Performance of Evaporators

Performance of evaporators

There are three main measures of evaporator performance:

Capacity = kg vaporized / time

Capacity is defined as the number of kilogram of water vaporized per hour.

Economy = kg vaporized / kg steam input

Economy (or steam economy) is the number kilogram of water vaporized from all the effects per kilogram of steam used.

Steam Consumption = Capacity/Economy, kg / h

Economy

The key factor in determining the economy of an evaporator is the number of effects.

The economy of a single effect evaporator is always less than 1.0.

Multiple effect evaporators have higher economy but lower capacity than single effect.

The thermal condition of the evaporator feed has an important impact on economy and performance.

If the feed is not already at its boiling point, heat effects must be considered.

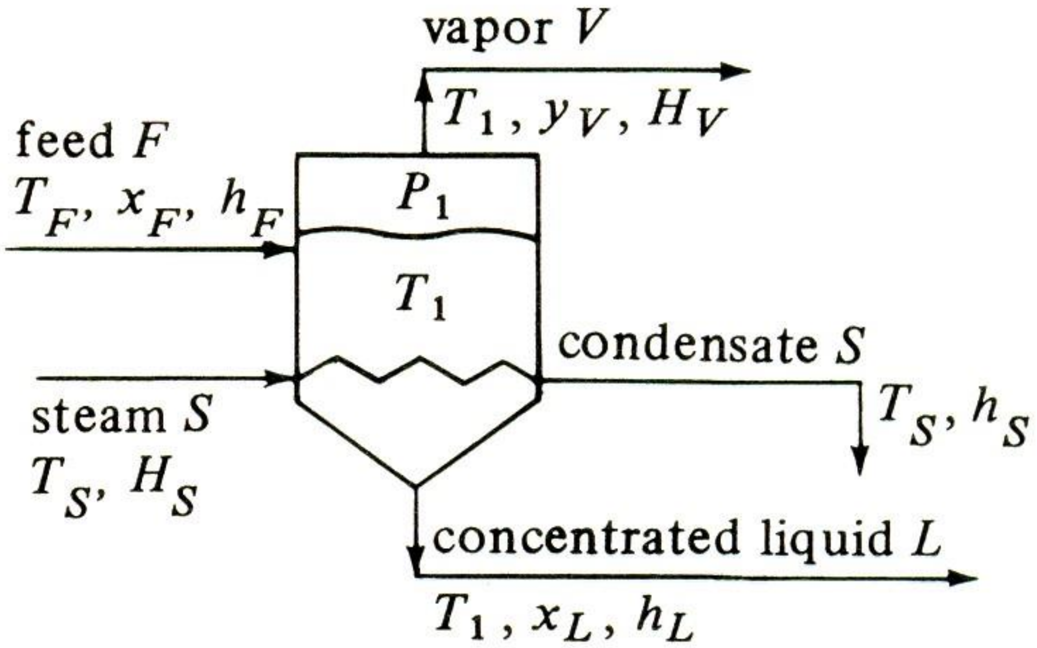
If the feed is cold (below boiling) some of the heat going into the evaporator must be used to raise the feed to boiling before evaporation can begin; this reduces the capacity.

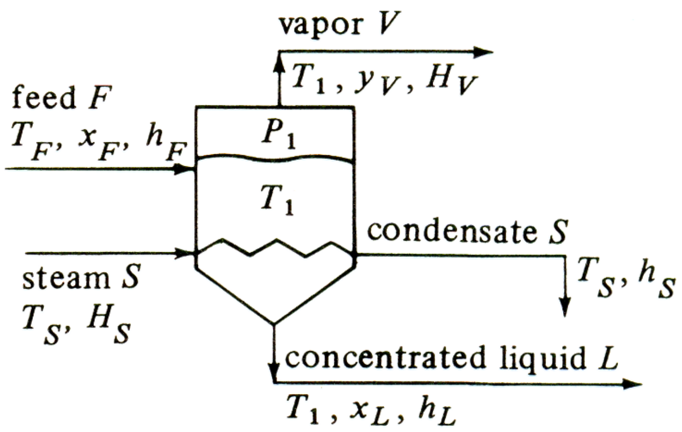
Heat and Material Balances for Evaporators

$$q = UA\ \Delta T$$

- The basic equation for solving for the capacity of a single-effect evaporator is $q = UA\ \Delta T$ (1)
- where ΔT (K, ^oF) is the difference in temperature between the condensing steam and the boiling liquid in the evaporator.
- In order to solve for the value of *q* in W(btu/h) must be determined by making a heat and material balance on the evaporator.

Heat and mass balance for single-effect evaporator





- The feed to the evaporator is F kg/h (lb_m/h) having a solids content of x_F mass fraction, temperature T_F, and enthalpy h_F J/kg (btu/lb_m).
- Coming out as a liquid is the concentrated liquid L kg/h (lbm/h) having a solids content of x_L, temperature T_1, and enthalpy h_L.
- The vapor V kg/h (lb_m/h) is given off as pure solvent having a solids content of $y_v = 0$, temperature T_1, and enthalpy H_v.
- Saturated steam entering is S kg/h (lb_m/h) and has a temperature of T_S and enthalpy of H_S.
- The condensed steam leaving of S kg/h is assumed usually to be at T_S, the saturation temperature, with an enthalpy of h_S.
- This means that the steam gives off only its latent heat, λ, where:

$$\lambda = H_S - h_S \qquad (2)$$

- Since the vapor V is in equilibrium with the liquid L, the temperatures of vapor and liquid are the same.
- Also, the pressure P_1 is the saturation vapor pressure of the liquid of composition x_L at its boiling point T_1. (This assumes no boiling-point rise.)
- For the material balance, since we are at steady state, the rate of mass in = rate of mass out. Then, for a total balance,

$$F = L + V \qquad (3)$$

- For a balance on the solute (solids) alone,

$$F\,x_F = L\,x_L \qquad (4)$$

- For the heat balance, since the total heat entering = total heat leaving,

heat in feed + heat in steam = heat in concentrated liquid + heat in vapor + heat in condensed steam (5)

- This assumes no heat lost by radiation or convection. Substituting into Eq. (5),

$$F h_F + S H_S = L h_L + V H_V + S h_S \qquad (6)$$

Substituting Eq. (2) into (6),

$$F h_F + S\lambda = L h_L + V H_V \qquad (7)$$

- The heat q transferred in the evaporator is then

$$q = S(H_S - h_S) = S\lambda \qquad (8)$$

- In Eq. (6) the latent heat λ of steam at the saturation temperature T_S can be obtained from the steam tables.
- However, the enthalpies of the feed and products are often not available; these enthalpy concentration data are available for only a few substances in solution.
- Hence, some approximations are made in order to make a heat balance. These are as follows:
- It can be demonstrated as an approximation that the latent heat of evaporation of 1 kg mass of the water from an aqueous solution can be obtained from the steam tables using the temperature of the boiling solution T1 (exposed surface temperature) rather than the equilibrium temperature for pure water. If the heat capacities of the liquid feed and of the product are known, they can be used to calculate the enthalpies. (This neglects heats of dilution, which in most cases are not known.)

EXAMPLE 1. Heat-Transfer Area in Single-Effect Evaporator

A continuous single-effect evaporator concentrates 9072 kg/h of a 1.0 wt % salt solution entering at 311.0 K (37.8°C) to a final concentration of 1.5 wt %. The vapor space of the evaporator is at 101.325 kPa (1.0 atm abs) and the steam supplied is saturated at 143.3 kPa. The overall coefficient (U = 1704 W/m^2.K). Calculate the amounts of vapor and liquid product and the heat-transfer area required. Assume that, since it is dilute, the solution has the same boiling point as water.

$F, L, V = ?$

$x_F\ ,\ x_L\ , = ?$

$P_1\ , T_1\ , = ?$

$P_F\ , T_F\ , h_F = ?$

$T_S\ , H_S = ?$

$H_V \quad = ?$

Solution:

- For the material balance, substituting into Eq. (3),

$$F = L + V \qquad (3)$$

$$9072 = L + V$$

- Substituting into Eq. (4) and solving,

$$F\, x_F = L\, x_L \qquad (4)$$

$$9072(0.01) = L(0.015)$$

$$L = 6048 \text{ kg/h of liquid}$$

Substituting into Eq. (3) and solving,

$$V = 3024 \text{ kg/h of vapor}$$

- Assume c_{pF} = 4.14 kJ/kg.K
- Boiling point of dilute solution is assumed to be that of water at 101.32 kPa, T_1 = 373.2 K (100^{0}C) as datum temperature.
- Latent heat of water H_v at 373.2 K (from steam tables) is 2257 kJ/kg.
- Latent heat of the steam λ at 143.3 kPa (saturation temp., T_S = 383.2 K) is 2230 kJ/kg
- Enthalpy of the feed can be calculated from:

$$h_F = c_{pF}(T_F - T_1)$$

- T_1 = 373.2 K; h_L = 0 since it is at the datum of 373.2 K; substitute into Eq. (7) gives

$$Fh_F + S\lambda = Lh_L + VH_V$$

$$9072(4.14)(311.0 - 373.2) + S(2230) = 6048(0) + 3024(2257)$$

$$S = 4108 \text{ kg steam/h}$$

The heat q transferred through the heating surface area A is, from Eq. (8),

$$q = S\,(\lambda) \qquad (8)$$

$$q = (4108)(2230)(l000/3600) = 2\,544\,000\ \text{W}$$

Substituting into Eq. (1), where $\Delta T = T_S - T_1$,

$$q = 2\,544\,000 = UA\,\Delta T$$

$$= 1704(A)(383.2 - 373.2)$$

Solving, $\underline{A = 149.3\ \text{m}^2}$

Effects of Processing Variables on Evaporator Operation

1. Effect of feed temperature

The inlet temperature of the feed has a large effect on the operation of the evaporator. If the feed is under pressure and enters the evaporator at a temperature above the boiling point in the evaporator, additional vaporization is obtained by flashing part of the entering hot feed. Preheating the feed can reduce the size of evaporator heat-transfer area needed.

2. Effect of pressure

A larger ΔT is desirable, since, as ΔT increases, the heating-surface area A and cost of the evaporator decrease. To reduce the pressure below 101.32 kPa, that is, to be under vacuum, a condenser and vacuum pump can be used. A large decrease in heating-surface area would be obtained.

3. Effect of steam pressure

Using higher-pressure, saturated steam increases ΔT, which decreases the size and cost of the evaporator. However, high-pressure steam is more costly as well as often being more valuable as a source of power elsewhere. Hence, overall economic balances are really needed to determine the optimum steam pressures.

Boiling -point elevation

As evaporation proceeds, the liquor remaining in the evaporator becomes more concentrated and its boiling point will rise.

The extent of the boiling-point elevation depends upon the nature of the material being evaporated and upon the concentration changes that are produced.

The extent of the rise can be predicted by Raoult's Law, which leads to

- $\Delta T = kx$

where ΔT is the boiling point elevation, x is the mole fraction of the solute and k is a constant of proportionality

Duhring plot

- Duhring's rule states that the ratio of the temperatures at which two solutions (one of which can be pure water) exert the same vapour pressure is constant.
- Thus, if we take the vapour pressure/temperature relation of a reference liquid, usually water, and if we know two points on the vapour pressure/temperature curve of the solution that is being evaporated, the boiling points of the solution to be evaporated at various pressures can be read off from the diagram called a Duhring plot.

- The Duhring plot will give the boiling point of solutions of various concentrations by interpolation, and at various pressures by proceeding along a line of constant composition.

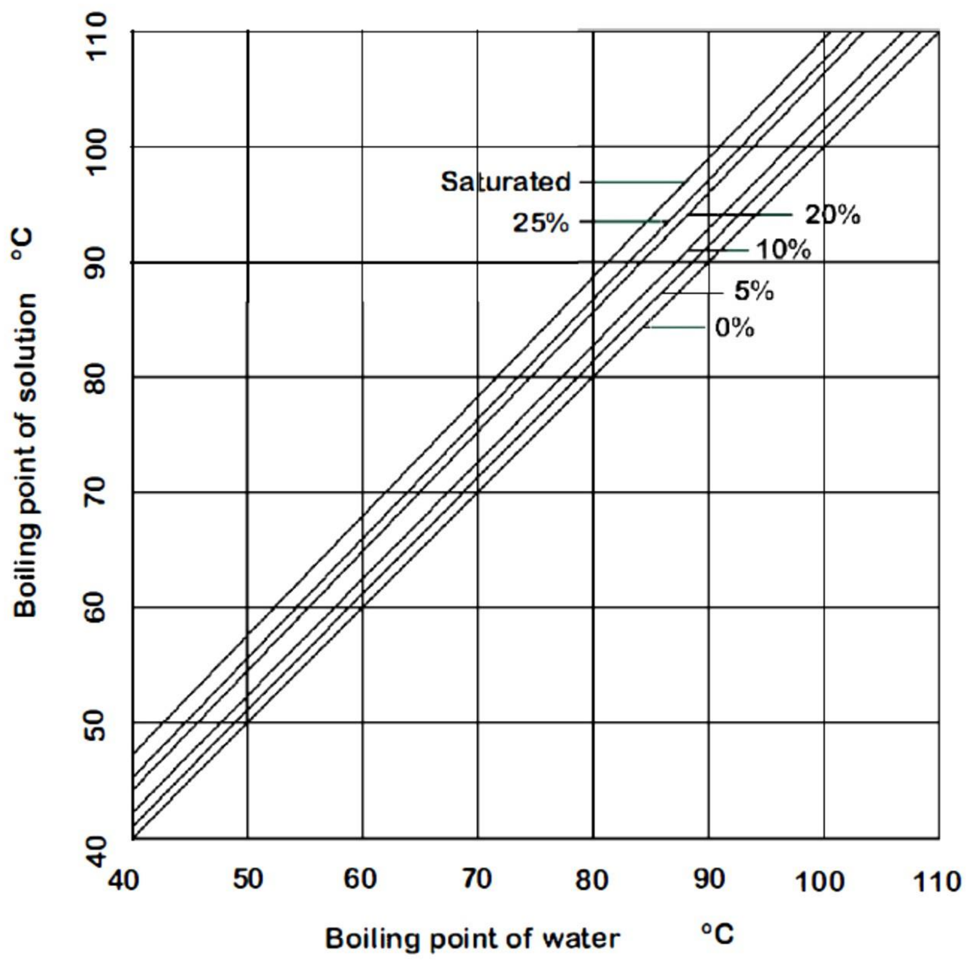


Figure 8.3 Duhring plot for boiling point of sodium chloride solutions

Triple effect evaporator

Estimate the heat transfer area, mass flow rate of evaporation, steam economy, steam requirement in triple effect evaporator. Feed is entering at a flow rate of 500 kg/h with a concentration of 10% to 30 %. Condensing steam is available at 200 kPa gauge pressure and 60 kPa (abs) is the operating pressure at the third effect evaporator. Assume negligible sensible heat, no boiling point elevation and equal heat transfer. U_1=2270 J/m^{2}s^{0}C; U_2=2000 J/m^{2}s^{0}C; U_3=1420 J/m^{2}s^{0}C.

Given:

F = 500 kg/h

X_f =10%, x_l =30%

Ps = 200kPa(g) = 300kPa(a) = 3 bar => Ts = 133.5^{o}C = λ_s = 2163.2kJ/kg

P_3 = 60kPa(a) = 0.6bar => T_3 = 85.95^{o}C = λ_3 = 2293.7kJ/kg

U_1=2270 J/m^{2}s^{0}C; U_2=2000 J/m^{2}s^{0}C; U_3=1420 J/m^{2}s^{0}C

Estimate 1. heat transfer area, 2. mass flow rate of evaporation, 3. steam economy, 4. steam requirement ??

i) Mass Balance
ii) Mass flow rate of evaporation
iii) Steam requirement
iv) Steam economy
v) Area of heat transfer

- Mass Balance

$F\,x_F = L\,x_L$

$L = \frac{500 * 0.1}{0.3}$ = 166.6 kg/h

E = 500 – 166.66 = 333.33kg/h

Since net transfer is equal;

$q_1 = q_2 = q_3$

$U_1A_1\Delta T_1 = U_2A_2\Delta T_2 = U_3A_3\Delta T_3$

Usually in multiple effect evaporator, $A_1 = A_2 = A_3$

Then $U_1\Delta T_1 = U_2\Delta T_2 = U_3\Delta T_3$ ------1

$\Delta T_{overall} = \Delta T_1 + \Delta T_2 + \Delta T_3$ ------2

$\Delta T_{overall} = T_s - T_3 = 133.5 - 85.95 = 47.5^oC$

From equation 1, $(U_1\Delta T_1 = U_2\Delta T_2 = U_3\Delta T_3)$

$$\Delta T_2 = \frac{U_1}{U_2}\,\Delta T_1 \text{ ----- } 3$$

$$\Delta T_3 = \frac{U_1}{U_3}\,\Delta T_1 \text{ ----- } 4$$

Substitute equ 3, 4 in equation 2 $(\Delta T_{overall} = \Delta T_1 + \Delta T_2 + \Delta T_3)$

$$\Delta T_{overall} = \Delta T_1 + \frac{U_1}{U_2}\,\Delta T_1 + \frac{U_1}{U_3}\,\Delta T_1$$

$$47.5^oC = \Delta T_1 \left[1 + \frac{U_1}{U_2} + \frac{U_1}{U_3}\right]$$

$$47.5^oC = \Delta T_1 \left[1 + \frac{2270}{2000} + \frac{2270}{1420}\right]$$

$\Delta T_1 = 12.72\ ^oC$;

$\Delta T_2 = \frac{U_1}{U_2} \Delta T_1 = \frac{2270}{2000} x12.72 = 14.43^{o}C$

$\Delta T_3 = \frac{U_1}{U_3} \Delta T_1 = \frac{2270}{1420} x12.72 = 20.33^{o}C$

Now,

$\Delta T_1 = 12.72\ ^{o}C = T_s - T_1 = 133.5 - T_1 \Rightarrow T_1 = 120.78\ ^{o}C = \lambda_1 = 2202$ kJ/kg

$\Delta T_2 = 14.43\ ^{o}C = T_1 - T_2 = 120.73 - T_2 \Rightarrow T_2 = 106.35\ ^{o}C = \lambda_2 = 2240$ kJ/kg

$\Delta T_3 = 20.33\ ^{o}C = T_2 - T_3 = 106.35 - T_3 \Rightarrow T_3 = 86.02\ ^{o}C = \lambda_3 = 2293.5$ kJ/kg

Mass flow rate of evaporation

$q_1 = q_2 = q_3$

$E_1 \lambda_1 = E_2 \lambda_2 = E_3 \lambda_3$ -----5

$E_1 + E_2 + E_3 = 333.34$ kg/h ----6

From equation 5,

$E_2 = \frac{\lambda_1}{\lambda_2} E_1; \quad E_3 = \frac{\lambda_1}{\lambda_3} E_1$

Equation 6 ➔ $E_1 + \frac{\lambda_1}{\lambda_2} E_1 + \frac{\lambda_1}{\lambda_3} E_1 = 333.34$ kg/h

$E_1 \left[1 + \frac{\lambda_1}{\lambda_2} + \frac{\lambda_1}{\lambda_3}\right] = 333.34$ kg/h ➔ $E_1 = 113.26$ kg/h

$E_2 = 111.31$ kg/h

$E_3 = 108.61$ kg/h

- Steam requirement

$m_s\lambda_s = E_1\lambda_1$

$$m_s = \frac{E_1\lambda_1}{\lambda_s} = \frac{113.2 \text{ x } 2202}{2163.2} = 115.3 \text{ kg/h}$$

- Steam Economy $= \frac{E}{m_s} = \frac{333.34}{115.3} = 2.89$

- Area of heat transfer

$$Q = UA\Delta T$$

$$A = \frac{Q_1}{U_1\Delta T_1} = \frac{m_s\lambda_s}{U_1\Delta T_1} = \frac{115.3 \text{ } kg/h \text{ x } 2163.2 \text{ } kJ/kg}{2270 \text{ J/m}^2\text{s}^0\text{Cx } 12.72^0\text{C}} \text{ x } \frac{1000}{3600} = 2.39 \text{ m}^2$$

Total heat transfer area = 3(2.39) = 7.19 m^2

Tomato juice is to be concentrated from 12% solids to 28% solids in a climbing film evaporator, 3 m high and 4 cm diameter. The maximum allowable temperature for tomato juice is 57°C. The juice is fed to the evaporator at 57°C and at this temperature the latent heat of vaporization is 2366 kJ kg^{-1}.

Steam is used in the jacket of the evaporator at a pressure of 170 kPa (abs). If the overall heat-transfer coefficient is 6000 J m^{-2} s^{-1} $°C^{-1}$, estimate the quantity of tomato juice feed per hour. Take heating surface as 3 m long x 0.04 m diameter.

Mass balance: basis 100kg feed

$Fx_f = Px_p$ ➔ 100*0.12 = P*0.28 ➔ P = 43kg/h ➔ E = 57kg/h

Heat balance

Area of evaporator tube *лDL*

= 3.14 x 0.04 x 3

= 0.38 m^2

Condensing steam temperature at 170 kPa (abs) = 115°C from Steam Tables.

Making a heat balance across the evaporator

$$q = UA\,\Delta T$$

$$= 6000 \times 0.38 \times (115 - 57)$$

$$= 1.32 \times 10^5 \text{ J s}^{-1}$$

Heat required per kg of feed for evaporation

$$= 0.57 \times 2366 \times 10^3$$

$$= 1.34 \times 10^6 \text{ J}$$

Rate of evaporation = $(1.32 \times 10^5)/ 1.34 \times 10^6)$

$$= 0.1 \text{ kg s}^{-1}$$

Rate of evaporation = 360 kg h^{-1}

Quantity of tomato juice feed per hour = 360 kg

A single effect evaporator is to produce a 35% solids tomato concentrate from a 6% solids raw juice entering at 18^oC. The pressure in the evaporator is 20kPa absolute and steam is available at 100kPa gauge. The overall heat transfer coefficient is 440$Jm^{-2} s^{-1} {}^oC^{-1}$, the boiling temperature of the tomato juice under the conditions in the evaporator is 60^oC, and the area of the heat transfer surface of the evaporator is 12m^2. Estimate the rate of raw juice feed that is required to supply the evaporator.

Mass balance: basis 1kg feed

$Fx_f = Px_p$ ➔ 1*0.06 = P*0.35 ➔ P = 0.17kg ➔ E =0.82kg

Making a heat balance across the evaporator

$$q = UA\,\Delta T$$
$$= 440 \times 12 \times (120 - 60)$$
$$= 317856 \text{ J/s}$$

- Heat required per kg of feed for evaporation

  $= m\ Cp\ \Delta T + m\lambda$

  = [1kg x 4.186kJ/kgC x (60-18)C] + [0.829kg x 2359 kJ/kg]

  = 2131kJ per kg of feed

The rate of feed of raw juice = Q/heat reqd

$$= \frac{317856\ J/s}{2131 kJ/kg} = 536\ kg/h$$

Apple juice is being concentrated in a natural-circulation single-effect evaporator. At steady-state conditions, dilute juice is the feed introduced at a rate of 0.67 kg/s. The concentration of the dilute juice is 11% total solids. The juice is concentrated to 75% total solids. The specific heats of dilute apple juice and concentrate are 3.9 and 2.3 kJ/(kg^{0}C), respectively. The steam pressure is measured to be 304.42 kPa. The inlet feed temperature is 43.3^{0}C. The product inside the evaporator boils at 62.2^{0}C. The overall heat-transfer coefficient is assumed to be 943 W/(m^2 ^{0}C). Assume negligible boiling-point elevation. Calculate the mass flow rate of concentrated product, steam requirements, steam economy, and the heat-transfer area.

Estimate the steam economy, mass flow rate of each evaporator in a double effect evaporator. Feed is entering at 10000kg/hr with concentration of 12% to 48% total solids in feed and product resp. Steam is available at 200 kPa gauge pressure and evaporation pressure at 2nd evaporator is 50 kPa. Assume there is no boiling point elevation, and have equal heat transfer. U_1 and U_2 are 2250 and 2350 J/m^2s^0C

Given:

$F = 10000$ kg/h

$X_f = 10\%$, $x_l = 48\%$

$Ps = 200kPa(g) = 300kPa(a) = 3$ bar => $Ts = 133.5^oC = \lambda_s = 2163.2$kJ/kg

$P_2 = 50kPa(a) = 0.5$bar => $T_2 = 81.35^oC = \lambda_2 = 2305.4$kJ/kg

U_1=2250 J/m^{2}s^{0}C; U_2=2350 J/m^{2}s^{0}C;

Estimate the 1. heat transfer area, 2. mass flow rate of evaporation, 3. steam economy, 4. steam requirement ??

- Mass Balance

$$F\,x_F = L\,x_L$$

$$L = \frac{10000 * 0.12}{0.48} = 2500 \text{ kg/h}$$

$$E = 10000 - 2500 = 7500 \text{ kg/h}$$

Since net transfer is equal;

$$q_1 = q_2$$

$$U_1 A_1 \Delta T_1 = U_2 A_2 \Delta T_2$$

Usually in multiple effect evaporator, $A_1 = A_2$

Then $U_1 \Delta T_1 = U_2 \Delta T_2$ ------1

$$\Delta T_{overall} = \Delta T_1 + \Delta T_2 \quad \text{------2}$$

$$\Delta T_{overall} = T_s - T_2 = 133.5 - 81.35 = 52.15^oC$$

From equation 1, ($U_1 \Delta T_1 = U_2 \Delta T_2$)

$$\Delta T_2 = \frac{U_1}{U_2} \Delta T_1 \text{ ----- } 3$$

Substitute equ 3, in equation 2 ($\Delta T_{overall} = \Delta T_1 + \Delta T_2$)

$$\Delta T_{overall} = \Delta T_1 + \frac{U_1}{U_2} \Delta T_1$$

$$52.15^oC = \Delta T_1 \left[1 + \frac{U_1}{U_2}\right]$$

$$52.15^oC = \Delta T_1 \left[1 + \frac{2250}{2350}\right]$$

$\Delta T_1 = 26.64\ ^oC$;

$$\Delta T_2 = \frac{U_1}{U_2}\Delta T_1 = \frac{2250}{2350} x 26.64 = 25.5^oC$$

Now,

$\Delta T_1 = 26.64\ ^oC = T_s - T_1 = 133.5 - T_1 \Rightarrow T_1 = 106.86\ ^oC = \lambda_1 = 2237.8$ kJ/kg

$\Delta T_2 = 25.5\ ^oC = T_1 - T_2 = 106.86 - T_2 \Rightarrow T_2 = 81.36^oC = \lambda_2 = 2305.4$ kJ/kg

- Mass flow rate of evaporation

$$q_1 = q_2$$

$$E_1 \lambda_1 = E_2 \lambda_2 \text{ -----5}$$

$$E_1 + E_2 = 7500 \text{ kg/h ----6}$$

From equation 5,

$$E_2 = \frac{\lambda_1}{\lambda_2} E_1;$$

Equation 6 ➔ $E_1 + \frac{\lambda_1}{\lambda_2} E_1 = 7500 \text{ kg/h}$

$$E_1 \left[1 + \frac{\lambda_1}{\lambda_2}\right] = 7500 \text{ kg/hr} \;➔\; E_1 = 3805.79 \text{ kg/h}$$

$$E_2 = 3694.202 \text{ kg/h}$$

- Steam requirement

$$m_s\lambda_s = E_1\lambda_1$$

$$m_s = \frac{E_1\lambda_1}{\lambda_s} = \frac{3805.79 \text{ x } 2237.8}{2163.2} = 3937.03 \text{ kg/h}$$

- Steam Economy $= \frac{E}{m_s} = \frac{7500}{3937.03} = 1.9$

- Area of heat transfer

$$Q = UA\Delta T$$

$$A = \frac{Q1}{U_1\Delta T_1} = \frac{m_s\lambda_s}{U_1\Delta T_1} = \frac{3937.03 \; kg/h \text{ x } 2163.2 \; kJ/kg}{2250 \text{ J/m}^2\text{s}^0\text{C x } 26.64^0\text{C}} \text{ x } \frac{1000}{3600} = 39.46 \text{ m}^2$$

Total heat transfer area = 2(39.46) = 78.9 m^2

Estimate a) the evaporation temperature in each evaporator b) the requirement of steam c) the area of heat transfer surface for a double effect evaporator. Steam is available at 100 kPa gauge pressure and pressure at the evaporator is 20 kPa. Assume U_1 and U_2 are 600 and 450 J/m^2s^0C. The evaporator is to concentrate 50000 kh/hr of raw milk with 9.5% total solids to 35%. There is no boiling point elevation.

Given:

$F = 15000$ kg/h

$X_f = 9.5\%$, $x_l = 35\%$

Ps = 100kPa(g) = 200kPa(a) = 2 bar => Ts = 120.2°C = λ_s = 2201.6kJ/kg

P_2 = 20kPa(a) = 0.2bar => T_2 = 60.09°C = λ_2 = 2358.4kJ/kg

$U_1 = 600\ J/m^2s^0C$; $U_2 = 450\ J/m^2s^0C$;

Estimate the 1. heat transfer area, 2. mass flow rate of evaporation, 3. steam economy, 4. steam requirement ??

- Mass Balance

$$F\,x_F = L\,x_L$$

$$L = \frac{15000 * 0.095}{0.35} = 4071.42 \text{ kg/h}$$

$$E = 15000 – 4071.42 = 10928.52 \text{ kg/h}$$

Since net transfer is equal;

$$q_1 = q_2$$

$$U_1A_1\Delta T_1 = U_2A_2\Delta T_2$$

Usually in multiple effect evaporator, $A_1 = A_2$

Then $U_1\Delta T_1 = U_2\Delta T_2$ ------1

$$\Delta T_{overall} = \Delta T_1 + \Delta T_2 \quad \text{------2}$$

$$\Delta T_{overall} = T_s – T_2 = 120.2 – 60.09 = 60.11^oC$$

From equation 1, ($U_1 \Delta T_1 = U_2 \Delta T_2$)

$$\Delta T_2 = \frac{U_1}{U_2} \Delta T_1 \text{ ----- } 3$$

Substitute equ 3, in equation 2 ($\Delta T_{overall} = \Delta T_1 + \Delta T_2$)

$$\Delta T_{overall} = \Delta T_1 + \frac{U_1}{U_2} \Delta T_1$$

$$60.11^oC = \Delta T_1 \left[1 + \frac{U_1}{U_2}\right]$$

$$60.11^oC = \Delta T_1 \left[1 + \frac{600}{450}\right]$$

$\Delta T_1 = 25.79\ ^oC$;

$$\Delta T_2 = \frac{U_1}{U_2} \Delta T_1 = \frac{600}{450} x25.79 = 34.32^oC$$

Now,

$\Delta T_1 = 25.79^oC = T_s - T_1 = 120.2 - T_1 \Rightarrow T_1 = 94.41\ ^oC = \lambda_1 = 2272.8$ kJ/kg

$\Delta T_2 = 34.32^oC = T_1 - T_2 = 94.41 - T_2 \Rightarrow T_2 = 60.09^oC = \lambda_2 = 2358.8$ kJ/kg

- Mass flow rate of evaporation

$$q_1 = q_2$$

$$E_1 \lambda_1 = E_2 \lambda_2 \text{ -----5}$$

$$E_1 + E_2 = 10928.52 \text{ kg/h ----6}$$

From equation 5,

$$E_2 = \frac{\lambda_1}{\lambda_2} E_1;$$

Equation 6 ➔ $$E_1 + \frac{\lambda_1}{\lambda_2} E_1 = 10928.52 \text{ kg/h}$$

$$E_1 \left[1 + \frac{\lambda_1}{\lambda_2}\right] = 10928.52 \text{ kg/h} \rightarrow E_1 = 5565.55 \text{ kg/h}$$

$$E_2 = 5336.62 \text{ kg/h}$$

- Steam requirement

$$m_s\lambda_s = E_1\lambda_1$$

$$m_s = \frac{E_1\lambda_1}{\lambda_s} = \frac{5565.55 \text{ x } 2272.8}{2201.6} = 5745.54 \text{ kg/h}$$

- Steam Economy $= \frac{E}{m_s} = \frac{10928.52}{5745.54} = 1.9$

- Area of heat transfer

$$Q = UA\Delta T$$

$$A = \frac{Q1}{U_1\Delta T_1} = \frac{m_s\lambda_s}{U_1\Delta T_1} = \frac{5745.54 \ kg/h \text{ x } 2201.6 \ kJ/kg}{600 \text{ J/m}^2\text{s}^0\text{Cx } 25.79^0\text{C}} \text{ x } \frac{1000}{3600} = 227.07 \text{ m}^2$$

Total heat transfer area = 2(227.07) = 454.14 m^2

a) Calculate the evaporation in each effect for triple effect evaporator. The concentration of solution from 5% to 25% total solids at the input feed rate of 10000 kg/h. Steam is available at 100 kPa (g) and pressure in evaporting space is 55 kPa. U_1=600 J/m^{2}s^{0}C; U_2=500 J/m^{2}s^{0}C; U_3=350 J/m^{2}s^{0}C.

b) Calculate per kg of water evaporated.

Given:

$F = 10000$ kg/h

$X_f = 5\%$, $x_l = 25\%$

$Ps = 100kPa(g) = 2$ bar => $Ts = 120.2^oC = \lambda_s = 2201.6$ kJ/kg

$P_3 = 55kPa(a) = 0.55bar$ => $T_3 = 83.7\ ^oC = \lambda_3 = 2299.7$kJ/kg

U_1=600 J/m^{2}s^{0}C; U_2=500 J/m^{2}s^{0}C; U_3=350 J/m^{2}s^{0}C

Estimate the 1. heat transfer area, 2. mass flow rate of evaporation, 3. steam economy, 4. steam requirement ??

- Mass Balance

$$F\,x_F = L\,x_L$$

$$L = \frac{10000 * 0.05}{0.25} = 2000 \text{ kg/h}$$

$$E = 10000 - 2000 = 8000 \text{ kg/h}$$

Since net transfer is equal;

$$q_1 = q_2 = q_3$$

$$U_1A_1\Delta T_1 = U_2A_2\Delta T_2 = U_3A_3\Delta T_3$$

Usually in multiple effect evaporator, $A_1 = A_2 = A_3$

Then $U_1\Delta T_1 = U_2\Delta T_2 = U_3\Delta T_3$ -------1

$$\Delta T_{overall} = \Delta T_1 + \Delta T_2 + \Delta T_3 \text{ ------2}$$

$$\Delta T_{overall} = T_s - T_3 = 120.2 - 83.7 = 36.5^oC$$

From equation 1, ($U_1 \Delta T_1 = U_2 \Delta T_2 = U_3 \Delta T_3$)

$$\Delta T_2 = \frac{U_1}{U_2} \Delta T_1 \text{ ----- } 3$$

$$\Delta T_3 = \frac{U_1}{U_3} \Delta T_1 \text{ ----- } 4$$

Substitute equ 3, 4 in equation 2 ($\Delta T_{overall} = \Delta T_1 + \Delta T_2 + \Delta T_3$)

$$\Delta T_{overall} = \Delta T_1 + \frac{U_1}{U_2} \Delta T_1 + \frac{U_1}{U_3} \Delta T_1$$

$$36.5^oC = \Delta T_1 \left[1 + \frac{U_1}{U_2} + \frac{U_1}{U_3}\right]$$

$$36.5^oC = \Delta T_1 \left[1 + \frac{600}{500} + \frac{600}{350}\right]$$

$\Delta T_1 = 9.32\ ^oC$;

$$\Delta T_2 = \frac{U_1}{U_2}\Delta T_1 = \frac{600}{500} x 9.32 = 11.18\,^oC$$

$$\Delta T_3 = \frac{U_1}{U_3}\Delta T_1 = \frac{600}{350} x 9.32 = 15.97\,^oC$$

Now,

$\Delta T_1 = 9.32\ ^oC = T_s - T_1 = 120.2 - T_1 \Rightarrow T_1 = 110.88\ ^oC = \lambda_1 = 2230$ kJ/kg

$\Delta T_2 = 11.18\ ^oC = T_1 - T_2 = 110.88 - T_2 \Rightarrow T_2 = 99.7\ ^oC = \lambda_2 = 2259.6$ kJ/kg

$\Delta T_3 = 15.97\ ^oC = T_2 - T_3 = 99.7 - T_3 \Rightarrow T_3 = 83.73\ ^oC = \lambda_3 = 2301.2$ kJ/kg

- Mass flow rate of evaporation

$$q_1 = q_2 = q_3$$

$$E_1 \lambda_1 = E_2 \lambda_2 = E_3 \lambda_3 \text{ -----5}$$

$$E_1 + E_2 + E_3 = 8000 \text{ kg/h ----6}$$

From equation 5,

$$E_2 = \frac{\lambda_1}{\lambda_2} E_1; \quad E_3 = \frac{\lambda_1}{\lambda_3} E_1$$

Equation 6 ➔ $$E_1 + \frac{\lambda_1}{\lambda_2} E_1 + \frac{\lambda_1}{\lambda_3} E_1 = 8000 \text{ kg/h}$$

$$E_1 \left[1 + \frac{\lambda_1}{\lambda_2} + \frac{\lambda_1}{\lambda_3}\right] = 8000 \text{ kg/hr} \rightarrow E_1 = 2706.4 \text{ kg/h}$$

$$E_2 = 2670.9 \text{ kg/h}$$

$$E_3 = 2622.66 \text{ kg/h}$$

- Steam requirement

$$m_s\lambda_s = E_1\lambda_1$$

$$m_s = \frac{E_1\lambda_1}{\lambda_s} = \frac{2706.4 \text{ x } 2230}{2201.6} = 2741.31\text{kg/h}$$

- Steam Economy $= \frac{E}{m_s} = \frac{8000}{2741.31} = 2.89$

- Quantity of steam required $= \frac{m_s}{E} = \frac{2741.31}{8000} = 0.342$

- If in the problem 4, the boiling point elevation is 0.6^oC, 1.5^oC, 4^oC in the triple effect evaporators, what is the change in the requirement of input steam per kg of water evaporation.

$T_1 = 110.88\ ^oC + 0.6\ ^oC = 111.48\ ^oC \Rightarrow \lambda_1 = 2226.3$ kJ/kg

$T_2 = 99.7\ ^oC + 1.5\ ^oC = 101.2\ ^oC \Rightarrow \lambda_2 = 2254.3$ kJ/kg

$T_3 = 83.73\ ^oC + 4\ ^oC = 87.73\ ^oC \Rightarrow \lambda_3 = 2289.4$ kJ/kg

- Mass flow rate of evaporation

$$q_1 = q_2 = q_3$$

$$E_1 \lambda_1 = E_2 \lambda_2 = E_3 \lambda_3 \text{ -----}5$$

$$E_1 + E_2 + E_3 = 8000 \text{ kg/h ----}6$$

From equation 5,

$$E_2 = \frac{\lambda_1}{\lambda_2} E_1; \quad E_3 = \frac{\lambda_1}{\lambda_3} E_1$$

Equation 6 ➔ $E_1 + \frac{\lambda_1}{\lambda_2} E_1 + \frac{\lambda_1}{\lambda_3} E_1 = 8000 \text{ kg/h}$

$$E_1 \left[1 + \frac{\lambda_1}{\lambda_2} + \frac{\lambda_1}{\lambda_3}\right] = 8000 \text{ kg/h} \rightarrow E_1 = 2702.6 \text{ kg/h}$$

$$E_2 = 2669.0 \text{ kg/h}$$

$$E_3 = 2628.11 \text{ kg/h}$$

- Steam requirement

$$m_s\lambda_s = E_1\lambda_1$$

$$m_s = \frac{E_1\lambda_1}{\lambda_s} = \frac{2702.6 \text{ x } 2226.3}{2201.6} = 2732.92 \text{ kg/h}$$

- Steam Economy $= \frac{E}{m_s} = \frac{8000}{2732.92} = 2.92$

- Quantity of steam required $= \frac{m_s}{E} = \frac{2732.92}{8000} = 0.341$


Thank You.