Heat Transfer

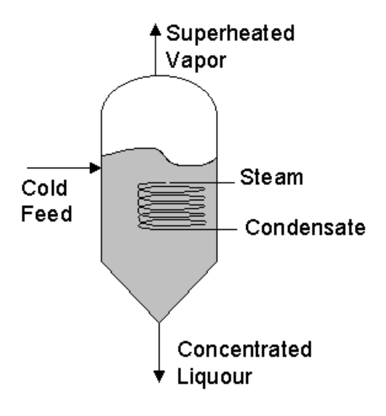
Evaporation

Dr. M. Subramanian

Department of Chemical Engineering
SSN College of Engineering

September 25, 2019

Evaporation



The objective of evaporation is to concentrate a non-volatile solute from a solvent, usually water. This is done by boiling off the solvent.

Evaporation (contd..)

An evaporator consists of a heat exchanger for boiling the solution and a means to separate the vapor from the boiling liquid. Different types are categorized by the length and alignment (horizontal or vertical) of the evaporator tubes. The evaporation tubes may be located inside or outside of the main vessel where the vapor is driven off.

Because many materials cannot tolerate high temperatures, evaporators often operate at reduced pressure so that the boiling point will also be reduced.

Evaporator Performance

There are three main measures of evaporator performance:

1. Capacity (kg vaporized/time)
2. Economy (kg vaporized/kg steam input)
3. Steam Consumption (kg/hr)

Note that the measures are related, since

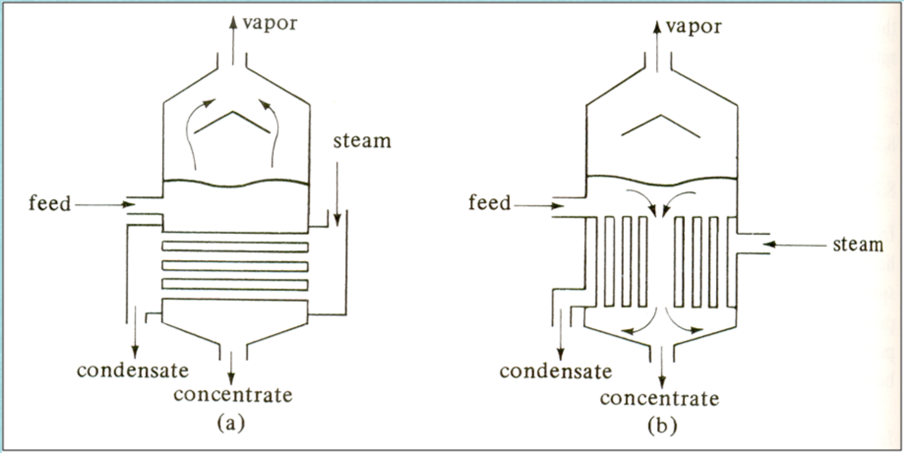
$$\text{Steam Consumption} = \frac{\text{Capacity}}{\text{Economy}}$$

Economy calculations are determined using enthalpy balances.
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.

Boiling Point Elevation

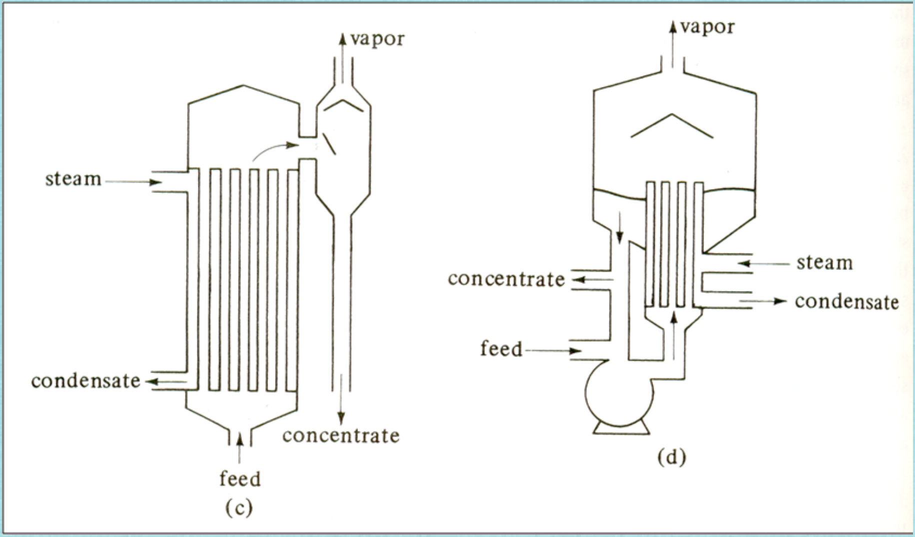
- Since evaporators dealing with boiling solutions, and in particular with solutions with non-volatile solutes, any calculations must account for the effect of boiling point elevation.
- The vapor pressure of an aqueous solution is less than that of pure water at the same temperature; so the boiling point of the solution will be higher than that of the water. This is called Boiling Point Elevation or vapor pressure lowering.
- Note that the equilibrium vapor rising from a solution exhibiting boiling point elevation will exist at a temperature and pressure such that it is superheated with respect to pure vapor. The vapor rises at the solution boiling point, elevated with respect to the pure component boiling point. The vapor, however, is solute free, so it won't condense until the extra heat corresponding to the elevation is removed, thus it is superheated.

Horizontal / Vertical Tube Evaporators



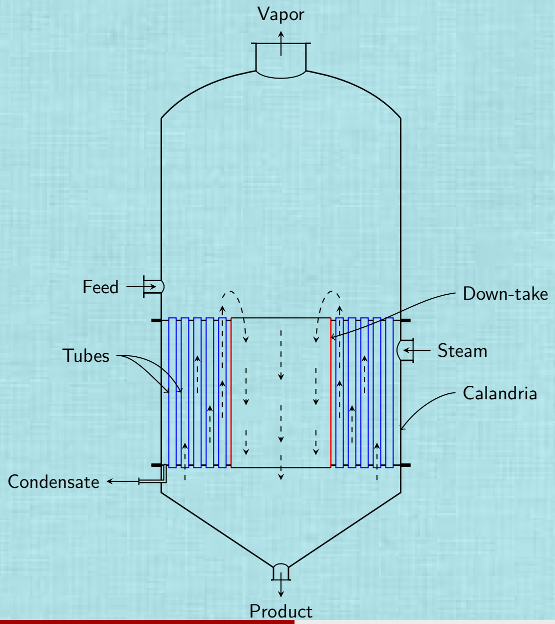
Different types of evaporators: (a) horizontal-tube type, (b) vertical-tube type,

Vertical Long-Tube Evaporators



Different types of evaporators: (c) long-tube vertical type, (d) forced-circulation type.

Standard Calandria Evaporator



Standard Calandria Evaporator

The calandria evaporator has a heat exchanger (with tubes usually less than six feet long) integral with the vapor body. The level is maintained in the upper portion of the tubes or above the top tubesheet, and the circulation pattern is up through the tubes and down through a central pipe called a "downcomer". Circulation is created by the difference in specific gravity between the body liquor and the heated liquor and vapor generated inside the tubes, plus a vapor lift effect.

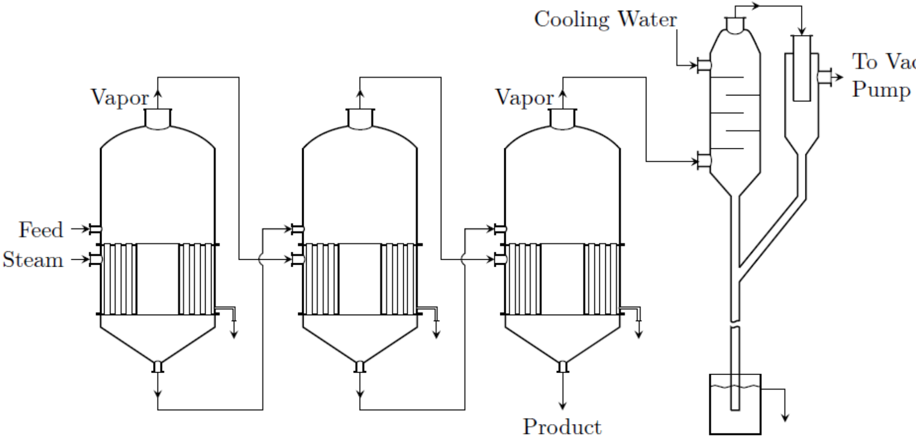
The circulation rate through the downcomer/downtake is many times the feed rate. The flow area of the downtake is normally approximately equal to the total tubular flow area.

Multiple Effect Evaporation

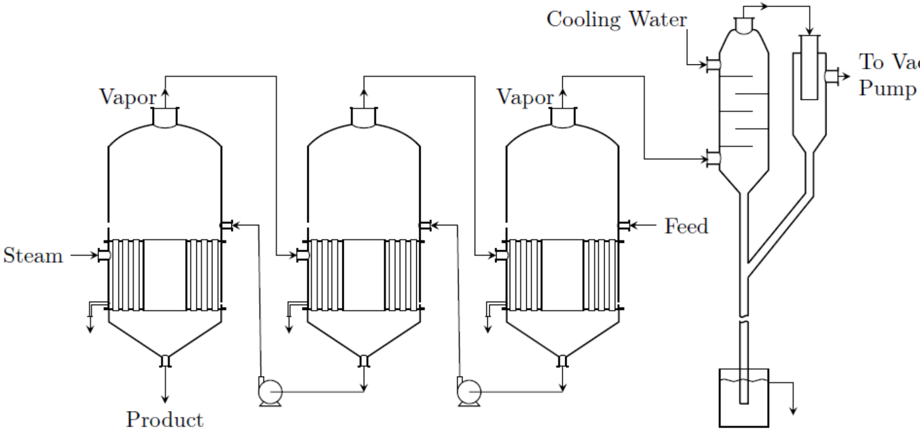
- In a multiple effect arrangement, the latent heat of the vapor product off of an effect is used to heat the following effect. Effects are thus numbered beginning with the one heated by steam. It will have the highest pressure.
- Vapor from Effect I will be used to heat Effect II, which consequently will operate at lower pressure. This continues through the train: pressure drops through the sequence so that the hot vapor will travel from one effect to the next.
- Normally, all effects in an evaporator will be physically the same in terms of size, construction, and heat transfer area. Unless thermal losses are significant, they will all have the same capacity as well.
- Evaporator trains may receive their feed in several different ways. The feed order is NOT related to the numbering of effects. Effects are always numbered according to decreasing pressure (steam flow).

Multiple Effect Evaporation

- **Forward Feed** arrangements follow the pattern I, II, III. These require a single feed pump (reduced fixed costs). They typically have reduced economy (higher operating costs) since the cold feed must be raised to the highest operating temperature. These also tend to have the most concentrated liquour, which tends to be the most viscous, in the lowest temperature effects, so their may be difficulties getting a good overall heat transfer coefficient.
- **Backward Feed** arrangements go III, II, I. These need multiple pumps to work against the pressure drop of the system; however, since the feed is gradually heated they usually have better economies. This arrangement also reduces the viscosity differences through the system and so is better for viscous solutions.
- **Mixed Feed** arrangements offer a compromise, with the feed entering in the middle of the system (i.e. II, III, I). The final evaporation is done at the highest temperature so economies are still better than forward feed, but fewer pumps are required than in a backward feed arrangement.
- **Parallel Feed** systems split the feed stream and feed a portion to each effect. This is most common in crystallizing evaporators where the product is likely to be a slurry.

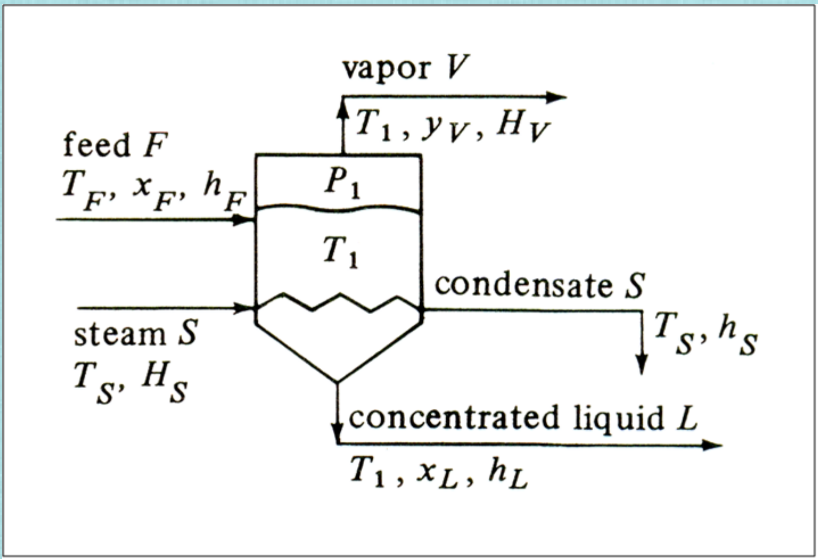


Multiple Effect Evaporators - Forward Feed Arrangement



Multiple Effect Evaporators - Backward Feed Arrangement

Mass and Heat Balances for a Evaporator



Material Balance:

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

Energy Balance:

$$FH_F + SH_S = LH_L + VH_V + SH_C$$
$$FH_F + S(H_S - H_C) = LH_L + VH_V$$
$$FH_F + S\lambda_S = LH_L + VH_V$$

By taking reference temperature as that of boiling point of solution, we get

$$FC_P(T_F - T_1) + S\lambda_S = L \times 0 + V\lambda_V$$
$$S\lambda_S = V\lambda_V - FC_P(T_F - T_1)$$

where λ_V is the latent heat of vaporization of water vapor at T_1.
If feed is at T_1 (i.e., at the boiling point of solution), then,

$$S\lambda_S = V\lambda_V$$

Solved Problems

Example 1: Evaporator

A solution containing 10% of solids is to be concentrated to a level of 50% solids. Steam is available at a pressure of 0.2 MPa (saturation temperature of 393 K). Feed rate to the evaporator is 30000 kg/hr. The evaporator is operating at a reduced pressure such that the boiling point is 323 K. The overall heat transfer coefficient is 2.9 kW/m^2.K. Estimate (i) The steam economy, and (ii) The heat transfer surface for (1) Feed introduced at 293 K, (2) Feed introduced at 308 K. (AU-Nov-2014)

Data:

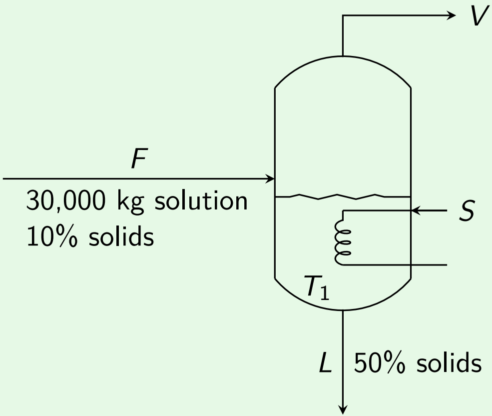
Specific heat of feed = 3.98 kJ/kg.K

Latent heat of condensation of steam at 0.2 MPa = 2202 kJ/kg

Latent heat of vaporization of water at 323 K = 2383 kJ/kg

Solved Problems (contd..)

Solution:



Solved Problems (contd..)

Mass balance:

Overall balance

$$F = L + V$$

$$30000 = L + V \tag{1}$$

Solute balance

$$Fx_F = Lx_L$$

$$30000 \times 0.1 = L \times 0.5$$

$$L = 6000 \text{ kg/hr}$$

Using the above in Eqn.(1), we get

$$V = 30000 - 6000 = 24000 \text{ kg/hr}$$

Solved Problems (contd..)

Feed temperature = 293 K

Energy balance: By choosing the reference temperature as boiling point of solution (T_1), we get

$$\begin{aligned}
S\lambda_S &= V\lambda_V + FC_P(T_1 - T_F) \\
S \times 2202 &= 24000 \times 2383 + 30000 \times 3.98 \times (323 - 293) \\
S &= 27,708.4 \text{ kg/hr} \\
\text{Economy} &= \frac{V}{S} = \frac{24000}{27708.4} = 0.87 \\
\text{Heat transfer area}(A) &= \frac{Q}{U\,\Delta T_m} \\
&= \frac{S\lambda_S}{U\,(T_S - T_1)} = \frac{(27708.4/3600) \times 2202}{2.9 \times (393 - 323)} \\
&= 83.5 \text{ m}^2
\end{aligned}$$

Solved Problems (contd..)

Feed temperature = 308 K
By similar calculations, we get $S = 26,786.1$ kg/hr, and,

$$\text{Economy} = 0.896 \qquad \text{Heat transfer area} = 80.7\ \text{m}^2$$

Because of the increase in feed temperature, steam economy increased, and required area for heat transfer got reduced.

Solved Problem

Example 2: Evaporator

An aqueous solution of a solute is concentrated from 5% to 20% (mass basis) in a single-effect short-tube evaporator. The feed enters the evaporator at a rate of 10 kg/s and at a temperature of 300 K. Steam is available at a saturation pressure of 1.3 bar. The pressure in the vapor space of the evaporator is 0.13 bar and the corresponding saturation temperature of steam is 320 K. If the overall heat transfer coefficient is 5000 W/(m^2.K), calculate the

(a) steam economy

(b) heat transfer surface area.

	Enthalpy (kJ/kg)	Heat of vaporization (kJ/kg)
Saturated steam (1.3 bar; 380 K)	-	2000
Saturated steam (0.13 bar; 320 K)	2200	-
Feed (5% ; 300 K)	80	-
Concentrated liquor (20% ; 325 K)	400	-

Boiling point elevation is 5 K. (GATE-2000)

Solved Problems (contd..)

Solution:

Mass balance:

Let us denote flow rates of feed as F, vapor as V, concentrated product as P ,steam as S and the mass fraction of solute as x.

Overall mass balance:

$$F = V + P \tag{1}$$

Balance on solute:

$$Fx_F = Px_P \tag{2}$$

From Eqs.(1) and (2)

$$P = \frac{10 \times 0.05}{0.2} = 2.5 \text{ kg/s}$$

And

$$V = F - P = 10 - 2.5 = 7.5 \text{ kg/s}$$

Solved Problems (contd..)

Energy balance:

$$FH_F + S\lambda_S = VH_V + PH_P \tag{3}$$

Given:

$H_F = 80$ kJ/kg; $\lambda_S = 2000$ kJ/kg

$H_V = 2200$ kJ/kg; $H_P = 400$ kJ/kg

Therefore,

$$\begin{aligned} 10 \times 80 + 2000\ S &= 7.5 \times 2200 + 2.5 \times 400 \\ S &= 8.35 \text{ kg/s} \end{aligned}$$

Solved Problems (contd..)

$$\text{Steam Economy} = \frac{V}{S} = \frac{7.5}{8.35} = 0.898 = 89.8\%$$

Estimation of heat transfer area:

$$\text{Rate of heat transfer } Q = S\lambda_S = 8.35 \times 2000 = 16700 \text{ kJ/s}$$

Also

$$Q = UA\Delta T$$

Therefore,

$$A = \frac{16700 \times 1000}{5000 \times (380 - 325)} = 60.73 \text{ m}^2$$

Questions for Practice

1. An aqueous solution at $15.5^\circ\mathrm{C}$, and containing 4% solids, is concentrated to 20% solids. A single effect evaporator with a heat transfer surface area of 37.2 m^2 and an overall heat transfer coefficient of 2000 $W/m^2.K$ is to be used. The calandria contains dry saturated steam at a pressure of 200 kPa(g) and the evaporator operates under a vacuum of 81.3 kPa. If the boiling point rise is 5 K, calculate the evaporator capacity. (AU-May-2017)
2. Hot exhaust gases of a stationary diesel engine are to be used to generate steam in an evaporator. Exhaust gases ($C_p = 1051$ J/kg.$^\circ\mathrm{C}$) enter the heat exchanger at $550^\circ\mathrm{C}$ at a rate of 0.25 kg/s while water enters as saturated liquid and evaporates at $200^\circ\mathrm{C}$. The heat transfer surface area of the heat exchanger based on water side is 0.5 m^2 and overall heat transfer coefficient is 1780 $W/m^2.^\circ\mathrm{C}$. Determine the rate of heat transfer, the exit temperature of exhaust gases and the rate of evaporation of water. (AU-Nov-2016)

Questions for Practice

3. A feed of 3000 kg/hr of a 1.2 wt% NaOH salt solution at 311 K enters continuously in a single effect evaporator and is being evaporated to 3.0 wt%. The evaporation is at atmospheric pressure and the area of the evaporator is 72 m^2. Saturated steam at 383.2 K is supplied for heating. Since the solution is dilute, it can be assumed to have the same boiling point as water. The heat capacity of the feed can be taken as 4.10 kJ/kg,K. Calculate the amounts of vapor and liquid product and the overall heat transfer coefficient. (AU-Nov-2015)

Questions for Practice

4. It is desired to concentrate a solution at $38^\circ\mathrm{C}$ and 10% solids to a product containing 50% solids. Steam is available at 1.8 bar and the last effect of a triple effect evaporation system with equal heat transfer area in each effect operates at a vacuum of 65 cm of mercury. Water is available for use at $30^\circ\mathrm{C}$ in the barometric condenser. Assume negligible BPR in each effect and specific heat of all solutions as 4 kJ/kg.K. Radiation losses are negligible and condensate from each effect leaves at saturation temperature. The overall heat transfer coefficients in the first, second, and third effects are 3400, 1450, and 725 W/m^2.K respectively. Calculate the steam consumption, heating surface required in each evaporator and the condenser water requirement. (AU-Nov-2006) Mass flow rate of feed is missing!

A feed of 3000 kg/hr of a 1.2 wt% NaOH salt solution at 311 K enters continuously in a single effect evaporator and is being evaporated to 3.0 wt%. The evaporation is at atmospheric pressure and the area of the evaporator is 72 m^2. Saturated steam at 383.2 K is supplied for heating. Since the solution is dilute, it can be assumed to have the same boiling point as water. The heat capacity of the feed can be taken as 4.10 kJ/kg,K. Calculate the amounts of vapor and liquid product and the overall heat transfer coefficient.

Latent heat of vaporization of steam at 383.2 K = 2230 kJ/kg

Latent heat of vaporization of steam at 1 atm(abs) = 2257 kJ/kg Problem of AU-Nov-2015; with data specified

Questions for Practice

An aqueous feed at 5°C containing 25% solids enters an evaporator at the rate of 500 kg/h. Saturated steam (100% quality) at atmospheric pressure enters the evaporator at the rate of 150 kg/h and leaves as condensate at 100°C. If the evaporator is operating at 65°C, determine:

(i) The solids content of the concentrated product.

(ii) The surface area of heat exchanger required.

(iii) Steam economy.

Assume that the specific heat of the feed and concentrated product are 4.0 kJ/kg.°C and 3.0 kJ/kg.°C respectively and that the overall heat transfer coefficient is 4 kW/m^2.°C.
Latent heat of vaporization of water at 65°C = 2345.4 kJ/kg; and, that 100°C = 2256.5 kJ/kg.

(Ans: 30.7%; 0.67 m^2; 0.62)

ΔT in Each Effect of Multiple Effect Evaporators

$$Q_i = U_i A_i \Delta T_i$$

It is desired to uniform equal heat transfer rates and areas, due to the following reasons:

- 1 kg of condensing steam can generate nearly 1 kg of water vapor. Hence from the point of consideration of steam it is better to have equal heat transfer rates in every effect of the multiple effect evaporation.
- With uniform heat transfer area, every effect will be of same size, leading to reduction in initial investment due to economy of scaling.

ΔT in Each Effect of Multiple Effect Evaporators (contd..)

Since Q_i, and A_i of every effect is the same, i.e.,

$$\frac{Q_i}{A_i} = \frac{Q_1}{A_1} = \frac{Q_2}{A_2} = \cdots = \text{constant}$$

we get

$$U_i \Delta T_i = U_1 \Delta T_1 = U_2 \Delta T_2 = \cdots = U_n \Delta T_n = \text{constant}$$

The total temperature drop across the effects is given as

$$\Delta T = T_s - T_n$$

where T_s and T_n are the temperatures of the steam to the first effect and the vapor formed in the last effect, n. This temperature drop is also equal to the sum of temperature drops in every effect, given as:

$$\Delta T = \Delta T_1 + \Delta T_2 + \cdots + \Delta T_n$$

ΔT in Each Effect of Multiple Effect Evaporators (contd..)

$$
\begin{aligned}
\Delta T &= \Delta T_1 + \Delta T_2 + \Delta T_3 + \cdots + \Delta T_n \\
&= \frac{\Delta T_1 U_1}{U_1} + \frac{\Delta T_1 U_1}{U_2} + \frac{\Delta T_1 U_1}{U_3} + \cdots + \frac{\Delta T_1 U_1}{U_n}
\end{aligned}
$$

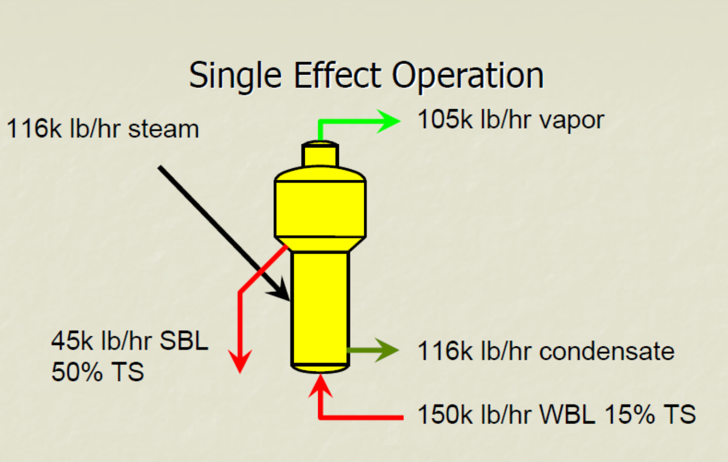
$$
\Longrightarrow \quad \Delta T_1 = \frac{\Delta T}{U_1 \sum_i \frac{1}{U_i}}
$$

Questions for Practice

1. A triple effect evaporator concentrates a liquid with no appreciable elevation in boiling point. If the temperature of the steam to the first effect is 395 K and the vacuum in the last effect brings down the boiling point to 325 K, what are the approximate boiling points of liquid in first and second effect? Assume the overall heat transfer coefficient as 3.1, 2.3 and 1.1 $kW/m^2.K$ in the first, second and third effects respectively. Assume that all the three evaporators have the same area ($A_1 = A_2 = A_3$), and same heat transfer rate ($Q_1 = Q_2 = Q_3$).

Questions for Practice

2. Calculate the steam economy for the data given in the schematic as below:



Questions for Practice

3. Calculate the steam economy for the data given in the schematic as below: