

Dairy Process Engineering



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Module 1. Evaporation

Lesson-5

Basic Concepts of Multiple Effect Evaporators

5.1. INTRODUCTION

Milk condensing in vacuum pan uses high amount of steam to evaporate water. Multiple effect evaporator is used for steam economy.

5.2. MULTIPLE-EFFECT EVAPORATION

In any evaporation operation, the major process cost is the steam consumed. Therefore, methods of reducing steam consumption (or of increasing economy, defined as mass of vapour produced per unit mass of steam consumed) are very important. The most common of the available methods is to use the vapour generated in the first evaporator as the heating medium for a second evaporator. Ideally, this method should produce almost 2 kg of vapour for every kg. of steam consumed. The method is feasible if the second evaporator is operated at a lower pressure than the first, so that a positive value of Δt is obtained across the steam-chest surface of the second evaporator. Several evaporators can be connected in series. In this way the amount of vapour (kg) produced per kg of steam consumed equal to the number of evaporator bodies. The increase in latent heat with decreasing pressure and additional radiation losses affect , the economy as the number of evaporators used is increased. This method of evaporation in series is called multiple-effect evaporation, and each stage is called an effect. The amount of steam consumption in multiple effect evaporators is already mentioned in Lesson 4.

Fig-5.1: Multiple-Effect Evaporation

5.2.1. Different level of vacuum in each effect of Multiple effect Evaporator

Here we assume that initially in all the calandria the level and temperature of feed is same. Now during starting of the plant steam is introduced in first calandria. So in that calandria milk initially will be heated and then raised to corresponding boiling point and vapour will be released. This vapour is going in the next calandria's heating jacket where the milk is cold and now start heating thereby the temperature difference between heating vapour and milk will decrease. It gives less condensation of vapour in second calandria. This gives rise of back pressure in first calandria tube and thereby the boiling point in first calandria will rise. The same principle will work for subsequent calandrias and last calandria will correspond to

condenser vacuum. Once this established than all the calandrias will operate at different vacuum levels.

By controlling the opening of orifice plates present in the airline of heating jackets is also used to control different vacuum levels in all the calandrias.

5.2.2. Multiple effect Evaporator capacity and steam economy

In addition to the economy increase in multiple-effect evaporation, a capacity variation would be expected. Note, however, that the temperature difference from initial steam to the final condenser which was available for a single-effect evaporator will be unchanged by inserting any additional effects between the steam supply and the condenser. For the simplest case, where each effect has area and coefficient equal to that of every other effect and where there are no boiling point rises $q_t = q_1 + q_2 + q_3 + \dots$ where q_t is the total heat-transfer rate in all effects and q_1, q_2, q_3 are the heat transfer rates in each of the individual effects.

$$q_t = U_1 A_1 \Delta t_1 + U_2 A_2 \Delta t_2 + U_3 A_3 \Delta t_3 + \dots$$

Since the areas and heat transfer coefficients are equal,

$$q_t = U_1 A_1 (\Delta t_1 + \Delta t_2 + \Delta t_3 \dots) = U_1 A_1 (\Delta t)_{\text{total}}$$

This rate of heat transfer is the same as that obtained with a single effect operating between the same ultimate temperature levels. Thus, multiple-effect evaporation using n effects increases the steam economy but decreases the heat flux per effect by a factor of about $1/n$ relative to single-effect operation under the same terminal conditions. Therefore, no increase in capacity is obtained and in fact, the additional complexity of equipment usually results in increased heat losses to the surroundings and a reduction in capacity. The increased steam economy must then, be balanced against the increased equipment cost. The result is that the evaporation using more than five or seven effects is rarely economical.

When the solution being evaporated has a significant boiling-point rise, the capacity obtained is very much reduced, for the boiling-point rise reduces the Δt in each effect.

5.2.3. Calculations for Multiple- Effect Evaporators

For a multiple – effect evaporator system calculations, the values required to be obtained are

- (i) The area of the heating surface in each effect,
- (ii) The kg of steam per hour to be supplied, and
- (iii) the amount of vapour leaving each effect, particularly in the last one.

The given values are usually as follows

- (1) Steam pressure to the first effect,
- (2) Final pressure in the vapour space of the last effect,
- (3) Feed conditions and flow to the first effect,
- (4) Final concentration in the liquid leaving the last effect,

(5) Physical properties such as enthalpies and / or heat capacities of the liquid and vapours, and

(6) Overall heat – transfer coefficients in each effect.

Usually, the areas of each effect are assumed equal.

The calculations are done using material balances, heat balances, and the capacity equations $q = UA\Delta T$ for each effect. A convenient way to solve these equations is by trial and error. The basic steps to follow are given as follows for a triple – effect evaporators.

5.2.4. Triple – Effect Evaporators' Calculation Method

1. Determine the boiling point in the last effect from the known outlet concentration and pressure in the last effect,
2. Determine the total amount of vapor evaporated by performing an overall material balance,
3. Estimate the temperature drops ΔT_1 , ΔT_2 and ΔT_3 in the three effects. Then calculate the boiling point in each effect,
4. Calculate the amount vaporized and the flows of liquid in each effect using heat and material balance in each effect,
5. Calculate the value of heat transferred in each effect. Using the rate equation $q=UA\Delta T$ for each effect, calculate the areas, A_1 , A_2 and A_3 . If these areas are reasonably close to each other, the calculations are complete and a second trial is not needed. Otherwise a second trial should be performed.

Example: Evaporation of Milk in a Triple – Effect Evaporator

A triple effect forward – feed evaporator is being used to evaporate a milk containing 10 % solids to a condensed milk of 50% T.S. The boiling point rise of the milk (independent of pressure) can be estimated from $BPR^{\circ C} = 1.78x + 6.22x^2$, where x is weight fraction of T.S. in milk (K1). Saturated steam at 205.5 kPa (121.1°C saturation temperature) is being used. The pressure in the vapor space of the third effect is 13.4 kPa. The feed rate is 22680 kg / h at 26.7 °C. The heat capacity of the milk is (K1) $C_p = 4.19 - 2.35x$ kJ/kg.K. The heat of milk is considered to be negligible. The coefficients of heat transfer have been estimated as $U_1 = 3123$, $U_2 = 1987$, and $U_3 = 1136$ W / m² . K. If each effect has the same surface area, calculate the area, the steam rate used, and the steam economy.

Solution : Following the above steps outlined, the calculations are as follows:

Step 1. For 13.4 kPa, the saturation temperature is 51.67°C from the steam tables. Using the equation for BPR for evaporator number 3 with $x = 0.5$,

$$BPR_3 = 1.78x + 6.22x^2 = 1.78(0.5) + 6.22(0.5)^2 = 2.45 \text{ }^{\circ}\text{C}, \text{ so } T_3 = 51.67 + 2.45 = 54.12 \text{ }^{\circ}\text{C}$$

Step 2. Making an overall and a solids balance to calculate the total amount vaporized ($V_1 + V_2 + V_3$) and L_3 ,

$$F = 22680 = L_3 + (V_1 + V_2 + V_3)$$

$$F x_F = 22680(0.1) = L_3(0.5) + (V_1 + V_2 + V_3)(0)$$

$$L_3 = 4536 \text{ Kg/h}$$

$$\text{total vapour} = (V_1 + V_2 + V_3) = 18\ 144 \text{ kg/h}$$

Assuming equal amount vaporized in each effect, $V_1 = V_2 = V_3 = 6048$ kg/h. Making a total

material balance on effects 1, 2, and 3 and solving.

$$(1) F = 22\,680 = V_1 + L_1 = 6048 + L_1, L_1 = 16\,632 \text{ kg/h}$$

$$(2) L_1 = 16\,632 = V_2 + L_2 = 6048 + L_2, L_2 = 10\,584 \text{ kg/h}$$

$$(3) L_2 = 10\,584 = V_3 + L_3 = 6048 + L_3, L_3 = 4536 \text{ kg/h}$$

Making a solids balance on effects 1, 2 and 3 and solving for x,

$$(1) 22\,680(0.1) = L_1 x_1 = 16\,632 (x_1), x_1 = 0.136$$

$$(2) 16\,632(0.136) = L_2 x_2 = 10\,584 (x_2), x_2 = 0.214$$

$$(3) 10\,584(0.214) = L_3 x_3 = 4536 (x_3), x_3 = 0.50$$

Step 3. The BPR in each effect is calculated as follows:

$$(1) \text{BPR}_1 = 1.78 x_1 + 6.22(x_1)^2 = 6.22(0.136)^2 = 0.36^\circ\text{C}$$

$$(2) \text{BPR}_2 = 1.78(0.214) + 6.22(0.214)^2 = 0.65^\circ\text{C}$$

$$(3) \text{BPR}_3 = 1.78(0.5) + 6.22(0.5)^2 = 2.45^\circ\text{C}$$

$$\sum \Delta T \text{ available} = T_{s1} - T_3 \text{ (saturation)} - (\text{BPR}_1 + \text{BPR}_2 + \text{BPR}_3)$$

$$= 121.1 - 51.67 - (0.36 + 0.65 + 2.45)$$

$$= 65.97^\circ\text{C}$$

Now

$$\Delta T_1 = \sum \left(\Delta T \frac{\frac{1}{U_1}}{\frac{1}{U_1} + \frac{1}{U_2} + \frac{1}{U_3}} \right)$$

$$= \frac{(65.97)(1/3123)}{\left(\frac{1}{3123}\right) + \left(\frac{1}{1987}\right) + \left(\frac{1}{1136}\right)}$$

$$\Delta T_1 = 12.40^\circ\text{C} \text{ similarly } \Delta T_2 = 19.50^\circ\text{C} \text{ and } \Delta T_3 = 34.07^\circ\text{C}$$

However, since a cold feed enters at effect number 1, this effect requires more heat. Increasing ΔT_1 and lowering ΔT_2 and ΔT_3 proportionately as a first estimate,

$$\Delta T_1 = 15.56^\circ\text{C}, \Delta T_2 = 18.34^\circ\text{C}, \Delta T_3 = 32.07^\circ\text{C}$$

To calculate the actual boiling point of the milk in each effect,

$$(1) T_1 = T_{s1} - \Delta T_1$$

$$= 121.1 - 15.56 = 105.54^\circ\text{C}$$

$$T_{s1} = 121.1^\circ\text{C} \text{ (Condensing temperature of saturated steam to effect 1)}$$

$$(2) T_2 = T_1 - \text{BPR}_1 - \Delta T_2$$

$$= 105.54 - 0.36 - 18.34 = 86.84^\circ\text{C}$$

$$T_{s2} = T_1 - \text{BPR}_1 = 105.54 - 0.36$$

$$= 105.18^\circ\text{C} \text{ (Condensing temperature of steam to effect 2)}$$

$$(3) T_3 = T_2 - \text{BPR}_2 - \Delta T_3$$

$$= 86.84 - 0.65 - 32.07 = 54.12^\circ\text{C}$$

$$T_{s3} = T_2 - BPR_2 = 86.84 - 0.65$$
$$= 86.19^\circ\text{C} \text{ (Condensing temperature of steam to effect3)}$$

The temperatures in the three effects are as follows:



Step 4. The heat capacity of the liquid in each effect is calculated from the equation $c_p = 4.19 - 2.35x$:

$$\begin{aligned}
 F : c_p &= 4.19 - 2.35(0.1) = 3.955 \text{ kJ/kg K} \\
 L_1 : c_p &= 4.19 - 2.35(0.136) = 3.869 \text{ kJ/kg K} \\
 L_2 : c_p &= 4.19 - 2.35(0.214) = 3.684 \text{ kJ/kg K} \\
 L_3 : c_p &= 4.19 - 2.35(0.5) = 3.015
 \end{aligned}$$

The values of the enthalpy H of the various vapour streams relative to water at 0°C as a datum are obtained from the steam table as follows:

Effect 1:

$$\begin{aligned}
 T_1 &= 105.54^\circ\text{C}, \quad T_{s2} = 105.18, \quad \text{BPR}_1 = 0.36 \quad T_{s1} = 121.1 \\
 H_1 &= H_{s2} (\text{Saturation enthalpy at } T_{s2}) + 1.884(0.36^\circ\text{C superheat}) \\
 &= 2684 + 1.884(0.36) = 2685 \text{ kJ/kg} \\
 \lambda_{s1} &= H_{s1} (\text{vapour saturation enthalpy}) - h_{s1} (\text{liquid enthalpy at } T_{s1}) \\
 &= (2708 - 508) = 2200 \text{ kJ/kg latent heat of condensation}
 \end{aligned}$$

Effect 2:

$$\begin{aligned}
 T_2 &= 86.84^\circ\text{C}, \quad T_{s3} = 86.19, \quad \text{BPR}_2 = 0.65 \\
 H_2 &= H_{s3} + 1.884(0.65) = 2654 + 1.884(0.65) = 2655 \text{ kJ/kg} \\
 \lambda_{s2} &= H_1 - h_{s2} = 2685 - 441 = 2244 \text{ kJ/kg}
 \end{aligned}$$

Effect 3:

$$\begin{aligned}
 T_3 &= 54.12^\circ\text{C}, \quad T_{s4} = 51.67, \quad \text{BPR}_3 = 2.45 \\
 H_3 &= H_{s4} + 1.884(2.45) = 2595 + 1.884(2.45) = 2600 \text{ kJ/kg} \\
 \lambda_{s3} &= H_2 - h_{s3} = 2655 - 361 = 2294 \text{ kJ/kg}
 \end{aligned}$$

Flow relations to be used in heat balance are

$$V_1 = 22\,680 - L_1, \quad V_2 = L_1 - L_2, \quad V_3 = L_2 - 4536, \quad L_3 = 4536$$

Write a heat balance on each effect. Using 0°C as a datum

$$(1) \quad Fc_p(T_F - 0) + S\lambda_{s1} = L_1c_p(T_1 - 0) + V_1H_1$$

Substituting the known values,

$$22\,680(3.955)(26.7 - 0) + S(2200) = L_1(3.869)(105.54 - 0) + (22\,680 - L_1)(2685)$$

$$(2) \quad L_1c_p(T_1 - 0) + V_1\lambda_{s2} = L_2c_p(T_2 - 0) + V_2H_2$$

$$L_1(3.869)(105.54 - 0) + (22\,680 - L_1)(2244) = L_2(3.684)(86.84 - 0) + (L_1 - L_2)(2655)$$

$$(3) \quad L_2c_p(T_2 - 0) + V_2\lambda_{s3} = L_3c_p(T_3 - 0) + V_3H_3$$

$$L_2(3.684)(86.84 - 0) + (L_1 - L_2)(2294) = 4536(3.015)(54.12 - 0) + (L_2 - 4536)(2600)$$

Solving the last two equations simultaneously for L_1 and L_2 and substituting into the first equation,

$$\begin{array}{lll}
 L_1 = 17\,078 \text{ kg/h} & L_2 = 11\,068 & L_3 = 4536 \\
 S = 8936 & V_1 = 5602 & V_2 = 6010 \quad V_3 = 6532
 \end{array}$$

The calculated values of V_1 , V_2 and V_3 are close enough to the assumed values that steps 2, 3, and 4 do not need to be repeated. If the calculation were repeated, the calculated values of V_1 , V_2 , and V_3 would be used starting with step 2 and a solid balance in each effect would be made.

Step 5. Solving for the values of q in each effect area,

$$\begin{aligned}
 q_1 &= S\lambda_{s1} = \left(\frac{8936}{3600}\right)(2200 \times 1000) = 5.460 \times 10^6 \text{ W} \\
 q_2 &= V_2\lambda_{s2} = \left(\frac{5602}{3600}\right)(2244 \times 1000) = 3.407 \times 10^6 \text{ W}
 \end{aligned}$$

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