5. ENERGY BALANCE

Basis:- 1 Hr. Operation

ENERGY BALANCES ACROSS THE FEED PREHEATING EQUIPMENT:-

The heating of cold 2-butanol feed is to be completed in three stages in order to avoid large heat losses. The cold feed is first preheated to its boiling point using steam as heating medium and then vaporized in a thermosyphon reboiler utilizing the heat contained in the reaction products. The vapor, which has entrained liquid is removed from the knock out drum, and then heated to reaction temperature using flue gas.

COLD FEED PREHEATER:-

Total feed = 23412.14+2605.77 kg

= 26017.91 kg

26017.91 kg per hour of 2-butanol is to be preheated from 25^0C it boiling point 107.5^0C.

Heat load on preheater, Q = 26017.91 x 1.497(380.5 – 288)

$= 3.603 \times 10^6$ KJ

The heating medium is used is dry saturated steam at 420K

$$\text{Steam requirement} = \frac{3.603 \times 10^6}{2123.4}$$

= 1696.8 kg/hr

2-BUTANOL VAPORIZER:-

2-butanol feed is vaporized at 107.5^0C using reaction products.

Heat load on vaporizer is , Q = M x λ

= 26017.91 x 557.43 kj

$= 14.5032 \times 10^6$ kj/hr

Average Cp of reaction products = 2.3 KJ / Kg ^{0}k

$$14.5032 \times 10^6 = 26017.91 \times 2.304\ (642 - T)$$

$T = 400\ K$

<u>FIRST SUPER HEATER</u>:-

2-butanol vapors is to be heat4ed from 380.5 k to 573k . using flue gas which enters at 673 k & cools to 423k.

Cp = 2.038 kj/kg k.

Heat load on super heater, $Q = M \times Cp \times (T_2 - T_1)$

$= 26017.91 \times 2.038\ (573 - 380.5)$

$Q = 10.207 \times 10^6$ kj/hr

Mass flow rate of flue gas $= \dfrac{10.2072 \times 10^6}{1.2 \times (673-423)}$

$= 3.4024 \times 10^4$ kg/hr

<u>SECOND SUPER HEATER:-</u>

It raises the temperature of vapor from 573 to 773 k . using flue gas which enters at 873k abd cools to 623k

Cp = 2.674 kj/kg k

Heat load on super heater $Q = M \times Cp \times (T_2 - T_1)$

$= 26017.91 \times 2.674\ (773 - 573)$

$= 13.9144 \times 10^6$ kj/hr

Flue gas requirement, $= \dfrac{13.9144 \times 10^6}{1.195 \times (873- 623)}$

$= 4.6575 \times 10^3$ kg/hr

<u>ENERGY BALANCE ACROSS THE REACTOR</u>:-

The feed enters the reactor at 773k and leaves at 663k. The conversion obtained in the reactor is 89.1%. The heat balance includes two terms i.e , sensible heat change due to cooling of reaction mixture and heat consume due to reaction.

$Q = M \times Cp \times (T_2 - T_1) + M \times \Delta H$

Mean Cp = 2.68 kj/kg k

ΔH = 73900 kj/kgmol

Total 2-butanol feed = 23412.14 + 2579.71 kg
= 25991.85 kg/hr
= 351.24 kmol/hr

Q = 26017.91 x 2.68 x (663- 773) + 351.24 x .891 x 73900
= 15.457 x 10^6

It is assume that a flue gas is available at 800k & leaving 750k.

Cp = 1.195 kj/kg k

Flue gas requirement, $= \dfrac{15.457 \times 10^6}{1.195 \times (800-750)}$
= 25.869 x 10^4 kg/hr

ENERGY BALANCE ACROSS THE CONDENSER :-

The vapor enters condenser at 127^0C (400k) at 1 bar pressure.
Liquid and the vapor leaving the condenser is in equilibrium. At the more mole fraction x = 0.88 of the condensate we get both liquid and vapor temperature from the T- x- y diagram and temperature are

299.6 k. = liquid temperature., 335.7 k = vapor temperature

We take cooling water enters at 24^0C and leaving at 42^0C

Cp_{H2} = 14650 J/ kg k
$Cp_{alcohol}$ = 1760 J/ kg k
Cp_{MEK} = 1664 J/ kg k

Cp_{mix} = 0.867 x 1664 + 0.1089 x 1760 + 0.0241 x 14650
= 1987.42 J/kg.
Heat loss to reduction in vapor temperature from 400k to 335.7k
Q_1= 26017.91 x 1.98742 (400- 335.7)
= 3.325 x 10^6 kj/ hr

Heat loss due to condensation
Q_2 = 2591.34 x 689.19 + 18931.44 x 486.11
= 10.989 x 10^6 kj/hr

Heat loss due to further cooling of a part of vapor is
Q_3 = 21522.78 x 1.987 x (335.7 – 299.6)

$= 1.544 \times 10^6$ kj/hr

Total heat lost = Q = $Q_1 + Q_2 + Q_3$
$= (3.325 + 10.989 + 1.544) \times 10^6$ kj/hr
$= 15.858 \times 10^6$ kj/hr

Mass flow of cooling water $= \dfrac{15.858 \times 10^6}{4.187 \times (42- 24)}$
$= 2.104 \times 10^5$ kg / hr

ENERGY BALANCE ACROSS THE ABSORBER :-

Heat of condensation of MEK $= 3707.072 \times 443.14$
$= 1.643 \times 10^6$ kj/hr

Heat of condensation of alcohol is $= 233.488 \times 560$
$= 0.1308 \times 10^6$ kj/hr

Heat of solution $= (3707.072 + 233.488) \times 0.35$
$= 0.001379 \times 10^6$ kj/hr

Heat loss in cooling gasses from 62.7 to 27^0C
$= (74.98 \times 1.47 + 8.392 \times 1.53 + 624.723 \times 14.65)(62.7 – 27)$
$= 0.3311 \times 10^6$ kj/hr

Total heat released $= 2.1063 \times 10^6$ kj/hr

Heat removed by water vapor = (204.045 x 2437.9)
$= 0.49744 \times 10^6$ kj/hr

Heat gained by irrigating liquor

a) Water: 31980.6816 x 4.186 (T – 300)

b) MEK: 3707.072 x 2.299 x (T-300)

c) Alcohol: 233.488 x 2.429 x (T- 300)

Total heat gained $= 0.49744 \times 10^6 + 0.142961 \times 10^6 (T-300)$ kj/hr

Heat released = heat gained

$\Rightarrow \quad 2.1063 \times 10^6 = 0.49744 \times 10^6 + 0.14296 \times 10^6 (T – 300)$

=> $T = 311.25$ k

ENERGY BALANCE ACROSS THE EXTRACTION COLUMN:-

It is assume that the extraction process is isothermal. All that streams come at 27^0C and leaves at 27^0C.

ENERGY BALANCE ACROSS THE SOLVENT RECOVERY & UNIT:-

Feed is not saturated liquid it is sub-cool liquid. Saturation temperature is 93^0C
From x-y diagram we get Rm = 0.38.

R= 2Rm = 0.76

Feed:

Alcohol = $\frac{233.48}{74}$ = 3.155 kmol /hr

MEK = $\frac{3577.639}{72}$ = 49.689 kmol/hr

TCE = $\frac{14992.191}{133.5}$ = 112.3kmol/hr

Water = $\frac{26.3613}{18}$ = 1.465 kmol /hr

Total = 166.609 kmol /hr

Mole fraction of MEK

$X_{MEK} = \frac{49.689}{166.609} = 0.2982$

Feed temperature = 27^0C

$F \cdot H_F = 3.155 \times 170.058\,(27-0) + 49.689 \times 165.726 \times 27 + 112.3 \times 148.56 \times 27 + 1.465 \times 75.36 \times 27$

$F \cdot H_F = 0.69025 \times 10^6$ kj/hr

Distillate:-

Alcohol = $\frac{233.488}{74}$ = 3.1552 kmol /hr

MEK = $\frac{(3577.639 - 21.3454)}{72}$ = 49.39 kmol/hr

Water = $\frac{(26.3613 - 25.9195)}{18}$ = 0.0246 kmol /hr

TCE = $\frac{2.5098}{133.5}$ = 0.0188 kmol/hr

Total = 52.5886 kmol/hr

D = 52.5886 kmol/hr

Mole fraction of MEK, $X_{MEK} = \frac{49.39}{52.5886}$ = 0.94

from T-x-y diagram distillate temperature = 80.4^0C

Cp_{MEK} = 170 kj/kmol k

$Cp_{alcohol}$ = 228 kj/kmol k

Cp_{water} = 75.37 kj/mol k

Cp_{TCE} = 148.56 kj/mol k

D. H_D = [3.1552 x 228 + 49.39 x 170 + 0.4421 x 75.37 + 0.0188x 148.56] (80.4)
= 0.7358 x 10^6 kj/hr

Residue:

MEK = 21.2454 kg = 0.2965 kmol/hr

TCE = $\frac{15199.421}{133.5}$ kmol = 113.85 kmol /hr

Water = $\frac{25.9195}{18}$ = 1.4399 kmol /hr

Total = 115.5864 kmol/hr

$X_{MEK} = \frac{0.2965}{115.5864}$ = 0.0026

From T-x-y diagram the temoerature obtained .
T = 112^0C = 385k (residue)

Cp_{MEK} = 175 kj/mol k
$Cp_{alcohol}$ = 260 kj/kmol k
Cp_{water} = 75.37 kj/kmol k

$Cp_{TCE} = 148.56$ kj/kmol k

$W. H_w = [\, 0.2965 \times 175 + 113.85 \times 148.56 + 1.4399 \times 75.37] \times (112)$
$= 1.9123 \times 10^6$ kj/hr

Condenser :-

$VH_v = D.H_D + L.\, H_L + Q_c.$

$VH_v = (D + L)\, .\, H_L + Q_c$

$Q_c = V \times (H_v - H_L)$

$Q_c = V \times \lambda$
$V = (1 + R) \times D$
$D = 52.5886$ kmole/hr
$V = (1 + 0.76) \times 52.5886 = 92.556$ kmole/hr.

$V\times\lambda = 92.556 \times 3.18445 \times 10^4$
$= 2.9474 \times 10^6$ kj/hr

$Q_c = 2.9474 \times 10^6$ kj/hr

$$\text{Cooling water requirement} = \frac{2.9474 \times 10^6}{4.187 \times (42 - 24)}$$
$$= 3.911 \times 10^4 \text{ kg/hr}$$

Reboiler:-

Overall heat balance

$F.\, H_F + Q_B = Q_c + D\, .\, H_D + WH_w$
$Q_B = Q_c + D\, .\, H_D + WH_w - F.\, H_F$

$Q_B = DH_D = WH_w + Q_c - FH_F$

$Q_B = 0.7358 \times 10^6 + 1.9123 \times 10^6 + 2.9474 \times 10^6 - 0.69025 \times 10^6$

$Q_B = 4.90525 \times 10^6$ kj/hr

Steam is available at 3.302 bar steam temperature = 410 k

Steam requirement is = $\frac{4.90525 \times 10^6}{2153.4}$

= 2277.91 kg/hr

One cooler is attached to cool the residue.

Residue enters the cooler at 112^0C and leaves at 27^0C

So, cooling water requirement = $\frac{1.451299 \times 10^6}{4.187 (42- 24)}$

= 1.92567×10^4 kg/hr

One more heat exchanger is used to raise the temperature of the mixed liquor of condensate and the distillate from the solvent recovery column to 82^0C

$$\left(\frac{2591.3424 \times 170.058}{74} + \frac{18931.435 \times 165.726}{72}\right)(26.6)$$

$$+ \left(\frac{212.9726 \times 260}{74} + \frac{3367.511 \times 175}{72} + \frac{2.5098 \times 148.56}{133.5}\right)$$

$$+ Q_B = \left(\frac{2804.315 \times 260}{74} + \frac{22298.946 \times 165.726}{72} + \frac{2.5098 \times 148.56}{133.5}\right)(82)$$

$Q_B = 2.981 \times 10^6$ KJ/hr

Steam is available at 3.302 bar, steam temperature = 410 K.
Steam requirement = $\frac{2.981 \times 10^6}{2153.4}$
= 1384.32 Kg/hr

ENERGY BALANCE ACROSS THE DISTILLATION COLUMN:-

Condenser:

$Qc = V \times \lambda$

$Qc = V \times \lambda = 541.261 \times 3.1 \times 10^7 + 5.4673 \times 4.5 \times 10^7$
$= 17.025 \times 10^6$

So, mass flow rate of cooling water = 17.025×10^6

$$4.187 \times (42-24)$$
$$= 2.25899 \times 10^6 \text{ kg/hr}$$

Reboiler:

$Q_B = DH_D + WHw + Qc - FH_F$

$$FH_F = \left(\frac{2804.315 \times 260}{74} + \frac{22298.946 \times 165.726}{72} + \frac{2.5098 \times 148.56}{133.5} \right)(82)$$

$$= 5.01696 \times 10^6 \text{ kj/hr}$$

$$DH_D = \left(\frac{225.0}{74} \times 228 + \frac{22275.0}{72} \times 170 \right) (80.5)$$
$$=4.2896 \times 10^6 \text{ kj/hr}$$

$$WHw = \left(\frac{2579.7131}{74} \times 260 + \frac{23.9731}{72} \times 175 + \frac{2.0846}{133.5} \times 148.65 \right) \times (107)$$
$$= 0.97632 \times 10^6 \text{ kj/hr}$$

$Q_B = 17.274$ kj/hr

Steam available at = 3.302 bar. Steam temperature = 410 k

$$\text{Steam requirement} = \frac{17.274 \times 10^6}{2153.4}$$
$$= 8021.733 \text{ kg/hr.}$$

Distillate & the residue both has to be cooled

Heat load to cool the distillate from 80.5 to 30 ^{0}C = $\left(\frac{225}{74} \times 228 + \frac{22275}{72} \times 170 \right)$ (80.5 – 30)

$$= 2.69099 \times 10^6 \text{ kj/hr.}$$

So, cooling water requirement, $= \dfrac{2.69099 \times 10^6}{4.187 \times (42-24)}$

$$=3.57056 \times 10^4 \text{ kg/hr}$$

Recycle 2-butanol is 107 to 27^{0}C

$$\text{Heat load} = \left(\frac{2579.7131}{74} \times 260 + \frac{239731}{72} \times 175 + \frac{2.0846}{133.5} \times 148.65 \right) \quad (107-27)$$

$$= 0.72996 \times 10^6 \text{ kj/hr}$$

$$\text{Cooling water requirement} = \frac{0.72996 \times 10^6}{4.187 \times (42-24)}$$

$$= 9685.52 \text{ kg/hr.}$$