Single effect

$\dot{m}_f = 21000$ kg/h

$x_f = 0.1$, $x_p = 0.5$

$BPR = 1.78x + 6.22x^2 = 2.45°C$

for 13.4 Kpa (1.941 psi), $T_{sat} = 51.67°C$

$T_1 = 51.67 + 2.45 = 54.12°C$

$C_{p,f} = 3726$ J/kg K (sugar solution)

Steam :- 205.5 Kpa $T_s = 121.06°C$

$\lambda_s = 2199.646$ KJ/kg

$\dot{m}_f x_f = \dot{m}_p x_p$

$21000 \times 0.1 = \dot{m}_p \times 0.5$

$\dot{m}_p = 4200$ kg/hr

$\dot{m}_f = \dot{m}_v + \dot{m}_p$

$\dot{m}_v = 16800$ kg/hr

$\dot{m}_f C_{pf} (T_f - T_{ref}) + \dot{m}_s \lambda_s = \dot{m}_v H_{vap} + \dot{m}_p C_{p_p} (T_s - T_{ref})$

$T_f = 25°C$ $H_{vap} = 2600$ KJ/kg (Steam table at $T_1 = 54.12°C$)

$T_{ref} = 0°C$ $C_{p_p} = 2923.608$ KJ/kg (" ")

$21000 \times 3726 \times 25 + \dot{m}_s \times 2199.646 = 16800 \times 2600 + 4200 \times 2923.6 \times 121.$

$\dot{m}_s = 19239.446$ kg/hr

$q = \dot{m}_s \lambda_s = 19239.446 \times 2199.646 = 42319970.91$ KJ/hr

$= 1.175 \times 10 \times 10^7$ W

$T_w = \frac{25 + 121.01}{2} = 73.03^\circ C$

$T_f = \frac{73.03 + 121.06}{2} = 97.045^\circ C$

$\rho_l = 942.92 \ (kg/m^3)$ } from steam table
$\rho_v = 1.12 \ (kg/m^3)$ }

$\mu_l = 0.0120 \times 10^{-3} \ Pa.S$ } at T_f
$K_l = 0.0235 \ W/m.K$ }

$$Nu = \frac{h_o L}{K_l} = 1.12 \left(\frac{\rho_l (\rho_l - \rho_v) g h_{fg} L^3}{\mu_l K_l \Delta T} \right)^{1/4}$$

$\Delta T = T_{sat} - T_w = 48.02^\circ C$

$h_o = 767.6 \ (W/m^2K)$

2 inch IPS → O.D = 2.38 inch
I.D = 1.939 inch

$L = 2m$

$\mu_l = 1.74 \times 10^{-3} \ Pa.S$

$C_p = .3726$

$K = 0.574$ → (at $t = 25^\circ C$)

$$Pr = \frac{1.74 \times 10^{-3} \times 3726}{0.574} = 11.2948$$

$$N_{Re} = \frac{4\dot{m}_f}{\pi D \mu_l} = \frac{4 \times 21000}{\pi \times 0.05 \times 1.74 \times 10^{-3} \times 3600} =$$

$= 85370.467$

μ_b — at $T_f = 97.045°C$

$\mu_b = 0.59\ cP$

$\mu_w = 0.66\ cP$

$D_i = 0.05m$

at T_w

$$N_{Nu} = \frac{h_i D_i}{k} = 0.027 \times N_{Re}^{0.8} N_{Pr}^{1/3} \times \left(\frac{\mu_b}{\mu_w}\right)^{0.14}$$

$$h_i = 6032.45\ w/m^2K$$

$$U = \frac{h_i h_o}{h_i + h_o} = 681.057$$

$q = UA\Delta T =$ $\Delta T = 121.06 - 54.12$

$A = 257.732\ m^2$

cost:-

$$C_p = C_{e,cs}\left[(1+f_p)f_m + (f_{er} + f_{al} + f_i + f_c + f_s + f_a)\right]$$

$C_{e,cs} = a + bS^n = 17000 + 13,500 \times (257.73)^{0.6} =$

$= 3,59,752.5629 \times 1.1016 = 396329.079$

$C_p = 11,512,010 \times 1.1016 \times 1.1016 = 12682451.2061$

$$N_T = \frac{257.73}{\pi \times 0.05 \times 2} = 724.88$$

$$A_{tube\ sheet} = \frac{0.88 \times 1 \times 724.88}{0.85} \times 10 = 7555.80$$

$$\frac{\pi D_{evap}^2}{4} = (1.25) A_T$$

$D_{evap} = 109.6605\ m$

$A_{evap} = 9444.66\ m^2$

$\frac{\pi d^2}{4} = A \Rightarrow d = \sqrt{\frac{4A}{\pi}}$

Steam inlet / condensate outlet

$A = \frac{\dot{m}_s}{\rho_v} = \frac{19239.446}{1.234 \times 27 \times 3600} = 0.1604\ m^2 \Rightarrow d = .4519\ m$

Vapour outlet

$A = \frac{\dot{m}_v}{\rho_v} = \frac{16809}{1.234 \times 27 \times 3600} = 0.1400\ m^2 \Rightarrow d = .4222\ m$

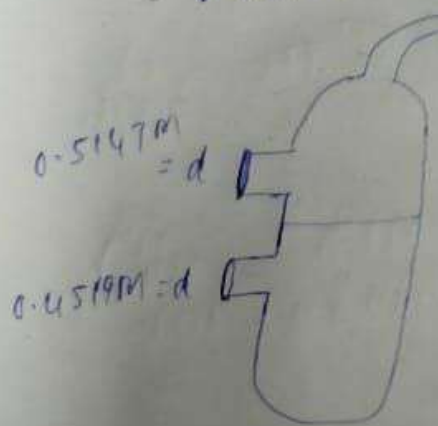
Fluid inlet

$A = \frac{\dot{m}_f}{\rho_f} = \frac{21000}{1.038 \times 27 \times 3600} = 0.2081\ m^2 \Rightarrow d = 0.5147\ m$

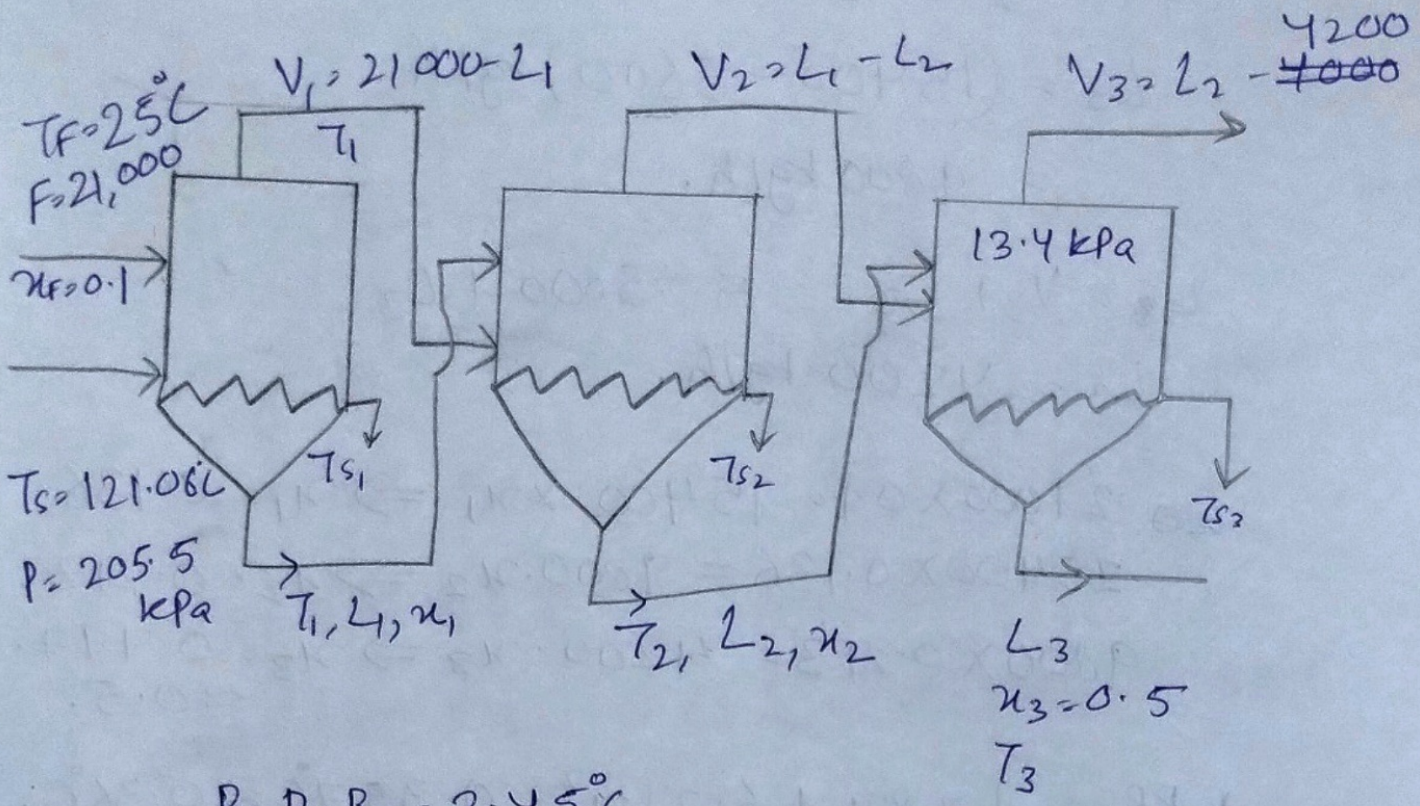
$R_d = \frac{\text{flowrate of steam}}{0.0172\ A_{evap}} \left(\frac{\rho_v}{\rho_L - \rho_v}\right)^{1/2}$

$= \frac{19239.446}{0.0172 \times 9444.66 \times 3600} \times \left(\frac{1.16}{941.92 - 1.16}\right)^{1/2}$

$= 0.00154$ → Hence no entrainment $(0 < Rd < 0.5)$



3-Effect Evaporator



B.P.R$_3$ = 2.45°C

T_3 = 54.12°C.

$F = 21,000 = L_3 + V_1 + V_2 + V_3$.

$21000 \times 0.1 = L_3 \times 0.5 + (V_1 + V_2 + V_3) \times 0$

$L_3 = 4200$ kg/h $= \dot{m}_p$.

$V_1 + V_2 + V_3 = 16,800$ kg/h.

$V_1 = V_2 = V_3 = 5600$ kg/h.

$F = 21000 = V_1 + L_1 =$

$L_1 = (21000 - 5600)$ kg/h.

$= 15400$ kg/h

$L_1 = V_2 + L_2$

$L_2 = (15400 - 5600)$ kg/h.

$= 9800$ kg/h.

$L_2 = V_3 + L_3 = 5600 + L_3$

$L_3 = 4200$ kg/h.

$21000 \times 0.1 = 15400 \times x_1 \Rightarrow x_1 = 0.136.$

$15400 \times 0.136 = 9800 \cdot x_2 \Rightarrow x_2 = 0.213.$

$9800 \times 0.213 = 4200 \cdot x_3 \Rightarrow x_3 = 0.497.$

$\approx 0.5.$

$BPR_1 = 1.78x_1 + 6.22x_1^2 = 0.357°C \approx 0.36°C.$

$BPR_2 = 1.78x_2 + 6.22x_2^2 = 0.66°C.$

$BPR_3 = 1.78x_3 + 6.22x_3^2 = 2.45°C.$

$\Delta T_{available} = 121.06 - 51.67 - (0.36 + 0.66 + 2.45).$

$= 65.92°C.$

$\Delta T_1 = \sum \Delta T_{avl.} \dfrac{1/U_1}{1/U_1 + 1/U_2 + 1/U_3}$

$= \dfrac{1/3123}{1/3123 + \frac{1}{1987} + \frac{1}{1136}} \times 65.92.$

$= 12.38°C \qquad 15.54$

$\Delta T_2 = 19.49^\circ C$ 18.35

$\Delta T_3 = 34.06^\circ C$ 32.04.

$T_1 = T_{S1} - \Delta T_1$

$= 121.06 - 15.54$

$= 105.52^\circ C$

$T_2 = 105.52 - 0.36 - 18.35 = 86.81^\circ C$

$T_{S2} = 105.52 - 0.36 = 105.16^\circ C$.

$T_3 = 86.81^\circ C - 0.66^\circ C$ $\overset{-32.04}{\cancel{86.15^\circ C}}$. $54.11^\circ C$.

$T_{S3} = 86.81 - 0.66 = 86.15^\circ C$

Effect 1 Effect 2 Effect 3 Condenser.

$T_{S1} = 121.06^\circ C \rightarrow T_{S2} = 105.16^\circ C \rightarrow T_{S3} = 86.15^\circ C \rightarrow T_{S4} = 57.66^\circ C$.

$T_1 = 105.52^\circ C$ $T_2 = 86.81^\circ C$ $T_3 = \cancel{86}.54.11^\circ C$

F: $C_p = 4.19 - 2.35(0.1) = 3.955\ kJ/kg.k$.

L1: $C_p = 4.19 - 2.35(0.136) = 3.869\ kJ/kg.k$.

L2: $C_p = 4.19 - 2.35(0.213) = 3.689\ kJ/kg.k$.

L3: $C_p = 4.19 - (2.35)(0.5) = 3.015\ kJ/kg.k$.

Effect 1:

$H_1 = H_{S2} + 1.884(BPR_1)$

$= 2684.1 + 1.884(0.36)$

$= 2684.78$

$= 2685\ KJ/kg.$

$\lambda_{S1} = H_{S1} - h_{S1}$

$= 2199.61\ KJ/kg.$

effect 2:

$H_2 = H_{S3} + 1.884\ (0.65)$

$= 2654 + 1.884 \cdot 0.66$

$= 2655.243.$

$\lambda_{S2} = 2243.241\ KJ/kg.$

effect 3:

$H_3 = 2594.04 + 1.884(2.45)$

$= 2599.66\ KJ/kg.$

$\lambda_{S3} = 2292.98\ KJ/kg.$

$V_1 = 21000 - L_1$

$V_2 = L_1 - L_2$

$V_3 = L_2 - 4200.$

$L_3 = 4200\ kg/h.$

$A \quad 5.14 \times 10^6 \qquad 105.91\,m^2.$

1) $F C_p (T_F - 0) + S \lambda_{S_1} = L_1 C_p (T_1 - 0) + V_1 H_1$

$21000 \times 3.955 (25) + S (2199.61)$
$= L_1 (3.869)(105.52 - 0)$
$+ (21000 - L_1)(2685)$

$1977500 + 2199.61 S = 408.25 L_1$
$+ 56385000 - 2685 L_1$

$2199.61 S = 54{,}407{,}500 - 2276.75 L_1$

2) $L_1 C_p (T_1 - 0) + V_1 \lambda_{S_2} = L_2 C_p (T_2 - 0) + V_2 H_2.$

$L_1 (3.869)(105.52) + (21000 - L_1)(2243.241)$
$= L_2 (3.689)(86.81)$
$+ (L_1 - L_2)(2655)$

$408.25 L_1 + 47108061 - 2243.241 L_1$
$= L_2 (320.242 - 2655).$
$+ 2655 L_1$

$47108061 = 4489.99 L_1 - 2334.758 L_2.$

3) $L_2 C_p (T_2 - 0) + V_2 \lambda_{s3} = L_3 C_p (T_3 - 0) + V_3 H_3$.

$L_2 (3.689)(86.81) + (L_1 - L_2)(2292.98)$

$= 4200(3.015)(54.11)$

$+ (L_2 - 4200)(2599.66)$.

$320.24 L_2 + 2292.98 L_1 - 2292.98 L_2$

$= 685;194.93 + 2599.66 L_2$

$- 10918572$.

$2292.98 L_1 - 4572.4 L_2 = -10233377.07$.

~~$S = 8414$~~

$S = 8414.99$.

$L_1 = 15767.1$ $\quad V_1 = 5232.9$

$L_2 = 10145$. $\quad V_2 = 5622.1$

$L_3 = 4200$. $\quad V_3 = 5945$

$q_1 = S \lambda_{s1} = \frac{8414.99}{3600} (2199.61) \times 1000$

$= 5.14 \times 10^6$ W.

$q_2 = V_1 \lambda_{s2} = \frac{5232.9}{3600} (2243.241) \times 1000$.

$= 3.26 \times 10^6$ W.

$q_3 = V_2 \lambda_{s3} = \frac{5622.1}{3600} (2292.98) \times 1000$

$= 3.58 \times 10^6$ W.

$$A_1 = \frac{5.14 \times 10^6}{3123 \times 15.54} = 105.41 m^2.$$

$$A_2 = \frac{q_2}{U_2 \Delta T_2} = \frac{3.26 \times 10^6}{1987 \times 18.35}$$

$$= 89.40 m^2.$$

$$A_3 = \frac{q_3}{U_3 \Delta T_3} = \frac{3.58 \times 10^6}{1136 \times 32.04}$$

$$= 98.35 m^2.$$

Cost:

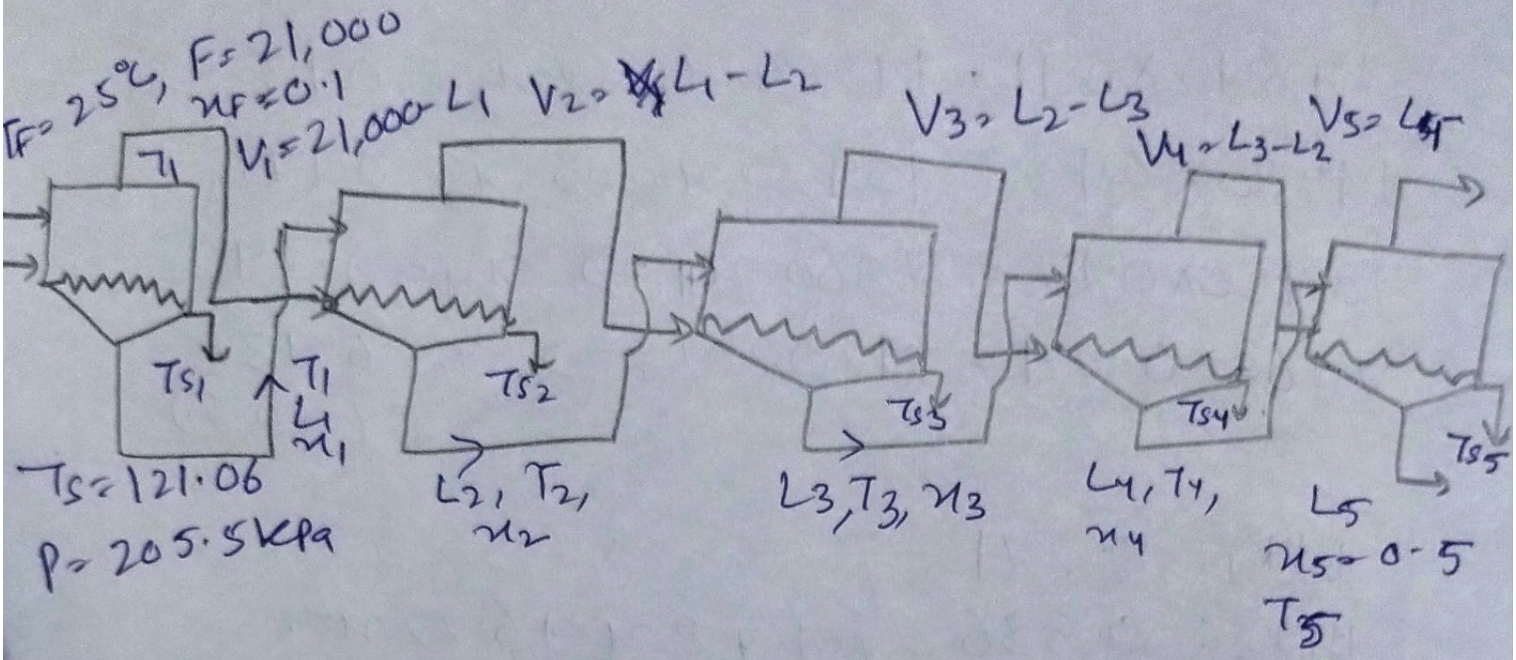
$$Ce = 17000 + 13500(98.35)^{0.6}.$$

$$= 228835.326.$$

$$Cp = 228835.326[(1+0.8)1 + (0.3+0.2 + 0.3+0.3+0.2 + 0.1)]$$

$$= ~~732~~ 732273.043.$$

5- Effect Evaporator



$BPR_5 = 2.45°C$

$T_5 = 54.12°C.$

$F = 21,000 = L_5 + V_1 + V_2 + V_3 + V_4 + V_5$

$21000 \times 0.1 = L_5 \times 0.5$

$L_5 = 4200 kg/h = \dot{m}_p$

$V_1 + V_2 + V_3 + V_4 + V_5 = 16000 kg/h.$

$V_1 = V_2 = V_3 = V_4 = V_5 = 3360 kg/h.$

$F = V_1 + L_1$

$L_1 = 17640 kg/hr$

$L_2 = 17640 - 3360 = 14,280 kg/hr$

$L_3 = 14280 - 3360 = 10920 kg/hr$

$L_4 = 10920 kg/hr - 3360 kg = 7560 kg/h$

$L_5 = 7560 - 3360 = 4200 kg/hr.$

$21000 \times 0.1 = 17640\, x_1 \Rightarrow x_1 = 0.11$.

$17640 \times 0.11 = 14280\, x_2 \Rightarrow x_2 = 0.13$.

$14280 \times 0.13 = 10920\, x_3 \Rightarrow x_3 = 0.17$.

$10920 \times 0.17 = 7560\, x_4 \Rightarrow x_4 = 0.24$

$7560 \times 0.24 = 4200\, x_5 \Rightarrow x_5 = 0.432$
(≈ 0.5).

$BPR_1 : 0.271$
$BPR_2 : 0.336$
$BPR_3 : 0.482$
$BPR_4 : 0.785$
$BPR_5 : 2.45$

$\Big\}\ 1.78x + 6.22x^2$.

$\Delta T_{available} = 121.06 - 51.67 - (0.27 + 0.33 + 0.49 + 0.79 + 2.45)$.

$= 65.06$.

$$\Delta T_1 = \sum \Delta T_{ava.} \frac{h_{U_1}}{h_{L_1} + h_{L_2} + h_{L_3} + h_{L_4} + h_{L_5}}$$

$$= 65.06 \frac{h_{3123}}{\left(h_{3123} + \frac{1}{2555} + \frac{1}{1907} + \frac{1}{1561.5} + \frac{1}{1136}\right)}$$

$= 7.61^\circ C$.

Similarly,

~~$T_2 = \sum$~~ $\Delta T_2 = 9.29\,^\circ C$

$\Delta T_3 = 12.07\,^\circ C$

$\Delta T_4 = 15.20\,^\circ C$

$\Delta T_5 = 20.89\,^\circ C$

Now,

$T_1 = T_{S_1} - \Delta T_1 = 121.06 - 7.61 = 113.45\,^\circ C$

$T_2 = T_1 - BPR_1 - \Delta T_2 = 103.889\,^\circ C$

$T_{S2} = T_1 - BPR_1 = 113.179\,^\circ C$

$T_3 = T_2 - BPR_2 - \Delta T_3 = 91.48\,^\circ C$

$T_{S_3} = T_2 - BPR_2 = 103.55\,^\circ C$

$T_4 = T_3 - BPR_3 - \Delta T_4 = 75.80\,^\circ C$

$T_{S4} = T_3 - BPR_3 = 90.998\,^\circ C$

$T_5 = T_4 - BPR_4 - \Delta T_5 = 54.115\,^\circ C$

$T_{S5} = 75.015\,^\circ C$

$T_{S6} = 51.67\,^\circ C$

Effect 1:

$H_1 = H_{S_2} + 1.884(BPR_1)$

$= 2696.87 + 1.884(0.271) = 2696.38\ kJ/kg$

T	H_{S_2}
113	2695.6
113.18	2696.87
114	2697.1

~~$\lambda_{S_1} = 2199.61$~~

$\lambda_{S_1} = H_{S_1} - h_{S_1} = 2199.61\ kJ/kg$

Effect 2:

$H_2 = 2681.73\ kJ/kg$

$\lambda_{S_2} = 2220.99\ kJ/kg$

T	H_{S_3}
103	2680.3
103.5	2681.73
104	2681.8

Effect 3:

$H_3 = 2661.2 + 1.88\,9(0.432) = 2662.10$ kJ/kg

$\lambda_{S_3} = 2247.16$ kJ/kg

90.9998 ~ 91

Effect 4:

$H_4 = 2636.08$ kJ/kg

$\lambda_{S4} = 2279.95$ kJ/kg

75.015 ~ 75°C

Effect 5:

$H_5 = 2598.84$ kJ/kg

$\lambda_{S5} = 2320.57$ kJ/kg

T	H_{S6}
51	2593.1
51.67	2594.23
52	2594.8

To find Cp

For F : $C_p = 4.19 - 2.35(0.1) = 3.955$ kJ/kg·K

L_1 : $C_p = 4.19 - 2.35(0.11) = 3.9315$ kJ/kg·K

L_2 : $C_p = 4.19 - 2.35(0.13) = 3.8845$ kJ/kg·K

L_3 : $C_p = 4.19 - 2.35(0.17) = 3.7905$ kJ/kg·K

L_4 : $C_p = 4.19 - 2.35(0.24) = 3.626$ kJ/kg·K

L_5 : $C_p = 4.19 - 2.35(0.5) = 3.015$ kJ/kg·K

Mass balance:

$V_1 = 21000 - L_1$

$V_2 = L_1 - L_2$

$V_3 = L_2 - L_3$

$V_4 = L_3 - L_4$

$V_5 = L_4 - 4200$

Energy balance:

1) $F C_p T_F + S\lambda_{S1} = L_1 C_p (T_1 - 0) + V_1 H_1$

$\Rightarrow 2076375 + S \times 2199.61 = L_1 (446.0286) + (21000 - L_1) \times 2696.38$

2) $L_1 C_p T_1 + V_1 \lambda_{S2} = L_2 C_p T_2 + V_2 H_2$

$\Rightarrow L_1 (446.0286) + (21000 - L_1) \times 2220.99 = L_2 (403.5607) + (L_1 - L_2) \times 2681.73$

3) $L_2 C_p T_2 + V_2 \lambda_{S3} = L_3 C_p T_3 + V_3 H_3$

$\Rightarrow L_2 (403.5607) + (L_1 - L_2) \times 2247.16 = L_3 (346.7549) + (L_2 - L_3) \times 2662.1$

4) $L_3 C_p T_3 + V_3 \lambda_{S4} = L_4 C_p T_4 + V_4 H_4$

$\Rightarrow L_3 \times 346.7549 + (L_2 - L_3) \times 2279.95 = L_4 (274.85) + (L_3 - L_4) \times 2636.08$

5) $L_4 C_p T_4 + V_4 \lambda_{S5} = L_5 C_p T_5 + V_5 H_5$

$\Rightarrow L_4 (274.8508) + (L_3 - L_4) 2320.57 = 685258.245 + (L_4 - 4200) * 2598.84$

On solving the above equations we get

$S = 6225.35\ m^3$ $\quad V_1 = 2845.39\ m^3$

$L_1 = 18154.61\ m^3$ $\quad V_2 = 3112.4\ m^3$

$L_2 = 15042.21\ m^3$ $\quad V_3 = 3389.79\ m^3$

$L_3 = 11652.42\ m^3$ $\quad V_4 = 3627.95\ m^3$

$L_4 = 8024.47\ m^3$ $\quad V_5 = 3824.47\ m^3$

$\therefore q_1 = S\lambda_{S1} = 6225.35 \times 2199.61 \times \frac{1000}{3600} = 3.803 \times 10^6\ W$

$q_2 = V_1 \lambda_{S_2} = 1.755 \times 10^6 \text{ W}$

$q_3 = V_2 \lambda_{S_3} = 1.992 \times 10^6 \text{ W}$

$q_4 = V_3 \lambda_{S_4} = 2.146 \times 10^6 \text{ W}$

$q_5 = V_4 \lambda_{S_5} = 2.338 \times 10^6 \text{ W}$

$$A_1 = \frac{q_1}{U_1 \Delta T_1} = 160.048 \text{ m}^2$$

$$A_2 = \frac{q_2}{U_2 \Delta T_2} = 73.956 \text{ m}^2$$

$$A_3 = \frac{q_3}{U_3 \Delta T_3} = 81.83 \text{ m}^2$$

$$A_4 = \frac{q_4}{U_4 \Delta T_4} = 90.45 \text{ m}^2$$

$A_5 = 98.498 \text{ m}^2$

$$A_{mean} = \frac{A_1 + A_2 + A_3 + A_4 + A_5}{5} = 100.9564 \text{ m}^2$$

Cost:

$C_e = 7000 + 13500 (100.9564)^{0.6} = 232186.0343$

$C_p = 232186.0343 \left[(1+0.8)1 + (0.3 + 0.2 + 0.3 + 0.3 + 0.2 + 0.1) \right]$

$= 742995.3097$