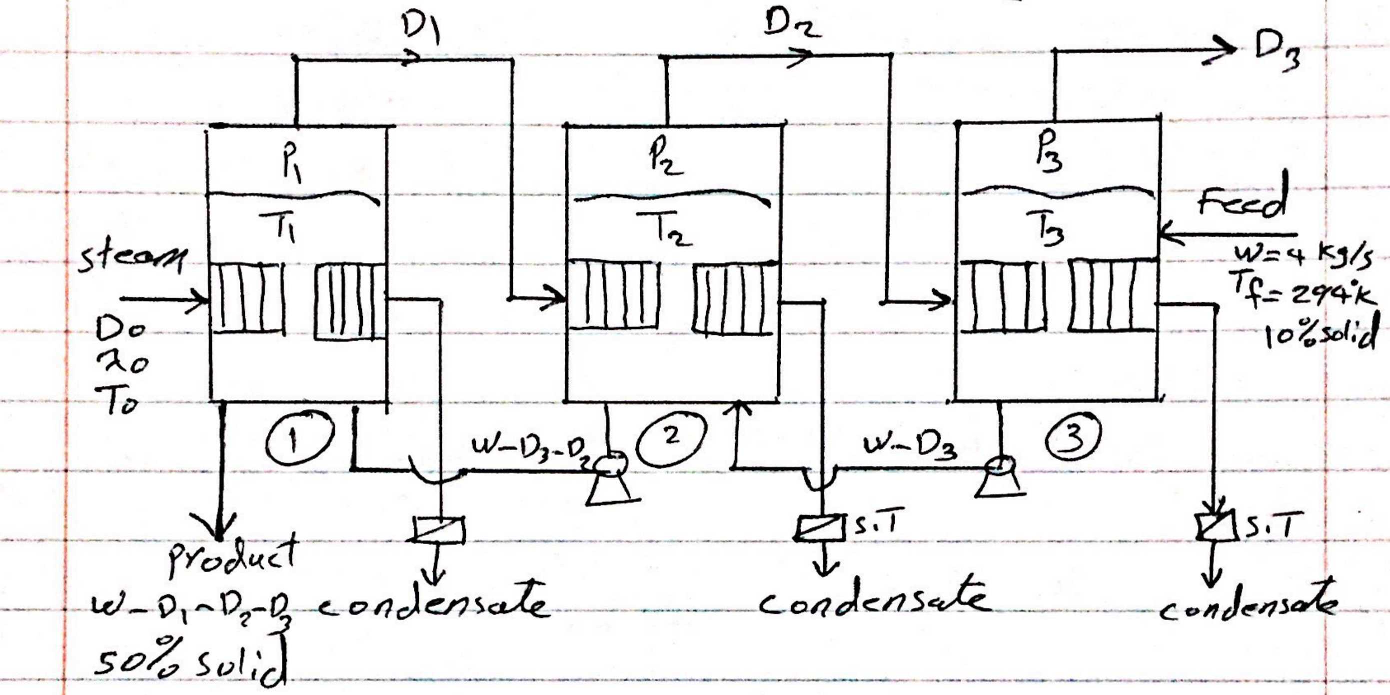
$$= \frac{D_1 + D_2 + D_3}{D_0} = \frac{3.2}{1.635} = 2.0$$

2

Example:

The same example (1) but Backword feed arrangement.

نحل السؤال الثاني وهو نفس السؤال الأول فقط يكون الاتجاه المعاكس



Effect (3) energy balance.

reference Temp. = T_3

$$D_2\lambda_2 + W\,cp(T_f - T_3) = D_3\lambda_3 + (W - D_3)\,cp\,\underbrace{(T_3 - T_3)}_{=0}$$

$$2334\,D_2 + 4 \times 4.18(294 - 325) = 2377\,D_3 \quad \text{—— (1)}$$

Effect (2) energy Balance.

reference Temp. = T_2

$$D_1\lambda_1 + (W - D_3)\,cp(T_3 - T_2) = D_2\lambda_2 + (W - D_3 - D_2)\,cp\,\underbrace{(T_2 - T_2)}_{=0}$$

$$2254\,D_1 + (4 - D_3)\,4.18\,(325 - 350) = 2314\,D_2 \quad \text{—— (2)}$$

Effect (1) energy balance.

reference Temp. = (T_1)

$$D_0\lambda_0 + (W - D_3 - D_2)\,cp(T_2 - T_1) = D_1\lambda_1 + (W - D_1 - D_2 - D_3)\,cp\,\underbrace{(T_1 - T_1)}_{=0}$$

$$2200\,D_0 + (4 - D_3 - D_2)\,cp\,(350 - 374) = 2254\,D_1 \quad \text{—— (3)}$$

$$D_1 + D_2 + D_3 = 3.2 \text{ kg/s} \quad \text{—— (4)}$$

ومن حل المعادلات بعد (4)

$D_1 = 1.261$

$D_2 = 1.086$

$D_3 = 0.853$

$D_0 = 1.387$ kg/s

$$A_1 = \frac{D_0 \lambda_0}{U_1 \Delta T_1} = \frac{(1.387)(2200)}{(3.1 \times 18)} = 54.6 \, m^2$$

$$A_2 = \frac{D_1 \lambda_1}{U_2 \Delta T_2} = \frac{(1.261)(2249)}{(2 \times 17)} = 83.411 \, m^2$$

$$A_3 = \frac{D_2 \lambda_2}{U_3 \Delta T_3} = \frac{1.086 \times 2293}{1 \times 34} = 71.83$$

$$\text{steam economy} = \frac{D_1 + D_2 + D_3}{D_0}$$

$$= \frac{3.2}{1.387} = 2.3$$

comparison between Forward & backword

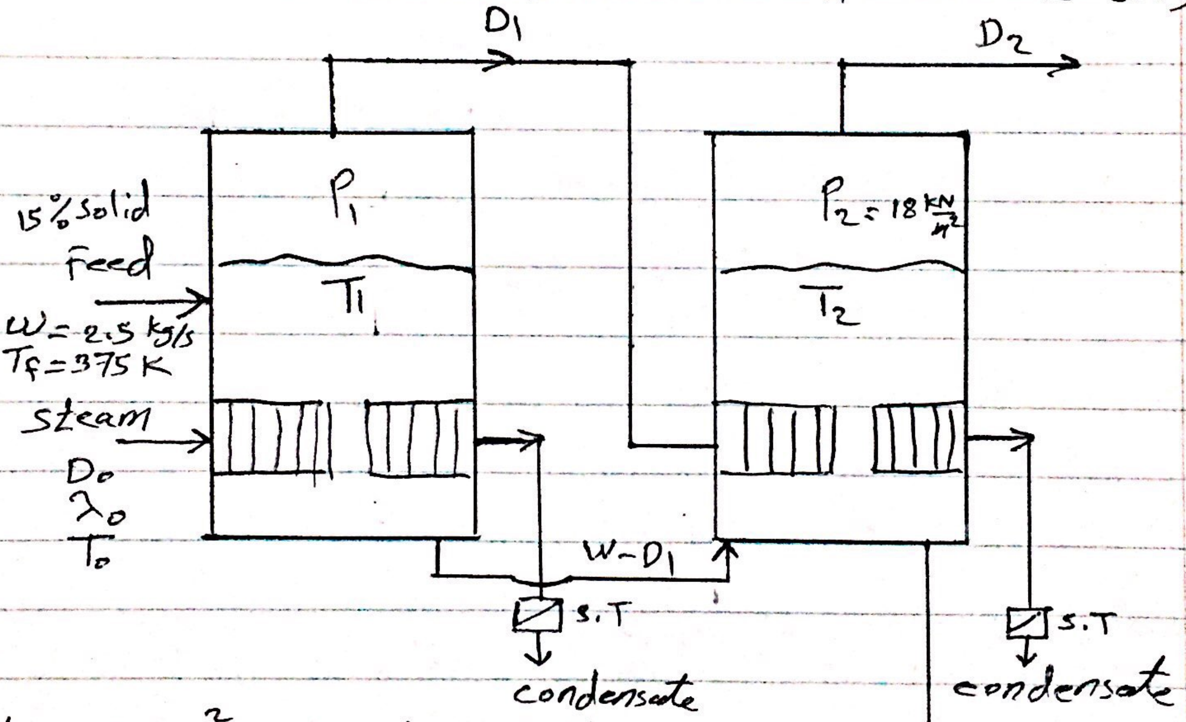
	Forward	backward
1) Total steam used	1.635 kg/s	1.387 kg/s
2) Steam economy	2.0	2.3
3) condenser load D_3 (kg/s)	1.44	0.853

∴ backword (countercurrent) is better,

(3)

Example:

A liquid containing 15% solid is concentrated to 55% solid in a double effect forward feed arrangement evaporated under pressure in the second effect of 18 kN/m². The feed is 2.5 kg/s at temperature of 375 K with cp of 3.75 kJ/kg K. (The boiling point rise B.P.R) of the concentrated liquor is 6 K and the steam feed to the first effect is 240 kN/m². U in the 1st and 2nd effect are 1.668 and 0.6 kW/m²K determine the heat transfer area on each effect. ($\lambda_0 = 2185$, $\lambda_1 = 2232$, $\lambda_2 = 2363$)



Product
$W - D_1 - D_2$
55% solid

At 18 kN/m² from steam table

$\Rightarrow T_2 = 331\ K$

$B.P.R. = 6\ K$

$\therefore T_2 = 331 + 6 = 337\ K$

$1.668\ \Delta T_1 = 0.6\ \Delta T_2$

$\Sigma\ \Delta T = \Delta T_1 + \Delta T_2$

$= 399 - 337 = 62\ K$

steam درجة حرارة　　　درجة حرارة المحلول

$\Sigma\ \Delta T = T_0 - T_2$

For steam input (saturated steam) at $240\ \frac{kN}{m^2} = 399\ k$

(11)

$\Delta T_2 + \Delta T_1 = 62$

$\Delta T_2 = 62 - \Delta T_1$ —— (1)

$U_1 \Delta T_1 = U_2 \Delta T_2$

$1.668\, \Delta T_1 = 0.6(62 - \Delta T_1)$

$\Delta T_1 = 16.4 \approx 17$

$\Delta T_2 = 45$

$T_0 = 399\ K$

$\left.\begin{array}{l}\Delta T_1 = T_0 - T_1 \\ 17 = 399 - T_1\end{array}\right\} \Rightarrow T_1 = 382$

$T_2 = 337$ $(\Delta T_2 = T_1 - T_2)\ (45 = 382 - T_2)$

<u>energy balance on stage (1)</u>

$D_0 \lambda_0 + W c_p (T_f - T_1) = D_1 \lambda_1 + 0$

$2185\, D_0 + 2.5 \times 3.75\, (375 - 382) = 2232\, D_1$ —— (1)

<u>energy balance on stage (2)</u>

$D_1 \lambda_1 + (W - D_1) c_p (T_1 - T_2) = D_2 \lambda_2 + 0$

$2232\, D_1 + (2.5 - D_1) \times 3.75\, (382 - 337) = 2363$ —— (2)

عندنا ثلاث مجاهيل D_0, D_1, D_2 ولهذا يجب أن نكون ثلاثة معادلات
المعادلة الثالثة تشتق كما يلي :-

	solid kg/s	liquid	Total	% solid
Feed	0.375	$2.5 - 0.375 = 2.125$	2.5	15 %
product	0.375	$0.375 \times \frac{45}{55} = 0.307$	0.682	55 %
Total		1.818	1.818	

$\therefore\ D_1 + D_2 = 1.818$

$D_0 = 0.924\ kg/s$

$D_1 = 0.875\ kg/s$

$D_2 = 0.943\ kg/s$

$$A_1 = \frac{D_0 \lambda_0}{U_1 \Delta T_1} = \frac{0.924 \times 2185}{1.66 \times 17} = 71.5 \ m^2$$

$$A_2 = \frac{D_1 \lambda_1}{U_2 \Delta T_2} = \frac{0.875 \times 2232}{0.63 \times 45} = 68.88 \ m^2$$

Hom work:

Solve the same example (3) but backward feed arrangement.