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Investigation of Multiple Effect Evaporator Design

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Abstract

Evaporator is one of the most energy intensive sections of a number of process industries such as pulp and paper, sugar, desalination, pharmaceuticals, dairy and food processing, etc. Single effect evaporator can be wasteful of energy if the vapor's heat is not used. This heat can be recovered and re-used by employing multiple-effect evaporators. In this study, investigation of selection of type of evaporator using some parameters is presented for multiple effect evaporator system. Energy and economical equations are given with a case study for multiple effect evaporator system. As result of calculations, it has been found that about 3.51 of overall economy is obtained according to single evaporator.

Key words: Multiple-effect evaporator, evaporator selection, design

1. Introduction

Evaporation is an important unit operation used to remove a liquid from a solution, suspension, or emulsion by means of vaporization or boiling. The evaporation process is as one that starts with a liquid product and ends up with a more concentrated which is still liquid and still pumpable concentrate as the main product from the process. Evaporation should not be confused with other somewhat similar thermal separation techniques that have more precise technical meanings, for example: distillation, stripping, drying, deodorizing, crystallization, and devolatilization. These operations are principally associated with separating or purifying a multicomponent vapor (distillation), producing a solid bottoms product (drying, crystallization), or "finishing" an already-concentrated fluid material (stripping, devolatilization, deodorizing) [1]. Evaporation uses for reduces transportation cost, storage costs, prepare for the next unit operation such as drying, crystallization, better microbiological stability and recovery of solvent.

Evaporators are similar to stills or re-boilers of distillation columns, except that no attempt is made to separate components of the vapor [2]. Evaporator is one of the most energy intensive sections of a number of process industries such as pulp and paper, sugar, desalination, pharmaceuticals, dairy and food processing, etc. Single effect evaporator can be wasteful of energy if the vapor's heat is not used. This heat can be recovered and re-used by employing a multiple effect evaporator. Steam heat is used for transfer of heat for subsequent vessels. Steam has very high heat content. Heat is given up at constant temperature and it can be used at high pressure to generate electric power and low-pressure exhaust steam is used for process heating. A wide variety of mathematical models for multiple effect evaporator can be found in the scientific literature. The main difference among these mathematical models is the experiential knowledge

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which is integrated in their development. These mathematical models are generally related to characterization of thermal properties, some specific parameters such as heat transfer coefficient, area, latent heat of vaporization, and concentrate mass per effect etc. [3-7].

In this study, investigation of selection of type of evaporator using some parameters is presented for multiple effect evaporator system. Energy and economical equations are given with a case study for multiple effect evaporator system. The case study is presented that multiple effect evaporator is has good overall steam economy instead of single evaporator. As result of calculations, it has been found that about 3.51 overall steam economy by a feed forward multiple effect evaporator.

2. Evaporators

The evaporator is called evaporation process on which the devices. Several types of evaporators are used in the different industry. An evaporator consists of a heat exchanger enclosed in a large chamber; a noncontact heat exchanger provides the means to transfer heat from low-pressure steam to the product. The basic parts of an evaporator are heat-exchanger, vacuum, vapor separator and condenser as shown in Figure 1. The product inside the evaporation chamber is kept under vacuum. The presence of vacuum causes the temperature difference between steam and the product to increase, and the product boils at relatively low temperatures, thus minimizing heat damage. The conditions under which the evaporation process is performed vary considerably in practice.

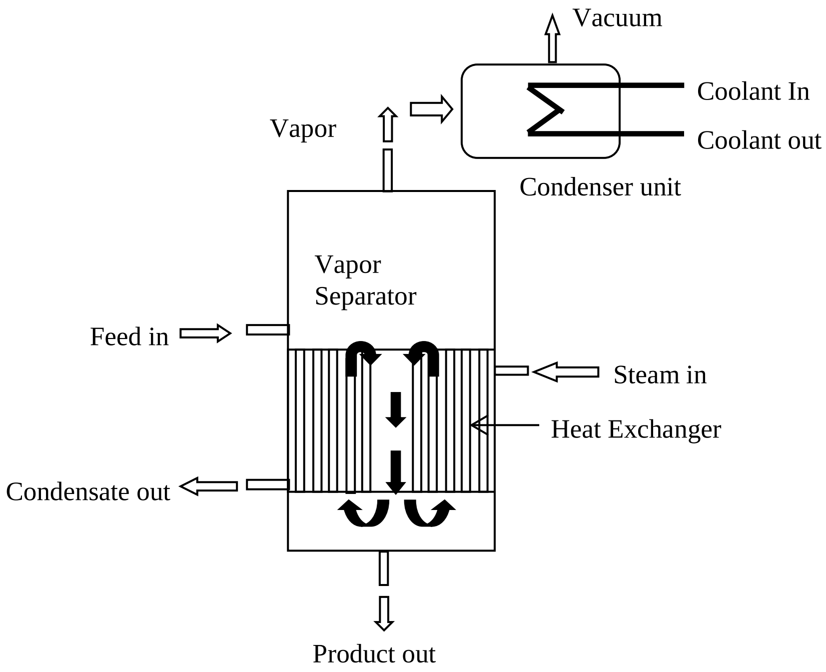

Figure 1. Schematic diagram of Evaporator

The liquid subjected to evaporation may be more viscous than water, more viscous to run, occurring to foam, may have a very high boiling point or may decompose at high temperature. These numerous problems cause very different appearances in the mechanical structures of the evaporators. In addition, evaporators have a wide variety of solutions, and evaporator types change accordingly. Practical reasons and habits in the various industries have a great impact on the planning of evaporators. Evaporators show great changes over time [8]. The more common of evaporator's types are given as;

- Direct flame heat evaporators.
- Evaporators heated by a heating medium in a double wall or jacket.
- Evaporators with tube heaters (heat exchangers) and heated by steam.
    - Short tube evaporators; horizontal short or vertical short
    - Long tube evaporators; up or vertical flow
- Forced circulating evaporators
    - Heating system inside
    - Heating system outdoors
- Special evaporators;
    - Spiral tube type
    - Mixer-film type

3. Multiple Effect Evaporator Design

Selection of type of evaporator using some parameters is presented for the best design of multiple effect evaporator in Table 1. The most of criteria in this table are selected and classifications are made by using the letters in various grades. The purpose of this tabulation is to provide a quick design and convenience in reviewing the properties of the evaporators collectively. Multiple-effect evaporator system such as condensate, feed and product flashing, vapor bleeding, steam splitting, variable physical properties and boiling point rise are accounted to develop of different models. Developed selections for multiple effect evaporator system are compared based on product concentration and steam economy to select the optimum model. Also these systems employ condensate, feed and product flashing to generate auxiliary vapor, which are then used in vapor bodies of appropriate effects to improve overall steam economy of the system. A multiple effect evaporator, steam is used only in the first effect. The use of vapors as a heating medium in additional effects results in obtaining higher energy-use efficiency from the system. The partially concentrated product leaving the first effect is introduced as feed into the second effect. After additional concentration, product from the second effect becomes feed for another effect. The product from the last effect leaves at the desired concentration. Efficient evaporators are designed and operated according to several key criteria:

- Heat Transfer; A large flow of heat across a metallic surface of minimum thickness or high heat flux) is fairly typical. The requirement of a high heat transfer rate is the major determinate of the evaporator type, size, and cost.
- Liquid-Vapor Separation; Liquid droplets carried through the evaporator system, known as entrainment, may contribute to product loss, lower product quality, erosion of metallic surfaces, and other problems. Generally, decreasing the level of entrainment in the evaporator increases both the capital and operating costs, although these incremental costs

are usually rather small. All these problems and costs considered, the most cost-effective evaporator is often one with a very low or negligible level of entrainment.

- Energy Efficiency; Evaporators should be designed to make the best use of available energy, which implies using the lowest or the most economical net energy input. Steam-heated evaporators, for example, are rated on steam economy—kilograms of solvent evaporated per kilogram of steam used [2, 9].

Table 1. Selection of type of evaporator using some parameters

	Short tube	Long tube		Vertical flow		Forced circulating		
		Natural flow	Forced flow	Natural flow	Forced flow	Vertical	Horizontal	Mixer film
Low viscosity fluid	A	A	A	A	A	A	A	X
High viscosity fluid	D	B	B	B	B	A	A	A
Sludge	D	B	B	D	D	A	A	A
Boiler cleaning or salting	C	D	E	D	E	B	B	A
Corrosive liquids	C, E	C, A	C, A	C, A	C, B	C, B	C, B	C, D
Crystal-formation fluids	D	B	B	E	E	B	B	A
Bubbling fluid	D	B	B	E	E	B	B	D
Heat-sensitive liquids	D	A	D	A	D	B	B	B
Conjoined, sticky fluid	X	X	X	X	X	E	B	B
High capacity	D	A	A	B	B	A	A	E
Using as a multiple-effective	A	A	B	A	B	A	A	E
Process feed	B	B	D	D	D	D	D	D
Limited vertical field	A	E	E	E	E	D	A	D
Small pressure difference	D	D	D	A	A	D	D	A
OTHER CRITERIA								
Resistance value	A	A	A	B	B	B	B	D
Power consumption	A	A	A	A	A	B	B	B
Easy cleaning	A	B	B	B	B	B	B	B
Heat transfer efficiency	D	B	B	B	B	A	A	A

Letters: A: Perfect or unlimited, B: Modest limits or problems, C: Minor problems in high value parts, D: limited, E: very limited, X: Not acceptable

A multiple effect evaporator is design to cut down the steam consumption by different operating strategies like feed, condensate and product flashing, vapor compression, vapor bleeding, feed and steam splitting and using an optimal feed flow sequence.

3.1. Feeding of multiple effect evaporator

Multiple effect evaporator divided in to four categories on the basis of feed direction as shown Figure 2-5. These are forward feed multi effect evaporator, backward feed multi effect evaporator, mixed feed multi effect evaporator and parallel feed multiple effect evaporator. In the forward feed operation, the raw feed is introduced in the first effect and is passed from effect to effect parallel to steam flow. The product is withdrawn from the last effect. This procedure is highly advantageous if the feed is hot. The method is also used if the concentrated product may be damaged or may deposit scale at high temperature. In the backward feed operation, the raw feed enters the last (coldest) effect and the discharge from this effect becomes a feed for the next to last effect. This technique of evaporations is advantageous, in case the feed is cold, as much less liquid must be heated to the higher temperature existing in the early effects. The procedure is also used if the product is viscous and high temperatures are required to keep the viscosity low enough to produce good heat transfer coefficients. In the parallel feed operation, a hot saturated solution of the feed is directly fed into each of the three effects in parallel without transferring the material from one to another. This is commonly used in the concentration of the salt solution, where the solute crystallizes on concentration without increasing the viscosity. Mixed feed operation is used in solutions having considerable change in viscosity with temperature over concentration range.

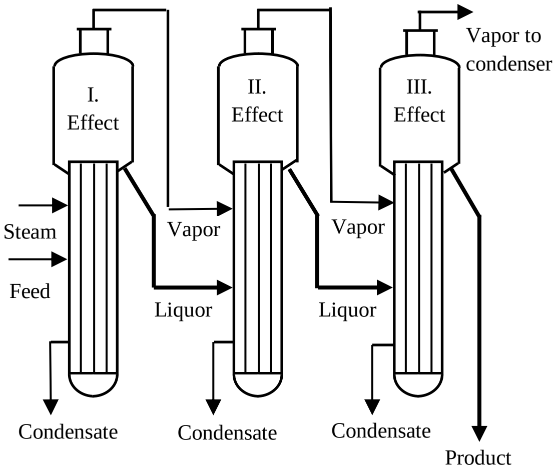

Figure 2. Forward feed multiple effect evaporator

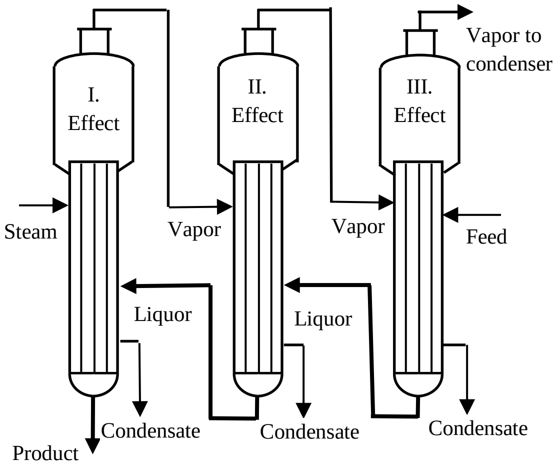

Figure 3. Backward feed multiple effect evaporator

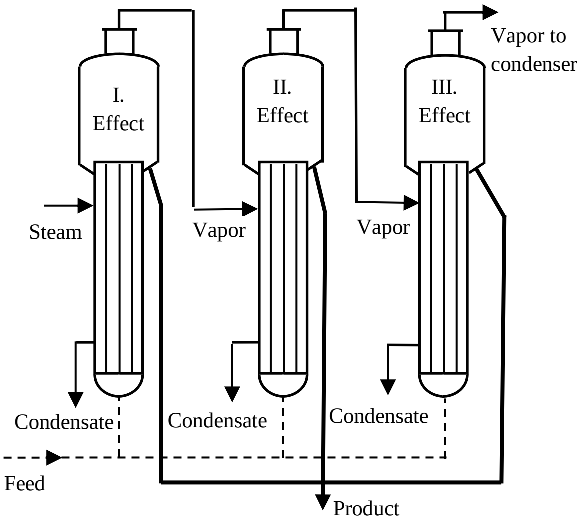

Figure 4. Parallel feed multiple effect evaporator

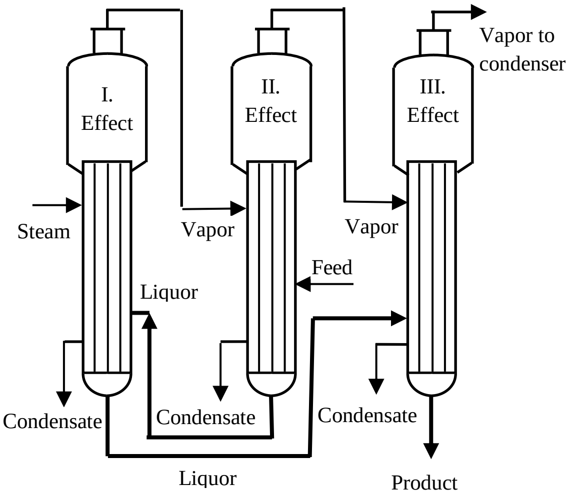

Figure 5. Mixed feed multiple effect evaporator

4. Analysis of multiple effect evaporator Design

The design calculations required for a multiple-effect evaporator are complex enough to provide a real challenge. Multiple effect evaporator calculations require an iterative solution procedure because so many of the required properties depend on unknown intermediate temperatures etc. The overall approach is basically the amount of steam consumed, the area of the heating surface required, the approximate temperatures in the various effects, and the amount of vapor leaving the last effect. The overall strategy is to estimate intermediate temperatures, solve the material balances for the solvent vapor flow rates, use these to determine the heat transferred in each effect, and from that information find the heat transfer area. The steps in the procedure can be summarized as: [10, 11]

- Use the overall material balance to completely determine the feeds and product streams.
- Calculate the total amount of solvent vaporized for each effect; usually it is convenient to split it equally.
- Use component and material balance to get estimates for the remaining flowrates within the system and the compositions of the intermediate streams.
- Use the compositions to estimate boiling point elevations **(**BPEs) and other properties.
- Determine the overall temperature drops between the steam and the saturation temperature of the last effect.
- Determine effect enthalpy balances and heat transfer areas for each effect.
- Determine energy, economy, and capacity.

A triple-effect evaporator, the forward feed system, is shown in Figure 6.

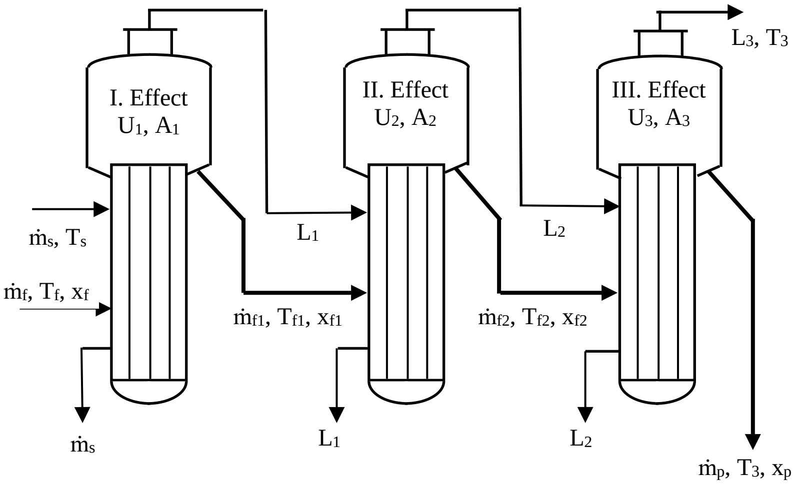

Figure 6. Schematic diagram of a triple-effect evaporator.

Liquid feed is pumped into the evaporator chamber of the first effect. Steam enters the heat exchanger and condenses through its heat transfer to the product. The condensate is discarded. The vapors produced from the first effect are used as the heating medium in the second effect, where the feed is the partially concentrated product from the first effect. The vapors produced from the second effect are used in the third effect as heating medium, and the final product with the desired final concentration is pumped out of the evaporator chamber of the third effect. Finally, product with the desired concentration leaves the third effect.

- Overall material balance

	Total	Dilute liquid	Vapor
Feed	$\dot{m}_f$	$\dot{m}_f x_f$	$\dot{m}_f(1-x_f)$
Product	$\dot{m}_p = \dot{m}_f x_f / x_p$	$\dot{m}_f x_f$	$\dot{m}_p(1-x_p)$
Water Evaporated	$L_{tot} = \dot{m}_f - \dot{m}_p$	or	$\dot{m}_f(1-x_f) - \dot{m}_p(1-x_p)$

- Mass balance analysis on the flow streams

Effect 1: $\dot{m}_{f1} = \dot{m}_f - L_1$ $x_{f1} = \dot{m}_f x_f / \dot{m}_{f1}$

Effect 2: $\dot{m}_{f2} = \dot{m}_{f1} - L_2$ $x_{f2} = \dot{m}_f x_f / \dot{m}_{f2}$

Effect 3: $\dot{m}_p = \dot{m}_{f2} - L_3$ $x_{f3} = x_p = \dot{m}_f x_f / \dot{m}_p$

- Overall temperature drops

Total Available $\Delta T_{tot} = T_s - T_3$

Sum of Boiling Point Elevations $\Sigma BP = BP_1 + BP_2 + BP_3$

Net Available $\Delta T_{net} = \Delta T_{tot} - \Sigma BP$

- Effect temperatures

Effect	Actual solution temperature	Steam saturation temperature
Effect 1:	$T_{f1} = T_s - \Delta T_{f1}$	$T_{s1} = T_{f1} - BP_1$
Effect 2:	$T_{f2} = T_{s1} - \Delta T_{f2}$	$T_{s2} = T_{f2} - BP_2$
Effect 3:	$T_3 = T_{s2} - \Delta T_{f3}$	$T_{s3} = T_3 - BP_3$

- Compute effect heat duties and Required heat transfer areas

	Compute effect heat duties	Required heat transfer areas
Effect 1:	$q_1 = (h_s - h_c)\dot{m}_s$	$A_1 = (U_1 - \Delta T_{f1})/q_1$
Effect 2:	$q_2 = (h_1 - h_{c1})L_1$	$A_2 = (U_2 - \Delta T_{f2})/q_1$
Effect 3:	$q_3 = (h_2 - h_{c2})L_2$	$A_3 = (U_3 - \Delta T_{f3})/q_3$

- Enthalpy balances

$h_s\dot{m}_s - h_f\dot{m}_f = h_1\dot{m}_{f1} + h_s\dot{m}_s + h_1L_1$

$h_1L_1 - h_1\dot{m}_{f1} = h_2\dot{m}_{f2} + h_{c1}L_1 + h_2L_2$

$h_2L_2 - h_2\dot{m}_{f2} = h_p\dot{m}_p + h_{c2}L_2 + h_3L_3$

- Energy, economy, and capacity

Steam Requirement: $\dot{m}_s$

Overall steam economy: $L_{tot}/\dot{m}_s$

Economy per effect:

Effect 1: $L_1/\dot{m}_s$

Effect 2: L_2/L_1

Effect 3: L_3/L_2

Capacity: Feed processed / Steam required: $\dot{m}_f/\dot{m}_s$

Product produced / Steam required: $\dot{m}_p/\dot{m}_s$

4.1. Case study

In this case study, assuming a triple-effect evaporator is to concentrate a caustic soda (Sodium hydroxide, NaOH) from 15% total solids to 50% total solids concentrate. The feed rate is 16 kg/s at 60 ^{o}C. Steam is supplied to the first effect at 150 ^{o}C. The overall heat-transfer coefficient are 3600, 2200 and 1400 (W/m^2 ^{o}K) in the first, second and third effect respectively. Calculations and equations results are done by using the Excel and Matlab programme. Calculation and results are overall material balance for product (NaOH) and steam requirement, compositions in the effects mass balance analysis on the flow streams, overall temperature drops, each effect's temperature, heat duties, required heat transfer areas, energy, economy, and capacity. Results are presented in Table 2-7 by using equations. Calculations and equations results are done by using the Excel and Matlab programme.

Table 2. Overall material balance in evaporators system

	Total	NaOH	Vapor
Feed (kg/s)	16	2.4	13.6
Product (kg/s)	4.8	2.4	2.4
Water evaporated (kg/s)	11.2		11.2

Table 3. Compositions in the effects mass balance analysis on the flow streams

	Mass fraction (NaOH)	Vapor feed (kg/s)
Effect 1	0.19	12.47
Effect 2	0.28	8.64
Effect 3	0.50	4.80

Table 4. Overall temperature drops

Total temperature drop (°C)	110.0
Sum of boiling point elevations (°C)	63.7
Net temperature drop (°C)	46.3

Table 5. Effect temperatures

Effect	Actual solution temperature (°C)	Steam saturation temperature (°C)	boiling point elevation (BP) (°C)
Effect 1	141.8	134.4	7.4
Effect 2	119.7	105.0	14.7
Effect 3	81.7	40.0	41.7

Table 6. Effect heat duties and required heat transfer areas

	Heat duties, q, (kW)	Heat transfer areas (m^2)
Effect 1:	6742	228.4
Effect 2:	9589	237.4
Effect 3:	8417	266.0

Table 7. Enthalpy balances results

	Condensate (kJkg)	Vapor (kJkg)		Feed (kJkg)	
		In	Out	In	Out
Effect 1:	631.9	2745.3	2740.3	216.7	519.3
Effect 2:	565.0	2740.3	2712.6	519.3	436.2
Effect 3:	440.1	2712.6	2656.7	436.2	472.6

- Energy, economy, and capacity

Steam requirement: 3.19 kg/s
Vapor generated: 11.20
Overall steam economy: 3.51
Economy per effect: effect 1: 1.11, effect 2: 1.09, and effect 3: 1.0
Capacity: Feed processed / Steam required: 5.016 and Product produced / Steam required: 1.505

Conclusions

In this study, investigation of selection of type of evaporator using some parameters is presented for multiple effect evaporator system. All of evaporator types are compared each other by using important parameters. Paper is presented categories as perfect or unlimited, modest limits or problems, minor problems in high value parts, limited, very limited and not acceptable for the evaporator types. Also feed configurations of multiple effect evaporator are presented with advantages or not. Important equation of analysis of multiple effect evaporator design are given such as material and mass balance, drops and effect of temperature, heat duties, heat transfer areas enthalpy balances energy, economy, and capacity. The case study is done using a forward feed multiple effect evaporator types according to given equations. Results are showed that multiple effect evaporator has 3.51 overall economy according to single evaporator.

Nomenclature

A	heat transfer area, (m^2)
BP	Boiling Point Elevations, (^{o}C)
h	Enthalpy (kJ/kg)
L	Boilup rate, (kg/s)
$\dot{m}$	Mass flow rate of liquid, (kg/s)
q	Heat duty, (kW)
T	Temperature, (^{o}C)
ΔT	Temperature difference, (^{o}C)
U	Overall heat transfer coefficient, (W/m^{2}K)
x	Mass fraction NaOH

Subscript

s	Steam
1, 2, 3	Effects 1, 2, 3, respectively
f	Feed dilute liquid
p	Product
tot	Total
c	condensate

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