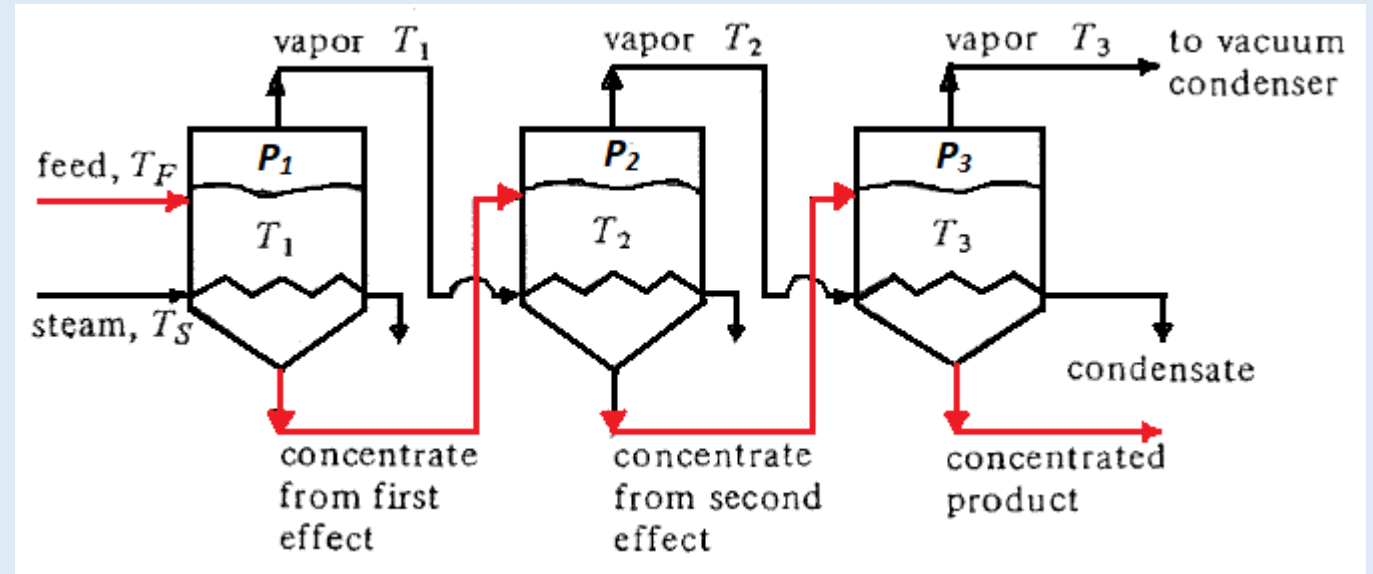


Evaporation

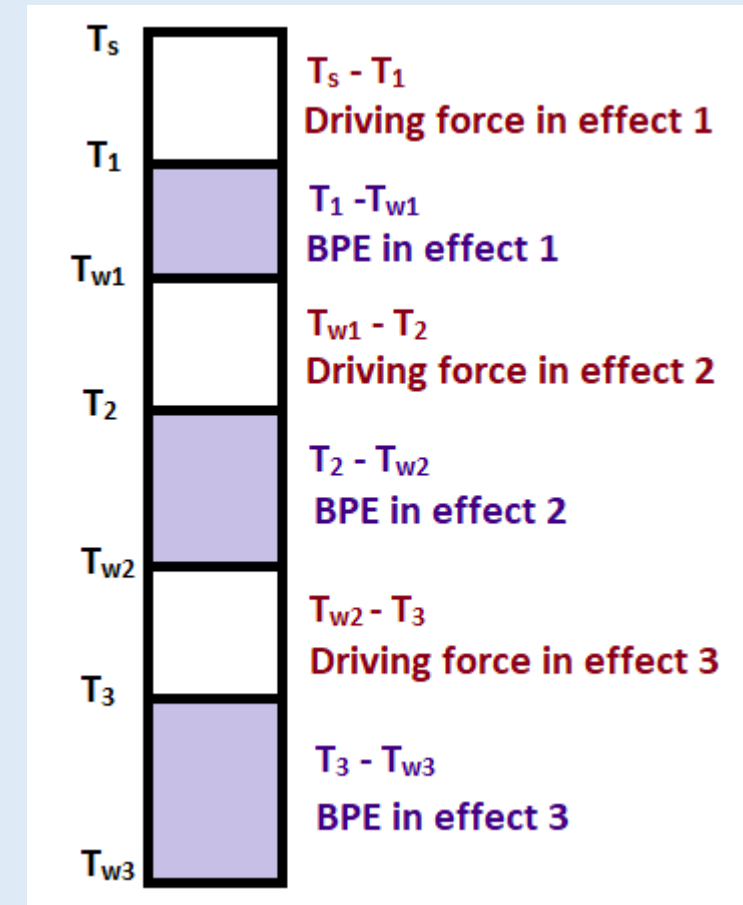
Multiple effect evaporators: Effect of boiling point elevation, temperature drop

Effect of boiling point elevation

- For a multiple effect evaporator, saturated steam (flowrate S , temperature T_S) enters the steam chest of the first effect
- The liquid in effect 1 boils at T_1 which is the temperature of the vapour generated in this effect
- The pressure in this effect is P_1 and the boiling point of the pure solvent at this pressure is T_{W1}
- The boiling point elevation in effect 1 is $(T_1 - T_{W1})$
- The vapour generated is a superheated vapour with superheat $\propto (T_1 - T_{W1})$
- The solution from effect 1 flows into effect 2 where the liquid boils at T_2 and the pressure is P_2 in the vapour space
- The boiling point of water at a pressure of P_2 is T_{W2} and the boiling point elevation (BPE) is $(T_2 - T_{W2})$
- The vapour from effect 1 enters the shell or steam chest of effect 2 with a degree of superheat
- The vapour immediately sheds the degree of superheat and attains the saturation temperature of T_{W1}



- The temperature driving force for heat transfer in the second effect is $(T_{w1} - T_2)$
 - Vapour from effect 2 enters the shell of effect 3 at a temperature of T_2
 - This vapour has a superheat $\propto (T_2 - T_{w2})$
 - This heat is immediately lost and the vapour attains a saturation temperature of T_{w2}
 - The boiling point of the liquid at $P = P_3$ is T_3 and boiling point elevation (BPE) is $(T_3 - T_{w3})$
 - The vapour generated in effect 3 is discarded
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- The boiling point elevation (BPE) and effective driving force in the three effects is shown alongside
 - The effective driving force in each effect is reduced because of BPE
 - In the first effect, the driving force is $(T_S - T_1)$ when it should have been $(T_S - T_{w1})$
 - The effect of BPE is the strongest in effect 3 as the liquid concentration is the highest here, leading to highest BPE
 - If a single evaporator at a pressure, P_3 is used instead of a triple effect evaporator., the available driving force will be $(T_S - T_3)$
 - This leads to the requirement of a smaller heat transfer area, but the steam economy will be much less



Temperature drop

- If the areas in the effects are A_1, A_2 and A_3 and the heat transfer coefficients are U_1, U_2 and U_3 then the heat transfer rates are written as,

$$Q_1 = U_1 A_1 (T_S - T_1) = U_1 A_1 \Delta T_1 \quad Q_2 = U_2 A_2 (T_{W1} - T_2) = U_2 A_2 \Delta T_2 \quad Q_3 = U_3 A_3 (T_{W2} - T_3) = U_3 A_3 \Delta T_3$$

- It is assumed that the heat transfer rates in the three effects are equal

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

- The *total available temperature drop* is $\sum \Delta T = \Delta T_1 + \Delta T_2 + \Delta T_3 = (T_S - T_{W3}) - \sum BPE$

- Where $\sum BPE = (T_1 - T_{W1}) + (T_2 - T_{W2}) + (T_3 - T_{W3})$

- The total available ΔT is distributed among the three effects

- It is usually customary to take $A_1 = A_2 = A_3 = A$, therefore, $U_1 \Delta T_1 A = U_2 \Delta T_2 A = U_3 \Delta T_3 A = Q$

$$\Delta T_1 = \frac{Q}{U_1 A}$$

$$\Delta T_2 = \frac{Q}{U_2 A}$$

$$\Delta T_3 = \frac{Q}{U_3 A}$$

$$\sum \Delta T = \frac{Q}{A} \left[\frac{1}{U_1} + \frac{1}{U_2} + \frac{1}{U_3} \right] = U_1 \Delta T_1 \left[\frac{1}{U_1} + \frac{1}{U_2} + \frac{1}{U_3} \right]$$

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

Similarly, ΔT_2 and ΔT_3 can be found out

Multiple effect evaporators: capacity and economy

- The *capacity of the triple effect evaporator* is obtained by adding the values for each evaporator

$$Q = Q_1 + Q_2 + Q_3 = U_1A_1\Delta T_1 + U_2A_2\Delta T_2 + U_3A_3\Delta T_3$$

- If A and U in each effect is the same,

$$Q = UA(\Delta T_1 + \Delta T_2 + \Delta T_3) = UA\Delta T$$

- If a single effect evaporator is used with the same U , A and ΔT , then we get the same Q , *i. e.*, the capacity is the same as a multi effect evaporator
- Thus, the total capacity of a multiple effect evaporator (having thrice the area) is not greater than that of a single effect evaporator having a heating surface equal to one of the effects and operating under the same end temperatures
- The boiling point elevation tends to make the capacity of the multiple effect evaporator less than that of the corresponding single effect
- The *steam economy of the triple effect evaporator* is given as,

$$\text{Steam economy} = \left(\frac{V_1 + V_2 + V_3}{S} \right)$$

- The increase in steam economy obtained in the multiple effect evaporator is at the expense of reduced capacity

Calculation for Multiple Effect Evaporators

- Overall balance:

$$F = L_3 + (V_1 + V_2 + V_3)$$

- Solid balance:

$$x_F F = x_3 L_3 + (V_1 + V_2 + V_3) \times 0$$

- Energy balance:

For Effect 1 : $Fh_F + S\lambda_{S1} = L_1h_{L1} + V_1H_{V1}$

$$\lambda_{S1} = H_S - h_S$$

$$h_F = C_{PF}(T_F - T_R)$$

$$h_{L1} = C_{PL}(T_1 - T_R)$$

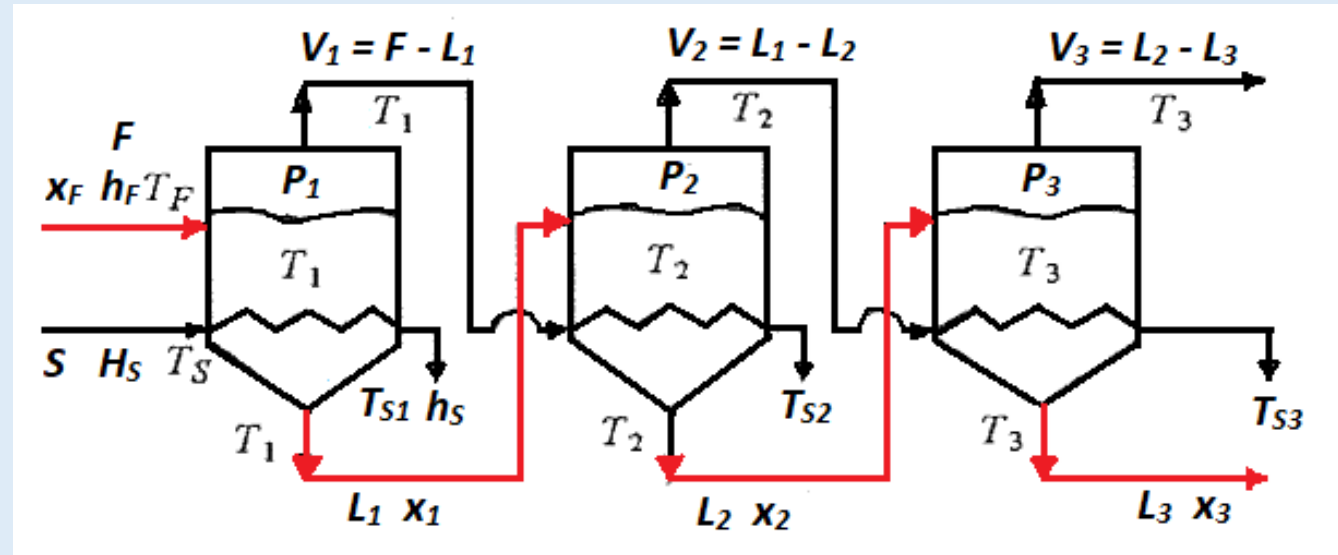
$$Fh_F + S\lambda_{S1} = (F - V_1)h_{L1} + V_1H_{V1}$$

For Effect 2 :

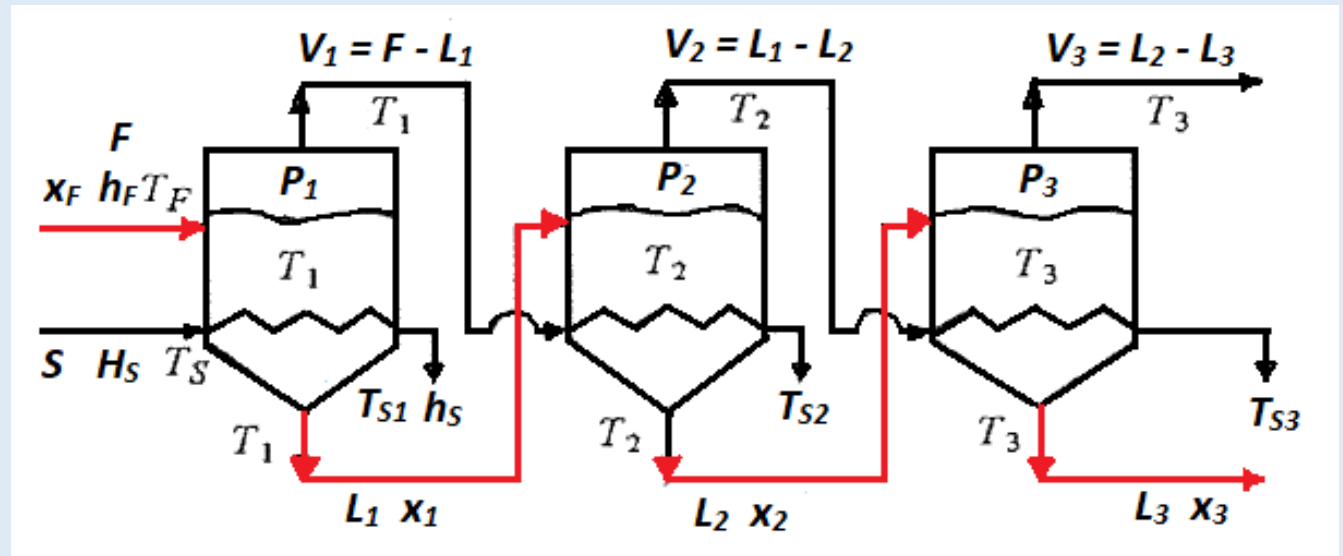
$$(F - V_1)h_{L1} + V_1\lambda_{S2} = (F - V_1 - V_2)h_{L2} + V_2H_{V2}$$

For Effect 3 :

$$(F - V_1 - V_2)h_{L2} + V_2\lambda_{S3} = (F - V_1 - V_2 - V_3)h_{L3} + V_3H_{V3}$$



- 1) The pressure (P_3) and the outlet composition (x_3) in the last effect is usually known – determine the boiling point in the last effect (with or without BPE)
- 2) Use overall mass balance and solid balance to determine total amount of vapour ($V_1 + V_2 + V_3$) evaporated
- 3) Assume equal amounts evaporated in each effect ($V_1 = V_2 = V_3$) to obtain L_1, L_2 and L_3
- 4) Estimate solid concentration in each effect, (x_1, x_2 and x_3)



- 5) Knowing the steam condition (T_s) and the temperature in the last effect (T_3), the total temperature drop ($\sum \Delta T$) can be estimated
- 6) This is used to calculate $\Delta T_1, \Delta T_2$ and ΔT_3 using previously given equations. If BPR is present, this has to be considered
- 7) Material and energy balance is carried out in each effect to determine the amounts vaporised (V_1, V_2, V_3) - these values should not vary too much from estimation in Step 3, otherwise calculations need to be repeated
- 8) Calculate Q_1, Q_2 and Q_3 in each effect ($Q_1 = S\lambda_{s1}, Q_2 = V_1\lambda_{s2}, Q_3 = V_2\lambda_{s3}$)
- 9) These values are then used to estimate A_1, A_2 and A_3
- 10) If A_1, A_2 and A_3 are not very close to each other, the calculations are repeated till this is achieved

Problem (double effect evaporator)

A 5% aqueous solution of high molecular weight solute has to be concentrated to 40% in a forward feed double effect evaporator at the rate of 8000 kg/h. The feed temperature is 40°C. Saturated steam at 3.5 kg/cm² gauge is available. A vacuum of 600 mm Hg is maintained in the second effect. Calculate the area, requirements, if two effects of equal areas are used.

The overall heat transfer coefficients are 550 kcal/hm²°C and 370 kcal/hm²°C in the first and second effect, respectively. The specific heat of the concentrated liquor is 0.87 kcal/kg°C.

- 1) The final concentration in the last effect is 40% or ($x_2 = 0.4$) and pressure in this effect is $(760 - 600) = 160 \text{ mm Hg}$

Temperature in this effect at 160 mm Hg pressure is = 61.36°C

- 2) Feed (F) = 8000 kg/h concentration = 5%

$$F = L_2 + (V_1 + V_2) \quad (\text{Total balance})$$

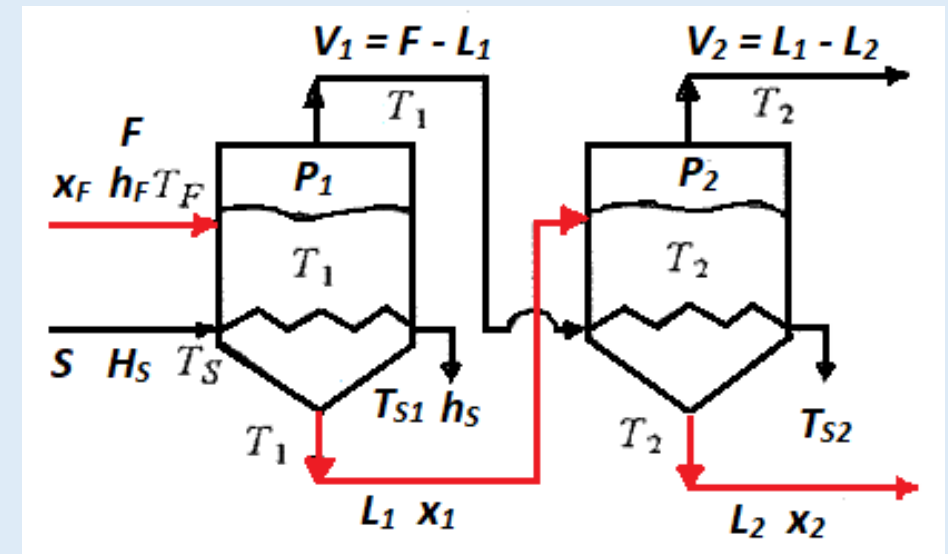
$$8000 = L_2 + (V_1 + V_2)$$

$$x_F F = x_2 L_2 \quad (\text{Solute balance})$$

$$0.05 \times 8000 = 0.4 \times L_2$$

$$L_2 = \mathbf{1000 \text{ kg/h}} \quad \text{and} \quad (V_1 + V_2) = \mathbf{7000 \text{ kg/h}}$$

- 3) Assume $V_1 = V_2 = \mathbf{3500 \text{ kg/h}}$



4) The steam used for heating is at $3.5 \text{ kg/cm}^2 \text{ gauge} = 3.5 \text{ kg/cm}^2 \text{ gauge} + 1 \text{ kg/cm}^2 = 4.5 \text{ kg/cm}^2 \text{ absolute} = 456 \text{ kPa}$

Saturation temperature of the steam = 148.36°C and the heat of vaporization (λ_{S1}) = 506.98 kcal/kg

5) Now, $\sum \Delta T = 148.36 - 61.36 = 87^\circ\text{C}$

6) If the areas are equal, $U_1 \Delta T_1 = U_2 \Delta T_2$

$$550 \Delta T_1 = 370 \Delta T_2$$

$$550 \Delta T_1 = 370(87 - \Delta T_1) = 32190 - 370 \Delta T_1$$

$$920 \Delta T_1 = 32190$$

$$\Delta T_1 = 34.989 = 35^\circ\text{C} \text{ and } \Delta T_2 = 52^\circ\text{C}$$

Therefore, **temperature in the first effect (ΔT_1) is $148.36 - 35 = 113.36^\circ\text{C}$**

7) Energy balance on the first effect (Reference temperature is taken as 0°C)

$$C_p \text{ of pure water at } 40^\circ\text{C} = 0.9987 \text{ kcal/h}^\circ\text{C}$$

$$C_p \text{ of concentrated liquor} = 0.87 \text{ kcal/h}^\circ\text{C}$$

$$C_p \text{ of liquid from 1st effect} = \frac{0.9987 + 0.87}{2} = 0.93435 \text{ kcal/h}^\circ\text{C}$$

$$Fh_F + S\lambda_{S1} = (F - V_1)h_{L1} + V_1H_{V1} \quad H_{V1} \text{ at } 113.36^\circ\text{C} = 645.11 \text{ kcal/kg}$$

$$8000 \times 0.9987(40 - 0) + S(506.98) = (8000 - V_1) \times 0.93435 \times (113.36 - 0) + V_1 \times 645.11$$

$$8000 \times 0.9987(40 - 0) + S(506.98) = (8000 - V_1) \times 0.93435 \times (113.36 - 0) + V_1 \times 645.11$$

$$319584 + S(506.98) = 847343.33 - 105.918V_1 + 645.11V_1$$

$$S(506.98) = 527759.33 + 539.192V_1$$

$$S = 1.0635 V_1 + 1040.986$$

Energy balance on the second effect (Reference temperature is taken as 0°C)

$$(F - V_1)h_{L1} + V_1\lambda_{S2} = (F - V_1 - V_2)h_{L2} + V_2H_{V2}$$

$$H_{V2} \text{ at } 61.36^\circ\text{C} = 624.88 \text{ kcal/kg}$$

$$(\lambda_{S2}) \text{ at } 113.36^\circ\text{C} = 531.34 \text{ kcal/kg}$$

$$(8000 - V_1) \times 0.93435 \times (113.36 - 0) + V_1 \times 531.34 = (8000 - V_1 - V_2) \times 0.87 \times (61.36 - 0) + V_2 \times 624.88$$

$$847343.33 - 105.918V_1 + V_1(531.34) = (8000 - 7000)53.3919 + 624.88V_2$$

$$425.422V_1 + 793951.43 = 624.88V_2$$

From mass balance, $(V_1 + V_2) = 7000 \text{ kg/h}$

Replacing this in the above equation we have, $425.422V_1 = 624.88(7000 - V_1) - 793951.43$

$$425.422V_1 = 4374160 - 624.88V_1 - 793951.43$$

$$1050.302V_1 = 3580208.57$$

$$V_1 = 3408.742 \text{ kg/h}$$

$$V_2 = 3591.258 \text{ kg/h}$$

$$S = 4666.183 \text{ kg/h}$$

$$A_1 = \frac{4666.183 \times 506.98}{550 \times 35} = 122.89 \text{ m}^2$$

$$A_1 = \frac{3408.742 \times 531.34}{370 \times 52} = 94.14 \text{ m}^2$$

Since the areas of the two effects are not equal, a second trial is carried out choosing different values of ΔT_1 and ΔT_2

Trial 2

6) Let us assume, $\Delta T_1 = 40^\circ\text{C}$ and $\Delta T_2 = 47^\circ\text{C}$

Temperature in the second effect (ΔT_1) is 61.36°C

H_{V2} at $61.36^\circ\text{C} = 624.88 \text{ kcal/kg}$

temperature in the first effect (ΔT_1) is $148.36 - 40 = 61.36 + 47 = 108.36^\circ\text{C}$

H_{V1} at $108.36^\circ\text{C} = 643.3 \text{ kcal/kg}$

Heat of vaporization (λ_{S2}) = 534.59 kcal/kg

7) **Energy balance on the first effect** (Reference temperature is taken as 0°C)

$$Fh_F + S\lambda_{S1} = (F - V_1)h_{L1} + V_1H_{V1}$$

$$8000 \times 0.9987(40 - 0) + S(506.98) = (8000 - V_1) \times 0.93435 \times (108.36 - 0) + V_1 \times 643.3$$

$$319584 + S(506.98) = 8100044.076 - 101.256V_1 + 643.3V_1$$

$$S(506.98) = 490460.076 + 542.043V_1$$

$$S = 1.0692 V_1 + 967.415$$

Trial 2 - Energy balance on the second effect (Reference temperature is taken as 0°C)

$$(F - V_1)h_{L1} + V_1\lambda_{S2} = (F - V_1 - V_2)h_{L2} + V_2H_{V2}$$

$$H_{V2} \text{ at } 61.36^\circ\text{C} = 624.88 \text{ kcal/kg}$$

$$(\lambda_{S2}) \text{ at } 108.36^\circ\text{C} = 534.59 \text{ kcal/kg}$$

$$(8000 - V_1) \times 0.93435 \times (108.36 - 0) + V_1 \times 534.59 = (8000 - V_1 - V_2) \times 0.87 \times (61.36 - 0) + V_2 \times 624.88$$

$$810044.076 - 101.256V_1 + V_1(534.59) = (8000 - 7000)53.3919 + 624.88V_2$$

$$433.334V_1 + 756652.18 = 624.88V_2$$

From mass balance, $(V_1 + V_2) = 7000 \text{ kg/h}$

Replacing this in the above equation we have, $433.334V_1 = 624.88(7000 - V_1) - 756652.18$

$$425.422V_1 = 4374160 - 624.88V_1 - 793951.43$$

$$1058.21V_1 = 3617507.82$$

$$V_1 = 3418.52 \text{ kg/h}$$

$$V_2 = 3581.48 \text{ kg/h}$$

$$S = 4622.496 \text{ kg/h}$$

$$A_1 = \frac{4622.496 \times 506.98}{550 \times 40} = 106.52 \text{ m}^2$$

$$A_1 = \frac{3418.52 \times 534.59}{370 \times 47} = 105.09 \text{ m}^2$$

Since the areas of the two effects are almost equal, these values are acceptable for areas of the two effects