CHE 315: UNIT OPERATIONS LABORATORY

Department of Chemical Engineering
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Experiment 4: Single and Double Effect Evaporator Efficiency

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Introduction

The objective of this experiment was to determine the overall efficiency of a single effect evaporator and a double effect evaporator. An evaporator utilizes a heating medium, such as steam, to transfer heat to a solution. When sufficient heat is transferred, the solvent will vaporize leaving an increase of solute (the non-volatile component) concentration. The food and beverage industry can benefit from this process. In the single effect evaporator, liquid water at a flow rate of 0.2L/min was heated by steam. The steam was at vacuum pressure. The amount of steam used and the vaporized liquid were collected and measured. To increase the efficiency, another effect was added to the single effect evaporator, by using the steam from the first effect as the new heating medium to the second effect. This process is known as the double effect evaporator. Through a series of calculations and data collection, it was calculated that the efficiency for the single effect evaporator was 56.5%, while the double effect evaporator was 109.3%. Due to complications and sources of error, the values were not close to the theoretical value of 100% efficiency; resulting in a percent deviation of 43.5% and 9.3%. In conclusion, this experiment was unable to determine the exact value of efficiency for both processes. However, it was able to prove that the double effect evaporator was more efficient than the single effect evaporator.

Theoretical Background

Evaporation is a process, where a non-volatile solute is removed from a volatile solvent [1]. Evaporation can be greatly utilized in the food and beverage industry, such as in the production of concentrated fruit juices, to increase the concentration level of the solute. For example, Minute Maid, a multimillion dollar corporation that produces numerous volumes of concentrated cans, can exploit this process. One process carries out the initial mixture and a single or a multiple effect evaporator can evaporate the water, thus increasing the solutes (sugars, minerals, flavorings etc.) concentration.

An evaporator uses a heating medium (eg: steam) to reduce the amount of non-volatile solute from the solvent. Since the enthalpy of the heating medium is greater than the solution, the solute will vaporize [2]. This process is inefficient because energy is lost from the vapor. To increase efficiency, the newly vaporized solute is recycled in the process as the heating medium for another batch of solution. This is known as multiple effect evaporators because each time the vapor is used, it acts as a single effect evaporator.

The objective of this experiment is to determine the efficiency, capacity, and amount of energy (heat) in a single and double effect evaporator. Steam was the heating medium and liquid water was the solute and solvent.

In the single effect evaporator, steam surrounded the flask containing liquid water. According to heat transfer laws, the energy in the steam will transfer to the water causing some component of liquid to vaporize into gas (steam) [2]. The newly formed steam (distillate) is collected. While the double effect evaporator utilized the new steam as the new heating medium. The steam is at vacuum pressure rather than atmospheric pressure to reduce the boiling point of the liquid water. A decrease in boiling point results in less energy required to heat the system and less time for the system to reach steady state [3].

The following assumptions were made in the calculations [4]:

- Heat losses are negligible
- The energy required to pre-heat the feed liquor to the first effect are negligible
- No leakage or entertainment
- The flow of non-condensable is negligible
- Superheating and subcooling effects are negligible

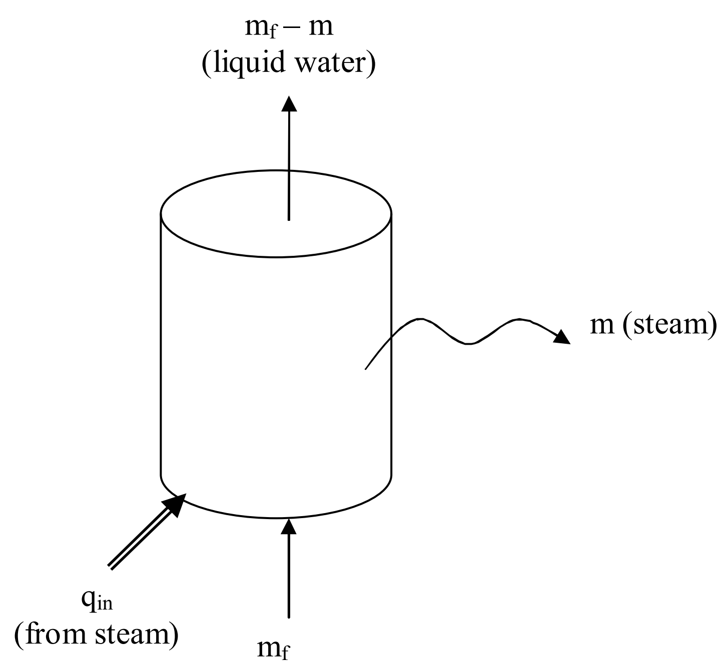

Figure 1: *Control Volume of evaporator flask*

Overall heat/energy balance (rate form): $q_{in} - q_{out} + q_{gen} = q_{acc}$ (1)

$q_{gen} = 0$ because no reaction is present within the system

$q_{acc} = 0$ because the system is in steady system

$$\therefore q_{in} = q_{out} \tag{2}$$

q_{in} = rate of heat transferred from steam

$= m_s\lambda_s$ (3)

where m_s is the rate of steam flow

λ_s is the latent heat of vaporization

q_{out} = rate of heat transferred from steam

$= m\lambda_v + m_f(H-H_f)$ (4)

where m is the rate of liquid evaporated

λ_v is the latent of evaporation at boiling point

m_f is the feed rate

H is the enthalpy of liquid at boiling point

H_f is the enthalpy of feed liquid

Combining equations (2), (3), and (4)

$$\therefore\ m_s\lambda_s = m\lambda_v + m_f(H-H_f) \quad (5)$$

Efficiency, $\varepsilon \equiv$ output / input (6)

$$\therefore\ \varepsilon = m / m_s \quad (7)$$

Rearranging (5) to solve (6),

$$\therefore\ \varepsilon = \frac{\dot{m}}{\dot{m}_s} = \frac{\lambda_s - \left[\frac{\dot{m}_f}{\dot{m}_s}\left(H - H_f\right)\right]}{\lambda_v} \quad (8)$$

The amount of heat removed by cooling water at the condenser can be determined [2]:

$Q = mC_p\Delta T$ (9)

where m is the mass of cooling water used

C_p is specific heat of water = 4.18 kJ/kg °C [2]

ΔT is the difference in inlet and outlet of the water temperature

Experimental Procedure

A similar procedure was preformed within this experiment as "The Experiment 4: Double Effect Evaporator Efficiency" in *CHE 315: Unit Operations Laboratory 1 – Laboratory Manual,* September 2006, by Dr. M. Mehrvar. [3]

In the single effect evaporator, steam at vacuum pressure surrounded a flask, containing liquid water at a flow rate of 0.2L/min. Based on heat transfer laws, heat from the steam transfers to the water causing the liquid to vaporize as steam. The steam (distillate) was collected and the amount of steam used was collected. Figure 2 is the general schematic of how a single effect evaporator operates.

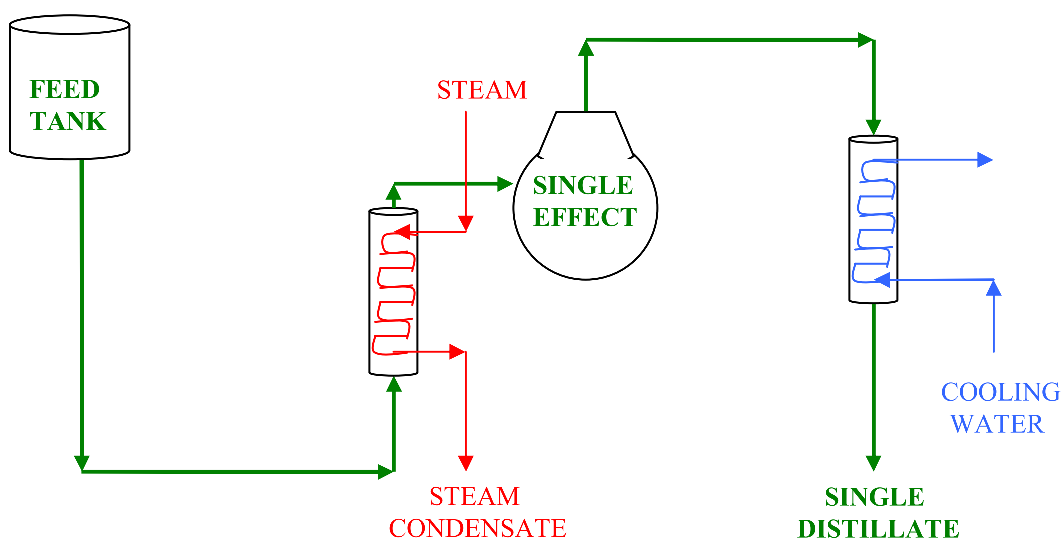

Figure 2: *Schematic of Single Effect Evaporator*

In the double effect evaporator, the procedure followed was similar to the single effect evaporator. However, the steam evaporated from the liquid water was then used as the new heating medium for a second flask. As a result, the amount of distillate from the first and second evaporator was collected and the overall amount of steam used was collected as well. Figure 3 illustrates the general schematics of the double effect evaporator.

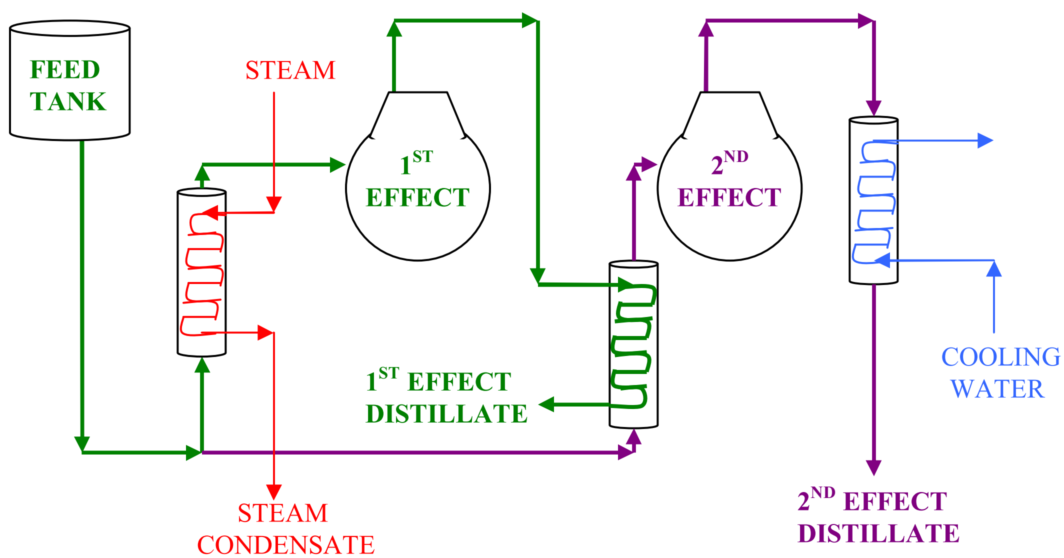

Figure 3: *Schematic of Double Effect Evaporator*

Results and Discussion

The rate of heat transfer to the condenser was calculated using equation (8), and tabulated in table 1. The rate of heat transfer from the condenser for the single effect evaporator tends to increase over time. The maximum rate was calculated as 10.73kW. The total heat transferred also increased, to a total of 12874kJ of energy.

For the double effect evaporator, although in general the rate does increase over the time, the maximum rate of heat transfer from the condenser was only 6.83kW. This is much less than for the single evaporator. The total heat transferred calculated for the double effect evaporator was about 84% less than the single effect evaporator. This may have been due to the sudden decrease in the outlet temperature, as shown in table 6 (in the raw data section).

Time (min)	Rate of Heat Transfer from the Condenser, q (kW)	Total Heat Transfer, Q (kJ)
0	0.00	0.00
2	0.00	0.00
4	2.93	702.24
6	8.78	3160.08
8	9.75	4681.60
10	9.75	5852.00
12	9.75	7022.40
14	9.75	8192.80
16	9.75	9363.20
18	10.73	11586.96
20	10.73	12874.40

Table 1: *Heat Transfer results for the single effect evaporator*

Time (min)	Rate of Heat Transfer from the Condenser, q (kW)	Total Heat Transfer, Q (kJ)
0	0.98	0.00
2	4.88	585.20
4	4.88	1170.40
6	6.83	2457.84
8	6.83	3277.12
10	6.83	4096.40
12	2.93	2106.72

Table 2: *Heat Transfer results for the Double-Effect Evaporator*

Under conditions of constant steam pressure and varying vacuum level, capacity is considered to be the total evaporation rate obtained per hour. That is, it is equivalent to the amount of water evaporated from the effect within a specific period of time.

For the single effect evaporator, the capacity was calculated to be 11.7L/hr. The capacity of the first effect of the double effect evaporator was determined to be 14.3L/hr; while the second effect was lower, at 4.4L/hr. The overall capacity of the double effect evaporator was 18.7L/hr. These results are shown in table 3.

If the equipment ran as two single effect evaporators, the capacity would be greatly increased to 23.5L/hr.

		Capacity (L/hr)	Efficiency (%)
Single effect evaporator		11.7	56.5
Double effect evaporator	First effect	14.3	83.6
	Second effect	4.4	30.8
	Overall	18.7	109.3
Two Single effect evaporator		23.5	56.5

Table 3: *Calculated efficiencies and capacities from Single and Double Effect Evaporators*

Efficiency of an evaporator is defined as a ratio of the amount of output (water) from the system to the amount of input (steam) to the system. [2] In the single effect evaporator, the amount of condensate collected is equivalent to the amount of steam supplied to the effect. This steam was used to evaporate water from the effect, and the evaporated water was collected as the distillate. For the single effect evaporator, the ratio of the distillate to the condensate is the efficiency. As seen in table 3, this efficiency was calculated to be 56.5%.

Also in table 3, efficiencies for each effect of the double effect evaporator is shown. The first effect was heated using steam, as in the single effect evaporator. However, this effect should a much higher efficiency than the single effect, at 83.6% efficiency. The second effect showed an efficiency of 30.8%.

The second effect was heated using the steam generated from the first effect. Therefore, there would be less heat loss from the system leading to an increase in the overall efficiency. The overall efficiency was calculated as 109%. This value is theoretically impossible because efficiency can not exceed 100%. Therefore, errors and difficulties were experienced as discussed in the error analysis section.

For the two single effect evaporators, while the capacity was larger, the overall efficiency is the same as that of the single effect evaporator.

In Table 4, it is shown that the steam and vacuum pressure were not constant throughout the experiment. These inconsistencies of pressure affected the concentration level of solute, the amount of distillate produced and collected, the capacity, and the efficiency of the system.

The purpose of the vacuum pressure was to lower the boiling point of the solvent (water). This will evaporate more solvent within a specific time, causing the concentration level to increase. The lower the pressure, the more solvent will vaporize.[4] However, the vacuum pressure was not constant during the experiment. This resulted in fluctuations in the boiling point of the water, which lead to varying rates of evaporation during the experiment. Concentrate production rate should increase with increasing vacuum levels, if the steam pressure is kept constant.[4] Distillate production rate would also increase as this is the rate at which the solvent is removed.[4]

Also, the steam pressure affected the amount of heat transferred to the system. Based on Gay-Lussac's Law, the change in pressure is the same amount as the change in temperature for an ideal gas.[5] The temperature of the steam varied over time and therefore resulted in varying rates of heat transfer to the water. In general, the total heat supplied to the evaporator is higher when the vacuum pressure is lower because the heat supplied is a function of temperature. The heat transferred to the single effect evaporated from the steam was calculated to be 9970kJ, at a rate of 8.3kW. For the double-effect evaporator, the rate of heat transferred from the steam was larger, at a rate of 12.8kW. The total heat transferred was less, only transferring 9240kJ of energy. However, this heat was used in a more efficient way as discussed above.

Error Analysis

The percent deviations were 43.51%, 43.51%, and 9.29% for the single, two single, and double effect evaporators. These deviations were affected by many factors.

Firstly, heat was lost throughout the system, due to poor insulation of pipes and glassware. This meant that the heat transferred from the steam was not equal to the heat transferred into the liquid water. Also, the discrepancies in the steam and vacuum pressures caused various boiling points to occur, which affected the amount of distillate produced and the level of concentration, as mentioned above.

Due to the nature of pipes, rusting would eventually occur. Rusted pipes, inside or outside, decreased the overall efficiency of the experiment because some of the heat and distillate was trapped or escaped. Therefore, less distillate was recovered over time.

A graduated cylinder was used to measure the amount of steam used and distillate recovered. This process caused errors because some of the water contents were lost during measuring. The condensate and distillates from both experiments were collected as condensed steam. It is expected that some of this steam was lost because it was not fully condensed.

Lastly, there was leakage within the system. Thus, less water was collected for the single effect evaporator. However, the double effect evaporator contained more water than expected. It was due to a mechanical error; the vacuum pressure was reduced during the double effect experiment. The error was then fixed within the experiment, while the first effect was still being collected. While this could be accounted for in the volume of steam condensate collected, the distillate of the first effect may have been erroneous. The volume of the distillate was greater than expected.

Conclusions and Recommendations

In conclusion, the efficiency for the single effect evaporator was 56.5% and the efficiency for the double effect evaporator was 109.3%. Thus, the double effect evaporator was more efficient than the single effect evaporator as expected. However, it was not expected that the double effect evaporator would exceed 100%. Also, it was not expected that the capacity of the single effect evaporator (11.7 L/hr) was greater than the double effect evaporator (23.5 L/hr).

To improve upon the experiment, the following could have been conducted:

- shorter pipe lines (to reduce rust and heat loss)
- better measuring instruments (to avoid spillage in measuring)
- insulate all glassware and pipe lines (to reduce heat loss)
- better machinery where the steam and vacuum pressure were maintained (to maintain a constant rate of vaporization)
- more effect evaporators (to increase efficiency)

References

[1] Treybal, R.E., *Mass Transfer Operations*, 1980, McGraw-Hill

[2] Winnick J., *Chemical Engineering Thermodynamics,* 1997, John Wiley & Sons

[3] Mehrvar, M., C*HE 315: Unit Operations Laboratory I, Laboratory Manual for Experiment 4, Double Effect Evaporator*, September 2006, Ryerson University

[4] Geankoplis, C.J., *Separation Process and Unit Operations*, 1993, Allyn and Bacon Inc.

[5] Leigh, N., *Gay-Lussac's Law- (Gas in a Rigid container)*, Western Illinois University, Accessed on 24/09/06, from http://www.wiu.edu/users/msncl/Chapter8/sld012.htm

Appendix

Raw Data

Time (min)	2nd Effect Temperature (°C)	2nd Effect Vacuum Pressure (bar)	Inlet Water Temperature (°C)	Outlet Water Temperature (°C)	Steam Pressure (bar)
0	66	-0.72	13	13	0.62
2	68	-0.72	13	13	0.72
4	70	-0.72	13	16	0.81
6	70	-0.73	13	22	0.81
8	70	-0.73	13	23	0.81
10	70	-0.73	13	23	0.81
12	70	-0.73	13	23	0.81
14	70	-0.73	13	23	0.81
16	70	-0.73	13	23	0.81
18	70	-0.73	13	24	0.81
20	70	-0.73	13	24	0.81

Table 4: *Experimental Results for Single-Effect Evaporator*

	Volume (mL)
Steam Condensate	6940
Vapor Distillate - 2nd Effect	3920

Table 5: *Amount of Distillate and Condensate for Single-Effect Evaporator*

Time (min)	1st Effect Temperature (°C)	1st Effect Vacuum Pressure (bar)	2nd Effect Temperature (°C)	2nd Effect Vacuum Pressure (bar)	Inlet Water Temperature (°C)	Outlet Water Temperature (°C)	Steam Pressure (bar)
0	90	-0.30	78	-0.45	13	14	1.10
2	86	-0.40	68	-0.65	13	18	1.00
4	86	-0.40	70	-0.70	13	18	0.98
6	86	-0.45	70	-0.70	13	20	1.00
8	86	-0.45	70	-0.70	13	20	1.00
10	86	-0.45	70	-0.70	13	20	0.97
12	86	-0.42	72	-0.68	13	16	0.97

Table 6: *Experimental Results for Double-Effect Evaporator*

	Time Taken (min)	Volume (mL)
Steam Condensate	27	7700
Distillate - 1st Effect	12	2860
Distillate - 2nd Effect	12	880

Table 7: *Amount of Distillate and Condensate for Double-Effect Evaporator*

Sample Calculations

Single Effect Evaporator

Heat transferred from condenser:

Using equation $q = mCp\Delta T$ (ρ_{H2O} = 1 g/mL; Cp = 4.18 J/g.°C)

q = (14L/min)*(1g/mL)*(4.19J/g.°C)*(outlet temp. – inlet temp)°C*(1min/60sec)

For example, at 6 mins:

q = (14L/min)* (1g/mL)*(4.19J/g.°C)*(22-13)°C*(1min/60sec) = 8.78kW

Heat transferred from the steam:

Using equation (4): $q_{out} = m\lambda_v + m_f(H-H_f)$

m = rate of liquid evaporated

$$= \frac{3.92\ L}{20\ min} * \frac{1kg}{L} * \frac{min}{60\ s} = 3.27 x 10^{-3} kg/s$$

λ_v = latent heat of evaporation of liquid at boiling point (62°C) = 2353 kJ/kg

m_f = feed rate

$$= \frac{0.2L}{min} * \frac{1kg}{L} * \frac{min}{60\ s} = 3.33 x 10^{-3}\ kg/s$$

H = enthalpy of liquid at boiling point (62°C) = 269.46 kJ/kg

H_f = enthalpy of feed liquid (assume room temperature, 20°C) = 83.86 kJ/kg

$$q = \left(\frac{0.00327 kg}{s} * \frac{2353\ kJ}{kg}\right) + \left(\frac{0.00333\ kg}{s}\ \frac{(269.46 - 83.86)\ kJ}{kg}\right)$$

= 7.69kW + 0.618kW

= 8.308kW

Q = 8.308kW*20min*60sec/min

=9970kJ

Capacity = Total Distillate/ Total Time

$$= \frac{3920\ mL * 1L * 60\ min}{1000\ ml * 20\ min * 1hr} = 11.76\ L/hr$$

Efficiency = Amount of evaporated water/amount of steam applied

= Distillate/Condensate * 100%

$$= \frac{3920\ mL}{6940\ mL} * 100\% = 56.5\%$$

Double Effect Evaporator

Capacity:

First Effect = First Effect Distillate/Time

$$= \frac{2860\ mL}{12\ min} * \frac{1L}{1000\ mL} * \frac{60\ min}{hr} = 14.3L/hr$$

Second Effect = Second Effect Distillate/Time

$$= \frac{880\ mL}{12\ min} * \frac{1L}{1000\ mL} * \frac{60\ min}{hr} = 4.4L/hr$$

Overall Effect = Total Distillate/Time

$$= \frac{(2860 + 880)mL}{12\ min} * \frac{1L}{1000\ mL} * \frac{60\ min}{hr} = 18.7\ L/hr$$

Efficiency:

$$\text{First Effect} = \frac{\text{Volume of First Effect Distillate}}{\text{Volume of Condensate}} * 100\%$$

$$= \frac{2860\ mL * 27\ min}{7700\ mL * 12\ min} * 100\% = 83.6\%$$

Second Effect = Second Effect Distillate/First Effect Distillate * 100%

$$= \frac{880\ mL}{2860\ mL} * 100\% = 30.8\%$$

Overall Effect = Total Distillate/Condensate * 100%

$$= \frac{(880 + 2860)\, mL * 27 \min}{7700\, mL * 12 \min} * 100\% = 109.3\%$$

Two Single Effect Evaporators

If the system was considered to be two single-effect evaporators, each effect would theoretically evaporate the same volume of liquid. Therefore, we can say that each of the single effect would produce a distillate of 3.92L

Capacity = mass of water evaporated / time

$$= \left(\frac{[3.92\, L + 3.92\, L]}{20 \min} * \frac{60 \min}{1 hr} \right) = 23.5\text{L/hr}$$

$$\textit{Efficiency} = \frac{\text{Rate of Liquid Evaporated}}{\text{Rate of Steam Supplied}} * 100\%$$

$$= \left(\frac{[3.92\, L + 3.92\, L]}{[6.94\, L + 6.94\, L]} \right) * 100\% = 56.5\%$$