Evaporator

Total Feed, $w_F = 50,000$ lb/hr

Solid concentration $= 10\%$.

Total Solids in feed $= 0.1 \times 50,000 = 5000$ lb/hr

Total product $= \frac{5000}{0.5} = 10,000$ lb/hr

Total evaporation $= 50,000 - 10,000$

$= 40,000$ lb/hr

$t_F = 100°F$

T_s at 12 psig $= 244°F$

T_f at 26 in Hg (1.95 psia) $= 125°F$

$C_F = 1.0$

Total temp. difference $= 119°F$

a) 3 - Effect Evaporator

The balances appyying here are,

First effect : $W_s \lambda_s + w_F (t_F - t_1) = w_1 \lambda_1$

Second effect : $w_1 \lambda_1 + (w_F - w_1)(t_1 - t_2) = w_2 \lambda_2$

Third effect : $w_2 \lambda_2 + (w_F - w_1 - w_2)(t_2 - t_3) = w_3 \lambda_3$

Material : $w_1 + w_2 + w_3 = w_{1-3}$

where, $W_s \rightarrow$ steam to first effect, lb/hr

$w_1, w_2, w_3 \rightarrow$ water removed in effects 1 to 3, lb/hr

$t_1, t_2, t_3 \rightarrow$ Boiling points of liquor in effects 1 to 3, lb/hr

$w_{1-3} \rightarrow$ total water removed by evaporation, lb/hr

Avg. pressure diff. = $\dfrac{26.7 - 1.95}{3}$ = 8.25 psi/effect

The below table shows breakup of total pressure diff.

	Pressure, psia	ΔP	Steam (°F)	λ (Btu/lb)
1^{st} Effect	26.7	....	$T_s = 294$	$\lambda_s = 949$
2^{nd} Effect	18.45	8.25	$t_1 = 224$	$\lambda_1 = 961$
3^{rd} Effect	10.2	8.25	$t_2 = 194$	$\lambda_2 = 981$
vapor to cond.	1.95	8.25	$t_3 = 125$	$\lambda_3 = 1022$

Equations after substitution,

$$949\, W_s + 50{,}000\,(100 - 224) = 961\, w_1$$
$$961\, w_1 + (50{,}000 - w_1)(224 - 194) = 981\, w_2$$
$$981\, w_2 + (50{,}000 - w_1 - w_2)(194 - 125) = 1022\, w_3$$
$$w_1 + w_2 + w_3 = 40{,}000$$

Solving the equations simultaneously,

$$w_1 = 12{,}400$$
$$w_2 = 13{,}300$$
$$w_3 = 14{,}300$$
$$w_{1-3} = \Sigma w_i = 40{,}000$$
$$W_s = 19{,}100$$

$$A_1 = \frac{W_s \lambda_s}{U_1 (T_s - t_1)} = \frac{19100 \times 949}{600 \times 20} = 1510 \text{ ft}^2$$

$$A_2 = \frac{w_1 \lambda_1}{U_2 (t_1 - t_2)} = \frac{12400 \times 961}{250 \times 30} = 1590 \text{ ft}^2$$

$$A_3 = \frac{w_2 \lambda_2}{U_3 (t_2 - t_3)} = \frac{13300 \times 981}{125 \times 69} = 1510 \ ft^2$$

Heat to condenser $= w_3 \lambda_3 = 14300 \times 1022$

$= 14710000$ Btu/hr

$$\text{water Required} = \frac{14710000}{(120 - 85)} = 420{,}000 \ lb/hr$$

steam company (lb evaporation / lb steam) $= \dfrac{40{,}000}{19{,}100} = 2.09$ lb/lb

Total Area $= \Sigma A_i = 4610 \ ft^2$

b) 2- Effect Evaporator

The balances applying here are,

First Effect : $W_s \lambda_s + w_F (t_F - t_1) = w_1 \lambda_1$

Second Effect : $w_1 \lambda_1 + (w_F - w_1)(t_1 - t_2) = w_2 \lambda_2$

Material : $w_1 + w_2 = w_{1-2}$

$$\text{Avg. pressure diff} = \frac{26.7 - 1.95}{2} = 12.375 \text{ psi}$$

The below table shows breakup of total pressure diff.

	Pressure, psia	ΔP	Steam (°F)	λ (Btu/lb)
1st Effect	26.7	....	$T_s = 244$	$\lambda_s = 949$
2nd Effect	19.325	12.375	$t_1 = 211$	$\lambda_1 = 971$
Vap. to Cond.	1.95	12.375	$t_2 = 125$	$\lambda_2 = 1022$

On substituting the above values,

$$949\, W_s + 50000\,(100 - 211) = 971\, w_1$$

$$971\, w_1 + (50000 - w_1)(211 - 125) = 1022 w_2$$

$$w_1 + w_2 = 40000$$

On solving the above eqn's simultaneously,

$$w_1 = 19182 \qquad w_2 = 20818$$

$$\Sigma w_i = w_{1-2} = 40{,}000$$

$$W_s = 25475$$

$$A_1 = \frac{W_s \lambda_s}{U_1 (T_s - t_1)} = \frac{25475 \times 949}{600\,(244 - 211)} = 1221\ ft^2$$

$$A_2 = \frac{w_1 \lambda_1}{U_2 (t_1 - t_2)} = \frac{19182 \times 971}{250\,(211 - 125)} = 866\ ft^2$$

$$\text{Steam Economy} = \frac{\Sigma w_i}{W_s} = 1.57$$

Heat to Condencor $= w_2 \lambda_2 = 21275996$ BtU/hr

Water requirement $= \dfrac{21275996}{(120 - 85)} = 607885$ lb/hr

Total Area $= \Sigma A_i = 2087\ ft^2$

c) 4 · effect Evaporator

The balances applying here are,

First Effect : $W_s \lambda_s + w_F (t_F - t_1) = w_1 \lambda_1$

Second Effect : $w_1 \lambda_1 + (w_F - w_1)(t_1 - t_2) = w_2 \lambda_2$

Third Effect : $w_2 \lambda_2 + (w_F - w_1 - w_2)(t_2 - t_3) = w_3 \lambda_3$

Fourth Effect : $w_3 \lambda_3 + (w_F - w_1 - w_2 - w_3)(t_3 - t_4) = w_4 \lambda_4$

Material : $w_1 + w_2 + w_3 + w_4 = w_{1-4}$

Avg. Pressure Differance $= \dfrac{26.7 - 1.95}{4} = 6.1875$ psi

	Pressure, psia	ΔP	Steam (°F)	λ (BtU/lb)
1^{st} Effect	26.7	....	$T_s = 244$	$\lambda_s = 949$
2^{nd} Effect	20.5125	6.1875	$t_1 = 229$	$\lambda_1 = 959$
3^{rd} Effect	14.325	6.1875	$t_2 = 211$	$\lambda_2 = 971$
4^{th} Effect	8.1375	6.1875	$t_3 = 185$	$\lambda_3 = 988$
vap. to Cond.	1.95	6.1875	$t_4 = 125$	$\lambda_4 = 1022$

On subsituting the above values,

$$949 W_s + 50{,}000(100 - 230) = 959 w_1$$
$$959 w_1 + (50{,}000 - w_1)(230 - 211) = 971 w_2$$
$$971 w_2 + (50{,}000 - w_1 - w_2)(211 - 185) = 988 w_3$$
$$988 w_3 + (50{,}000 - w_1 - w_2 - w_3)(185 - 125) = 1022 w_4$$
$$w_1 + w_2 + w_3 + w_4 = 40{,}000$$

On sowing the above eqn's simultaneously,

$w_1 = 8933.6$ lb/hr $w_2 = 9584.5$ lb/hr $w_3 = 10311.8$ lb/h $w_4 = 11170.2$ lb/h

$\Sigma w_i = w_{1-4} = 40{,}000$

$W_s = 15824.38$ lb/hr

$$A_1 = \frac{W_s \lambda_s}{U_1 (T_s - t_1)} = 1568.59 \ ft^2$$

$$A_2 = \frac{w_1 \lambda_1}{U_2 (t_1 - t_2)} = 1903.85 \ ft^2$$

$$A_3 = \frac{w_2 \lambda_2}{U_3 (t_2 - t_3)} = 2659.01 \ ft^2$$

$$A_4 = \frac{w_3 \lambda_3}{U_4 (t_3 - t_4)} = 1405.24 \ ft^2$$

(Using 2700 ft^2/effect)

Steam Economy = $\frac{\Sigma w_i}{W_s}$ = 2.53

Heat to Condensor = $w_4 \lambda_4$ = 11415893.3 Btu/hr

Water requirement = 326168.38 lb/hr = 652.34 gpm

Total Area = ΣA_i = 7636.69 ft^2

Price of steam = Rs 1.53 / kg , Price of water = Rs 11.1 / 1000 kg

Assuming that there are total 300 working days and 10hr use of evaporator per day

Total running time = $300 \times 10 \times 3600 = 1.08 \times 10^7$ sec

a) For 2-effect, $w_s = 25475$ lb/hr = 3.21 kg/s

Total price of steam = $3.21 \times 1.08 \times 10^7 \times 1.53$

= Rs 53042040 /year

Total price of water = Rs 9181609.2 / year

b) For 3-effect, $w_s = 19100$ lb/hr = 2.41 kg/s

Total price of steam = $2.41 \times 1.53 \times 1.08 \times 10^7$

= Rs 39822840 /year

Total price of water = $52.919 \times 1.08 \times 10^7 \times 11.1 \times 10^{-3}$ = Rs 6343929.72 /year

c) For 4-effect, w_s = 15824.38 lb/hr = 1.994 kg/s

Total price of steam = $1.994 \times 1.53 \times 1.08 \times 10^7$

= Rs 32948856 /year

Total price of water = Rs 4927068 /year

Annualized Capital costs

a = 3012799.99 , b = 37660 , c = 1 , Interest = 10%

Time period = 5 yrs

a) For 2-effect,

Number of units (N) = 2

Raw cost = $N(a + b(\text{area}/N)^c)$

= 2 (3012799.99 + 37660 (193.89/2))

= Rs 13327497.38 /year

Cost = Raw cost × Annuinity factor = Rs 50524542.57 /year

(Annuity factor = $(1 - (1+i)^n / I)$ = 3.791)

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b) For 3-effect,

Number of units (N) = 3

Raw Cost = $N(a + b(\text{area}/N)^c)$

$= 3(3012799.99 + 37660(4128/3))$

= Rs 25167424.77/year

Cost = Raw Cost × Annunity factor = Rs 95409707.3/year

c) For 4-effect,

Number of units (N) = 4

Raw Cost = $N(a + b(\text{area}/N)^c)$

$= 4(3012799.99 + 37660(4130.76/4))$

= Rs 28273621.56 /year

Cost = Raw Cost × Annunity factors

= Rs 107185299.3/year

	2-effect	3-effect	4-effect
Amount for Steam utility	Rs. 53042640/year	Rs 39822840/year	Rs 32948856/year
Area Target	2087 ft^2	4610 ft^2	4636.69 ft^2
Annunity cost	Rs. 13327497/year	Rs 25167424.77/year	Rs 107185299.3/year
Amount for water utility	Rs 9181609.2 /year	Rs 6343929.72 /year	Rs 4927068.0 /year
Total cost	Rs 75551146.2/year	Rs 71334194.42 /year	Rs 145061223.3 /year

Discussion

An evaporator is a device used in a process to turn the liquid form of a chemical substance, such as water, into its gaseous form - vapour. The liquid is evaporated or vaporized, into a gas form of the targeted substance in that process.

The steam economy is defined as the amount of evaporation per unit amount of steam used. For, the three-effect vapour is generated at the first and second effect. As we keep increasing the number of effects increases, the steam economy increases as the vapour increases. One should prefer more steam economy, as the same arrangement provides more amount of steam with increase in the number of effects. Thus, the steam economy increases with an increase in the number of effects. We the same amount of steam utility we get more vapour as the number of effects increases. Though, the operating costs keep increasing with the increase in the number of effects.

During operation, the equal pressure-drop distribution may not maintain itself. This will occur if there is undue scaling in one of the effects, if a body is gas bound, or if liquor levels are not properly maintained. Another factor may be the withdrawal of a large quantity of steam from one of the effects as a source of low-pressure heating steam. Any deviation from an equal pressure-drop distribution does not mean that the entire multiple-effect assembly will fail to operate but instead that the unit will assume a new pressure distribution and operate with a reduced capacity and steam economy.

Resources

1) Process Heat Transfer Principles and Applications by Robert. W. Sarat
2) Process Heat Transfer by D.Q.Kern
3) Equipment Sizing and Capital Cost Estimation by Warren D. Seider, University of Pennsylvania
4) Chemical Technology An Indian Journal Vol. 11 Issue 2 (2016)
5) General Process Plant Cost Estimating (ENGINEERING DESIGN GUIDELINE)
6) Process Equipment Cost Estimation by H.P. Loh, Jennifer Lyons and Charles W. White