An evaporator needs to be designed to concentrate a sugar solution containing 10 wt % solids to a concentrated solution of 50%. The boiling-point rise of the solutions (independent of pressure) can be estimated from BPR°C = 1.78x + 6.22x**2** (BPR°F = 3.2x + 11.2x**2**), where x is wt fraction of sugar in solution. Saturated steam at 205.5 kPa is being used. The pressure in the vapor space of the final effect is 13.4 kPa (1.94 psia). The feed rate is 1000 x N kg/h, where N is group number.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| EXAMPLE 8.5-1. Evaporation of Sugar Solution in a Triple-Effect Evaporator A triple-effect forward-feed evaporator is being used to evaporate a sugar solution containing 10 wt % solids to a concentrated solution of 50%. The boiling-point rise of the solutions (independent of pressure) can be estimated from BPR°C = 1.78x + 6.22x**2** (BPR°F = 3.2x + 11.2x**2**), where x is wt fraction of sugar in solution (K1). Saturated steam at 205.5 kPa (29.8 psia) [121.1°C (250°F) saturation temperature] is being used. The pressure in the vapor space of the third effect is 13.4 kPa (1.94 psia). The feed rate is 22 680 kg/h (50 000 lb**m**/h) at 26.7°C (80°F). The heat capacity of the liquid solutions is (K1) c**p** = 4.19 – 2.35x kJ/kg · K (1.0 – 0.56x btu/lb**m** · °F). The heat of solution 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/m**2** · K, or 550, 350, and 200 btu/h · ft**2** · °F. If each effect has the same surface area, calculate the area, the steam rate used, and the steam economy.  Solution: The process flow diagram is given in Fig. 8.5-1. Following the eight steps outlined, the calculations are as follows:   |  |  | | --- | --- | | **Step 1.** | For 13.4 kPa (1.94 psia), the saturation temperature is 51.67°C (125°F) from the steam tables. Using the equation for BPR for evaporator number 3 with x = 0.5,  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image18.gif | | **Step 2.** | Making an overall and a solids balance to calculate the total amount vaporized (V**1** + V**2** + V**3**) and L**3**,  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image19.gif  Assuming equal amount vaporized in each effect, V**1** = V**2** = V**3** = 6048 kg/h (13 333 lb**m**/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 kg/h (33 667 lb**m**/h) | | (2) | L**1** = 16 632 = V**2** + L**2** = 6048 + L**2**, | L**2** = 10 584 (23 334) | | (3) | L**2** = 10 584 = V**3** + L**3** = 6048 + L**3**, | L**3** = 4536(10 000) |   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** = 0.500 | (check balance) | | | **Step 3.** | The BPR in each effect is calculated as follows:   1. BPR**1** = 1.78x**1** + 6.22https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image20.gif = 1.78(0.136) + 6.22(0.136)**2** = 0.36°C (0.7°F) 2. BPR**2** = 1.78(0.214) + 6.22(0.214)**2** = 0.65°C (1.2°F) 3. BPR**3** = 1.78(0.5) + 6.22(0.5)**2** = 2.45°C (4.4°F)   https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image21.gif  Using Eq. (8.5-6) for ΔT**1** and similar equations for ΔT**2** and ΔT**3**,  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image22.gif  However, since a cold feed enters effect number 1, this effect requires more heat. Increasing ΔT**1** and lowering ΔT**2** and ΔT**3** proportionately as a first estimate,  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image23.gif  To calculate the actual boiling point of the solution in each effect,   |  |  |  |  | | --- | --- | --- | --- | | (1) | T**1** | = | T**S1** – ΔT**1** | |  |  | = | 121.1 – 15.56 = 105.54°C | |  | T**S1** | = | 121.1°C (condensing temperature of saturated steam to effect 1) | | (2) | T**2** | = | T**1** – BPR**1** – ΔT**2** | |  |  | = | 105.54 – 0.36 – 18.34 = 86.84°C | |  | T**s2** | = | T**1** – BPR**1** = 105.54 – 0.36 | |  |  | = | 105.18°C (condensing temperature of steam to effect 2) | | (3) | T**3** | = | T**2** – BPR**2** – ΔT**3** | |  |  | = | 86.84 – 0.65 – 32.07 = 54.12°C | |  | T**S3** | = | T**2** – BPR**2** | |  |  | = | 86.84 – 0.65 = 86.19°C (condensing temperature of steam to effect 3) |   The temperatures in the three effects are as follows:  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image24.gif | | **Step 4.** | The heat capacity of the liquid in each effect is calculated from the equation c**P** = 4.19 – 2.35x:  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image25.gif  The values of the enthalpy H of the various vapor streams relative to water at 0°C as a datum are obtained from the steam table as follows:  Effect 1:  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image26.gif  Effect 2:  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image27.gif  Effect 3:  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image28.gif  (Note that the superheat corrections in this example are small and could possibly have been neglected. However, the corrections were used to demonstrate the method of calculation.) Flow relations to be used in heat balances are  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image29.gif  Write a heat balance on each effect. Using 0°C as a datum, since the values of H of the vapors are relative to 0°C (32°F), and noting that (T**F** – 0)°C = (T**F** – 0) K and (T**1** – 0)°C = (T**1** – 0) K,   |  |  | | --- | --- | | (1) | Fc**p**(T**F** – 0) + Sλ**S1** = L**1**c**p**(T**1** – 0) + V**1**H**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) |  | L**1**c**p**(T**1** – 0) + V**1**λ**S2** = L**2**c**p**(T**2** – 0) + V**2**H**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) | L**2**c**p**(T**2** – 0) + V**2**λ**S3** = L**3**c**p**(T**3** – 0) + V**3**H**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,  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image30.gif  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 solids balance in each effect would be made. | | **Step 5.** | Solving for the values of q in each effect and area,  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image31.gif    https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image32.gif  The average area A**m** = 104.4 m**2**. The areas differ from the average value by less than 10% and a second trial is not really necessary. However, a second trial will be made starting with step 6 to demonstrate the calculation methods used. | | **Step 6.** | Making a new solids balance on effects 1, 2, and 3, using the new L**1** = 17 078, L**2** = 11 068, and L**3** = 4536, and solving for x,   |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | | (1) | 22 680(0.1) | = | 17 078(x**1**), | x**1** = 0.133 |  | | (2) | 17 078(0.133) | = | 11 068(x**2**), | x**2** = 0.205 |  | | (3) | 11 068(0.205) | = | 4536(x**3**), | x**3** = 0.500 | (check balance) | | | **Step 7.** | The new BPR in each effect is then   1. BPR**1** = 1.78x**1** + 6.22https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image33.gif = 1.78(0.133) + 6.22(0.133)**2** = 0.35°C 2. BPR**2** = 1.78(0.205) + 6.22(0.205)**2** = 0.63°C 3. BPR**3** = 1.78(0.5) + 6.22(0.5)**2** = 2.45°C   https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image34.gif  The new values for ΔT are obtained using Eq. (8.5-11):  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image35.gif  These ΔT' values are readjusted so that https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image36.gif = 16.77, https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image37.gif = 16.87, https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image38.gif = 32.36, and ∑ ΔT = 16.77 + 16.87 + 32.36 = 66.00°C. To calculate the actual boiling point of the solution in each effect,   |  |  |  |  |  | | --- | --- | --- | --- | --- | | (1) | T**1** | = | T**S1** – https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image39.gif = 121.1 – 16.77 = 104.33°C, | T**S1** = 121.1°C | | (2) | T**2** | = | T**1** – BPR**1** – https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image40.gif = 104.33 – 0.35 – 16.87 = 87.11°C | | |  | T**S2** | = | T**1** – BPR**1** = 104.33 – 0.35 = 103.98°C | | | (3) | T**3** | = | T**2** – BPR**2** – https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image41.gif = 87.11 – 0.63 – 32.36 = 54.12°C | | |  | T**S3** | = | T**2** – BPR**2** = 87.11 – 0.63 = 86.48°C | | | | **Step 8.** | Following step 4, the heat capacity of the liquid is c**p** = 4.19 – 2.35x:  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image42.gif  The new values of the enthalpy H are as follows in each effect:   |  |  |  |  | | --- | --- | --- | --- | | (1) | H**1** | = | H**S2** + 1.884(°C superheat) = 2682 + 1.884(0.35) = 2683 kJ/kg | |  | λ**S1** | = | H**S1** – h**s1** = 2708 – 508 = 2200 kJ/kg | | (2) | H**2** | = | H**S3** + 1.884(0.63) = 2654 + 1.884(0.63) = 2655 kJ/kg | |  | λ**s2** | = | H**1** – h**S2** = 2683 – 440 = 2243 kJ/kg | | (3) | H**3** | = | H**S4** + 1.884(2.45) = 2595 + 1.884(2.45) = 2600 kJ/kg | |  | λ**s3** | = | H**2** – h**S3** = 2655 – 362 = 2293 kJ/kg |   Writing a heat balance on each effect,   |  |  |  |  |  | | --- | --- | --- | --- | --- | | (1) | 22 680(3.955)(26.7 – 0) + S(2200) | | | | |  |  |  | = L**1**(3.877)(104.33 – 0) + (22 680 – L**1**)(2683) | | | (2) | L**1**(3.877)(104.33 – 0) + (22 680 – L**1**)(2243) | | | | |  |  |  |  | = L**2**(3.708)(87.11 – 0) + (L**1** – L**2**)(2655) | | (3) | L**2**(3.708)(87.11 – 0) + (L**1** – L**2**)(2293) | | | | |  |  | = 4536(3.015)(54.12 – 0) + (L**2** – 4536)(2600) | | |   Solving,  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image43.gif  Note that these values from trial 2 differ very little from the trial 1 results. Following step 5, and solving for q in each effect and A,  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image44.gif  The average area to use in each effect is A**m** = 105.0 m**2**. Note that this value of 105.0 m**2** is quite close to the average value of 104.4 m**2** from the first trial.  https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image45.gif |  Figure 8.5-1. Flow diagram for triple-effect evaporation for Example 8.5-1. https://learning.oreilly.com/api/v2/epubs/urn:orm:book:013101367X/files/013101367X_ch08lev1sec5_image46.gif |