International Journal of Latest Trends in Engineering and Technology
Vol.(13)Issue(4), pp.015-021
DOI: http://dx.doi.org/10.21172/1.134.03
e-ISSN:2278-621X

APPROACH TO DESIGN, MODELLING AND SIMULATION OF MULTIPLE EFFECT EVAPORATORS

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Abstract: Evaporation is a process through which solvent is vaporized and solute remains in solution so that solution gets concentrated. It could be single effect or multiple effect evaporators. Evaporators are used in many process industries such as pharmaceuticals, dairy and food processing, paper and pulp industry, etc. Caustic soda industry is considered with four effect falling film evaporator. There is a forward feed flow pattern. Designing of this system has been done. In this paper description of steady state model of multiple effects evaporator is described for simulation purpose. The steam economy of each effect is in increasing order. This model includes overall and component mass balance along with energy balance equations to estimate product and evaporation rate in each effect which will help to find required area for each effect for forward feed flow. The effect of feed rate increment and effect number has also been discussed.The code has been developed by using MATLAB. Results of the present approach are validated with industrial data.

1. INTRODUCTION

Evaporation is a process through which solvent is vaporized to obtain desire solute from solution or slurry. It takes place at surface of liquid to change phase from liquid to gases. Multiple effect evaporation is applied in large scale industry to reduce steam consumption . It is an endothermic process where heat is absorbed. Evaporation is a gist process of water cycle and aim only to concentrate the solution. The process of evaporation is higher if carried out at higher temperature. Therefore, for achieving desire product, solution needs to make more concentrated by vaporising the solvent.

It is an integral part of many processes in industries such as pharmaceutical, dairy and food processing, pulp and paper industry, sugar, desalination, etc. Thus either improving design or operation will helps industry to expand its capacity. Evaporation often intrudes upon operations known as drying, crystallization and distillation. In evaporation, the surrounding gas must not be saturated with evaporating substance, component of vapour are not separatedand residue is always liquid which distinguish it from distillation and drying operation respectively. The desire product may or may not be a solid, but heat must be transferred to evaporator to evaporate the solution which distinguishes it from crystallization since production of crystal is not concern. Evaporative cooling is achieved by reducing temperature of liquid through removing heat from vaporised liquid. This process is carried out until equilibrium is obtained.

In this paper, the modelling of evaporator has done for forward feed flow system. The impact of increasing feed flow rate and reduction in effects number has also been discussed.

1.1 Classification of Evaporators

Evaporators are classified on the basis of heat/heating medium such as

1. Solar radiation used for heating
2. Coil, Jackets, Flat plates are used for heating medium
3. Heating medium and evaporating liquid are brought in direct contact
4. Evaporating liquid and heating medium separated through tubular heating surface.

There are many types of evaporators and those are enlisting below:

1. Horizontal spray film evaporators (HSFE)
2. Horizontal tube evaporators (HTE)
3. Vertical long tube evaporators
3.1. Rising or climbing film evaporators (RoCFE)
3.2. Falling film evaporators (FFE)
3.3. Rising-falling film evaporators (RFFE)
4. Short tube vertical evaporators
4.1. Inclined tube vertical evaporators (ITTE)
4.2. Basket type vertical evaporators (BTVE)
5. Forced circulation evaporators (FCE)

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6. Plate evaporators (PE)
7. Agitated thin film evaporators or wiped film evaporators (ATFE).

1.2 Parameters needed for selecting any evaporators

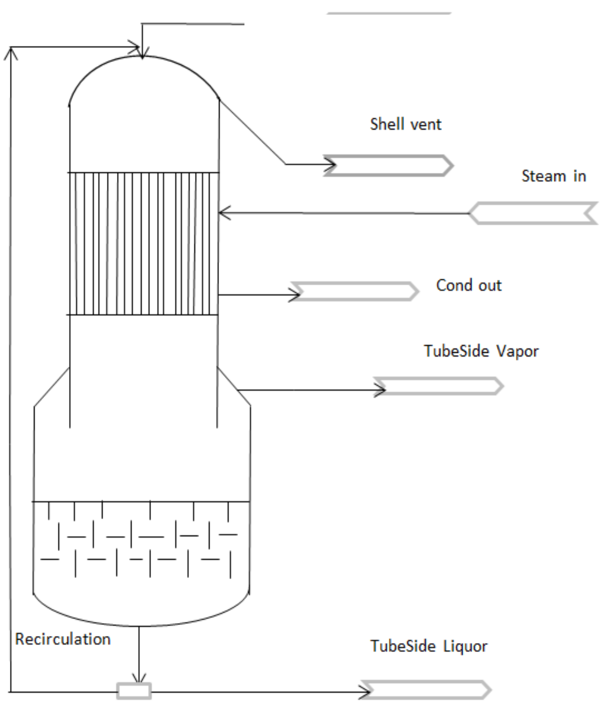
Selection of any evaporator is depend upon parameters like heat transfer coefficient, Area of contact, flow pattern, economic, fouling, heat sensitivity, easy cleaning, leakage probability, etc. The parameters affection on selection is shown in table 1.

Parameters → Evaporators	Heat transfer coefficient	Area	Flow pattern	Economic	Fouling	Heat sensitivity	Cleaning	leakage
HSFE	High	High	Annular, Stratified	Moderate	Min.	Nuclease Boiling	Easy	Gas
HTE	High	High	-	Appropriate	Handle	High	Easy	Less
RoCFE	High	Less	-	Good	Min.	High	Depend on viscosity	Less
FFE	High	less	-	Good	Min.	High	Easy	occur
RFFE	High	Less	-	Good	Min.	High	Moderate	-
ITTE	High	Less	-	Good	Min.	Depend on temp. drop	Difficult	Less
BTVE	High	High	-	less	Min.	Can't use for HS material	Easy	-
FCE	High	Less	-	Lesser	Control	Less	Easy	Less
PE	High	High	-	High for costly material	Less	High	Easy	High
ATFE	Less	Limited	-	Less	Min.	High	Moderate	-

Table 1.Parameters for different evaporators

Falling film Evaporator

a. Diagram



2. PROBLEM UTTERANCE

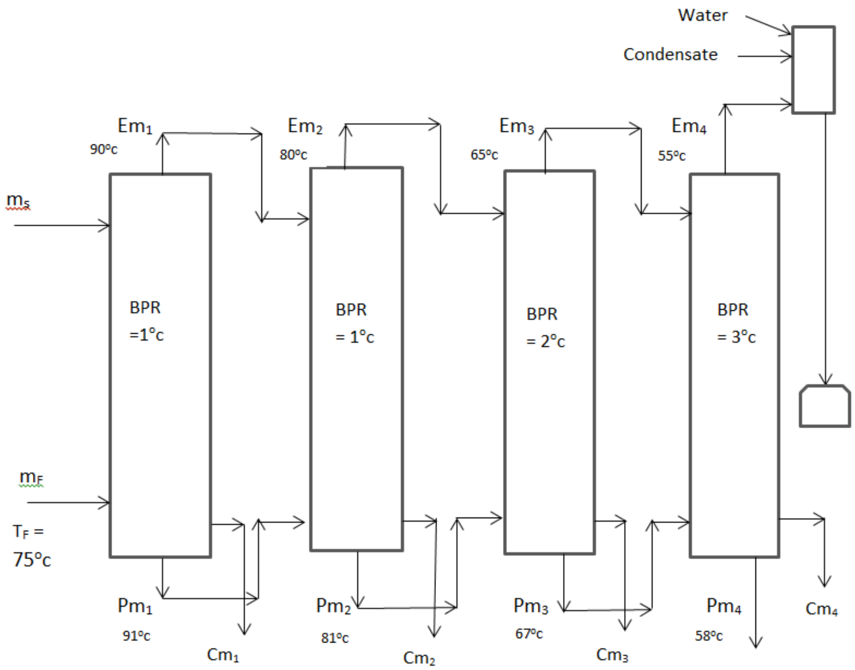
A forward flow sequence is considered where caustic soda is concentrating through falling film evaporator of four effect evaporating system. The operating parameters of this system are given below in table 2.

Sr. no.	Parameters	Value
1.	Effect number	4
2.	Feed flow rate	20,000 kg/hr
3.	Inlet concentration	0.05
4.	Outlet concentration	0.3
5.	Steam temperature	100oc
6.	Feed temperature	30oc

Table 2. Parameters for problem

3. DESIGN ASPECTS

3.1 Diagram



C_f = Specific heat of feed, kcal/kg^{o}c
Cp_1, Cp_2, Cp_3, Cp_4 = Specific heat of product from 1 to 4 effects, kcal/kg^{o}c
Cc_1, Cc_2, Cc_3, Cc_4 = Specific heat of condensate from 1 to 4 effects, kcal/kg^{o}c
T_f = temperature of feed, ^{o}c
T_s = Saturation temperature of feed in first effects, ^{o}c
T_1, T_2, T_3, T_4 = Evaporation temperature of effects 1 to 4, ^{o}c
Tp_1, Tp_2, Tp_3, Tp_4 = Outlet temperature of product in effects 1 to 4, ^{o}c
t_1, t_2, t_3, t_4 = Boiling point elevation in effect 1 to 4, ^{o}c
Ls = Latent heat of steam to 1st effect, kcal/kg
LE_1, LE_2, LE_3, LE_4 = Latent heat of evaporated water in first to four effects, kcal/kg
Q_F, Q_S, Q_C, Q_P, Q_E = Energy to feed, steam, condensate, product and evaporation respectively, kJ/kg
x = Initial total Dissolved solids
y = Final total dissolved solids
m_F = Mass flow rate of feed, kg/hr
Pm = Mass flow rate of product, kg/hr
Em = Mass flow rate of evaporated, kg/hr

3.2 Design procedures

The design of multiple effect evaporator includes are, number of tubes, flow rate, mass and energy balance. It's estimated as follow:
Find amount of product and amount of evaporation by Pm = (mF*x)/y and mF = Pm + Em respectively.
Now, find amount of steam (ms) required for desired separation by assuming steam economy. Thus, ms = Amount of water evaporated (Em) / steam economy (SE)
Now, use mass and energy balance equation for each effects to estimate the amount of product and amount of water evaporate.
mF = Pm + Em (1)
QF + QS = QC + QP +QE (2)
Concentration per effect is determined by,
Xnew = (Xold* flow rate of feed in that effect) / (product flow rate from that effect)
Repeat it till desired concentration of product is achieved by assuming new steam economy every time.
Area for each effect is varying and found by, A = (ms* Ls)/ U*ΔT
The number of tubes required in each effect can be found by,
N = A / (π*D*L)
The flow rate of pump for each effect can be found by,
Q = velocity * no. of tubes * area

3.3 Computation
This system will be analysed in various parameters such as varying flow rates, varying effects number and varying steam economy.
For the system given data is as follows:
mF = 20,000 kg/hr
x = 0.05 and y = 0.3
Therefore, amount of product can be calculated as
Pm = (mF * x) / y = 3333.33 kg/hr
Now, amount of evaporate water can be found by,
mF = Pm + Em
So, Em = mF– Pm
Em = 20,000 – 3333.33 = 16,666.67 kg/hr
Now, assuming new steam economy every time, the final steam economy as 3.5.
Total steam required, ms = Em / SE
ms = 4761.90 kg/hr
The amount of product and evaporation can be determining by using mass and energy balance equation.
For 1st effect:
Since, mF = Pm1 + Em1
20,000 = Pm1 + Em1 ……………………………………. (1)
Since, QF + QP = QC1 + QP1 + QE1
(mF*CF*ΔT) + (ms*Ls) = (Cm1*Cc1*ΔT) + (Pm1*Cp1*ΔT) + (Em1*LE1)
So, (20,000*0.95*75)+(4761.90*539.9282) = (4761.90*1.0104*100) + (Pm1*0.91*91) + (Em1*546.2201)
→ 3514941.72 = 52.81*Pm1 + 546.2201*Em1 ……………………………….. (2)
By solving equation (1) and (2), we get
Pm1 = 15988.99178 kg/hr
Em1 = 4011.008219 kg/hr
Using different mass and energy balance equations for each effect, we can determine the amount of product and evaporation as shown in table 4.3.

Effects no.	Mass balance equation	Energy balance equation
1.	mF = Pm1 + Em1	QF + QP = QC1 + QP1 + QE1
2.	Pm1 = Pm2 + Em2	QP1 + QE1 = QC2 + QP2 + QE2
3.	Pm2 = Pm3 + Em3	QP2 + QE2 = QC3 + QP3 + QE3
4.	Pm3 = Pm4 + Em4	QP3 + QE3 = QC4 + QP4 + QE4

Table 3.1Effects and their mass and energy balance equations

Effects	Ls and LE for feed		Condensate at inlet (C)		Condensate at outlet (C)		Evaporation at outlet		Product at outlet (P)	
-	Ls or LE	T	Cc or CF	ΔT	Cc	ΔT	LE	T	CP	ΔT
	539.9282	100oc	0.95	75oc	1.0104	100oc	546.2201	90oc	0.91	91oc
	546.2201	90oc	0.91	91oc	1.0073	90oc	552.3445	80oc	0.89	81oc

	552.3445	80oc	0.89	81oc	1.0047	80oc	561.3158	65oc	0.88	67oc
	561.3158	65oc	0.88	67oc	1.0017	65oc	567.177	55oc	0.87	58oc

Table 3.2 Various operating parameters as per effects

Effects no. –	First	Second	Third	Fourth
Mass flow rate of product (kg/hr)	15988.99178	11827.30474	7608.23208	3431.48
Mass flow rate of evaporation (kg/hr)	4011.008219	4161.687042	4219.07266	4176.76

Table 3.3 Mass flow rate of product and evaporation

The area required for each effect can be found by using design procedure 5. The value of overall heat transfer will vary as per temperature variation.

Q = U*A*ΔT and Q = ms*L

Where, ΔT is temperature difference between steam inlet and product outlet temperature.

Therefore, A = (ms*Ls) / (U*ΔT). The area for each effect is shown in table 4.

Effect	Area (A), m2	U*ΔT	(ms*Ls)	Area Calculated
1.	A1	1400*9	4761.90*539.9282	204.06 m2
2.	A2	1200*9	4011.008219*546.2201	202.86 m2
3.	A3	1000*13	4161.687042*552.3445	176.82 m2
4.	A4	800*7	4219.07266*561.3158	422.90 m2

Table 4. Area for each effect

Consider a tube having O.D. of 50.8 mm, Length of 6 m and velocity of fluid in pump is 0.04 m/sec (Range 0.02 to 0.05 m/sec) Thus, the No. of tubes required and volumetric flow rate of pump is shown in table 5.

Effects	No. of tubes = N = A / (π*D*L)	Volumetric Flow rate = Q = v*N*A
1.	213	1738.59 m3/sec
2.	212	1720.2528 m3/sec
3.	185	1308.468 m3/sec
4.	442	7476.872 m3/sec

Table 5. No. of tubes and volumetric flow rate of pump

If three effect systems has been considered then variation in flow rate, area, no. of tubes and volumetric flow rate of pumps variation is shown in table 6.

Effects	Feed Flow rate	Product flow rate (kg/hr)	Evaporation flow rate (kg/hr)	Area (m2)	No. of tubes	Volumetric flow rate (m3/sec)
1.	20,000 kg/hr	17152.6100	2847.38	151.40	158	956.84
2.		14068.75084	3083.85	144.00	150	864
3.		10803.7236	3265.02	131.02	137	717.88

Table 6.Three effect system parameters

Now, if the feed flow rate is varying then all parameters associated with it will vary except concentration of TDS in solution. This can be shown in table 7.

Effects	Feed flow rate	Product flow rate (kg/hr)	Evaporation flow rate (kg/hr)	Area (m2)	Number of tubes	Volumetric flow rate of pump (m3/sec)	Concentration of TDS in solution (x)
1.	20,000 kg/hr	15988.99	4011.0082	204.06	214	1746.7536	0.06229
2.		11827.30474	4161.6870	202.86	212	1720.2528	0.08449
3.		7608.23208	4219.07266	176.82	186	1315.5408	0.131344
4.		3431.48	4176.76	422.90	442	7476.872	0.29680
1.	10,000 kg/hr	7994.5	2005.5	102.03	107	436.69	0.06229
2.		5913.66	2080.84	101.43	106	430.06	0.08449
3.		3804.12	2109.54	88.41	93	328.89	0.13134
4.		1715.74	2088.38	211.45	221	1869.22	0.29120

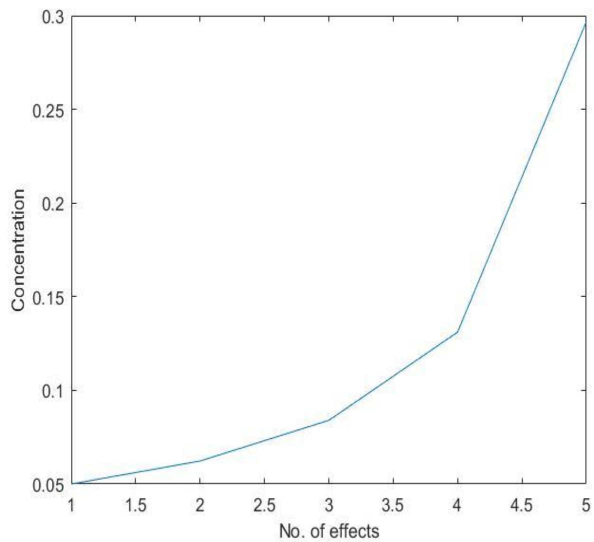
Table 7. On varying flow rate affected parameters

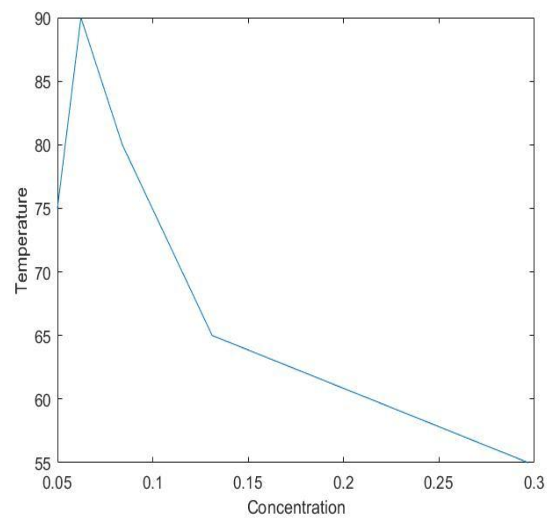
Therefore, from above table 8 it's clear that if we double the flow rate i.e. 10,000 kg/hr to 20,000 kg/hr then its product yield, evaporation rate, Area and number of tubes required doubles whereas volumetric flow rate of pump is four times and concentration remains unaffected.

4. RESULT
By all algorithms we get results as
Feed flow rate F: 20,000
Initial TDS x: 0.05
Final TDS y: 0.3
Steam economy: 3.5
No. of effects: 4

Effects	Feed flow rate	Product flow rate (kg/hr)	Evaporation flow rate (kg/hr)	Area (m2)	Number of tubes	Volumetric flow rate of pump (m3/sec)	Concentration of TDS in solution (x)
1.	20,000 kg/hr	15988.99	4011.0082	204.06	214	1746.7536	0.06229
2.		11827.30474	4161.6870	202.86	212	1720.2528	0.08449
3.		7608.23208	4219.07266	176.82	186	1315.5408	0.131344
4.		3431.48	4176.76	422.90	442	7476.872	0.29680

Graph is plotted between Temperature vs. Concentration and Concentration vs. no. of effects.





5. CONCLUSION
This system is operated at steam economy of 3.5. The feed flow rate and effect numbers are changed to evaluate effect on other parameters.The same methodology can be applied to other caustic soda medium to get results.

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