

Design and Optimization of Multiple Effect Evaporator for Sugar Industry

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Abstract: In Sugar Industry, Evaporators play a pivotal role in the concentration of sugar solutions, essential for the production of crystallized sugar. As global energy concerns intensify, optimizing evaporator designs becomes paramount to enhance steam economy and energy recovery. This project delves into the design and simulation of a multiple effect evaporator system using Aspen Plus software, with a focus on augmenting energy utilization efficiency through pinch analysis techniques. The necessity of evaporators in the sugar industry stems from the fundamental requirement to concentrate sugar solutions, a critical step in the sugar production process. However, the current landscape demands a paradigm shift towards enhancing steam economy and energy utilization. This imperative arises from the escalating energy costs and the pressing need for sustainable industrial practices.

Addressing this challenge, our project meticulously examines various design parameters and operational conditions to optimize evaporator performance. Through meticulous calculations including vapour bleeding, vapour splitting, and condensate flashing, alongside exploring both forward and backward arrangements, we aim to determine the most efficient evaporator configuration. By leveraging advanced simulation techniques and incorporating insights from pinch analysis, our study endeavours to not only increase the efficiency of evaporator steam economy but also enhance overall energy recovery in the sugar industry. The findings of this research hold significant promise in steering the sugar industry towards a more sustainable and economically viable future, aligning with the broader imperative of energy conservation and resource optimization.

Keywords: Multiple effect, Sugar Industry, Forward Feed, Backward Feed

I. INTRODUCTION

Worldwide, raw sugar is produced from sugarcane, which consists of roughly one-seventh sucrose, one-seventh fibrous material, with the rest being mostly water. The juice is extracted from the cane using a series of crushing mills, leaving behind a mixture of fibrous material and water known as bagasse. This bagasse is utilized as fuel in boilers to produce steam needed to power steam turbines and for process

heating within the factory. The extracted juice is then heated through a series of juice heaters before being transferred to a clarifier, where most of the insoluble impurities are removed. The clarified juice is subsequently sent to a multi-effect evaporator (MEE) system, where over 90% of the water in the juice is evaporated.

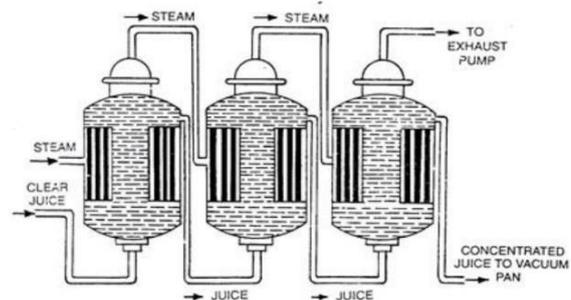
A. Single- & multiple Effect Evaporator

A single-effect evaporator consists of a single unit where the solution is boiled to evaporate the solvent (usually water). The heat required for this process is supplied to the unit, and the vapor generated is condensed and removed.

A multiple-effect evaporator consists of a series of single-effect evaporators (stages) arranged in such a way that the vapor produced in one effect is used as the heating medium for the next. This cascade system significantly improves energy efficiency.

B. Principle of Multiple-Effect Evaporator

The principle of a multiple-effect evaporator (MEE) revolves around the efficient use of energy to evaporate water from a solution. In an MEE system, the evaporators are arranged in a series, with each subsequent evaporator operating at a lower pressure and temperature than the previous one. This configuration allows the vapor produced in one effect to be used as the heating medium for the next, significantly improving energy efficiency.



In a single-effect evaporator, the solution is heated to

its boiling point, and the resulting vapor is condensed and removed. This process requires a substantial amount of energy because each unit of vapor must be heated and condensed separately. In contrast, a multiple-effect evaporator takes advantage of the heat released during the condensation of vapor in one stage to provide the energy needed to evaporate the solution in the next stage.

The process begins in the first effect, where the solution is heated by steam to its boiling point, causing the water to evaporate. The vapor generated is then directed to the second effect, where it condenses, releasing its latent heat. This released heat is used to boil the solution in the second effect, which is under lower pressure, thereby requiring a lower boiling point. The vapor from the second effect is then used to heat the third effect, and this cascade continues through multiple stages.

By reusing the latent heat of the vapor across several stages, a multiple-effect evaporator significantly reduces the overall energy required for the evaporation process. Each stage, or effect, operates at progressively lower pressures and temperatures, which ensures that the heat from the vapor can effectively drive the evaporation process in the subsequent stages.

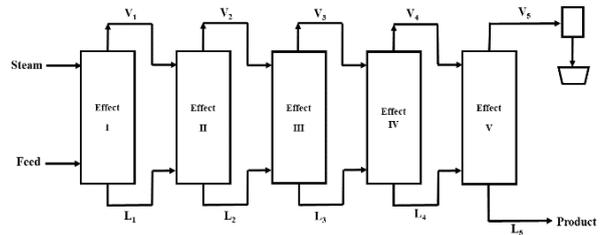
This principle not only enhances energy efficiency but also lowers operational costs. The initial investment for an MEE system is higher due to its complexity, but the savings in energy costs make it a more economical choice in the long run. This makes multiple-effect evaporators particularly suitable for industries like sugar manufacturing, where large quantities of water need to be evaporated. By maximizing energy use, MEE systems contribute to more sustainable and cost-effective production processes.

II. DESIGN METHODOLOGY

Table: Feed Conditions

Total Number of Effects	5	
Steam Temperature	120	°C
Pressure	1.7	Bar
Feed Flow Rate	10000	Kg/hr
Feed Temperature	40	°C
Outlet Temperature	55	°C
Solids in Feed	15	%
Solids Out of the Last Effect	60	%

1. Design of Forward Feed



1.1 Assumptions for Design

- Flow Rate of Product (L5)

The calculations of product flow rate are based on the solids conditions present in the sugar syrup at the inlet and at the outlet.

$$L_5 = \frac{F(x)}{y}$$

- Overall Material Balance

$$F = L + V$$

- Individual Material Balance

Assuming the equal amount is vaporized in each effect (Kg/Hr)

$$V_1 = V_2 = V_3 = V_4 = V_5 = \frac{V}{N}$$

Where,

V = Total Amount of Vapor

N = No. of Effects

To Calculate Liquid Flow Rate of Each Effect (Kg/hr)

$$F = L_1 + V_1$$

$$L_1 = L_2 + V_2$$

$$L_2 = L_3 + V_3$$

$$L_3 = L_4 + V_4$$

$$L_4 = L_5 + V_5$$

- U assumed

$$U_1 = 900$$

$$U_2 = 825$$

$$U_3 = 750$$

$$U_4 = 675$$

$$U_5 = 600$$

1.2 Actual Calculation

- Calculations for solid Balance

$$F(x) = L1(x1)$$

- Calculation of Boiling Point Rise

$$BPR = 1.78x + 6.22x^2$$

- Heat Capacity Calculations

$$Cp = 4.19 - 2.35x$$

- Calculation of ΔT

$$\Sigma \Delta T \text{ Available} = Ts - T5 - (\Sigma BPR)$$

$$\Delta T = \Sigma T \frac{1/U1}{\frac{1}{U1} + \frac{1}{U2} + \frac{1}{U3} + \frac{1}{U4} + \frac{1}{U5}}$$

- Boiling Point Calculations

$$T1 = Ts1 - \Delta T1$$

$$T2 = T1 - BPR1 - \Delta T2$$

$$Ts2 = T1 - BPR1$$

- Pressure Calculations

Relation Used for calculating the pressure

$$P = 10.17246 - 0.6167302 * T_{is} + 1.832249 * 10^{-2} * T_{is}^2 - 1.77376 * 10^{-4} * T_{is}^3 + 1.47068 * 10^{-6} * T_{is}^4$$

- Enthalpy & Latent Heat Calculation

$$H1 = Hs1(\text{Saturation Enthalpy at } Ts1) + 1.884(BPR1)$$

$$\lambda s1 = Hs1(\text{vapour Saturation Enthalpy}) - h s1(\text{Liquid Enthalpy at } Ts1)$$

- Energy Balance

$$F * Cp * (TF - 0) + s * \lambda s1 = L1 * Cp1 * (T1 - 0) + V1 * H1$$

$$L1 * Cp1 * (T1 - 0) + V1 * \lambda s2 = L2 * Cp2 * (T2 - 0) + V2 * H2$$

$$L2 * Cp2 * (T2 - 0) + V2 * \lambda s3 = L3 * Cp3 * (T3 - 0) + V3 * H3$$

$$L3 * Cp3 * (T3 - 0) + V3 * \lambda s4 = L4 * Cp4 * (T4 - 0) + V4 * H4$$

$$L4 * Cp4 * (T4 - 0) + V4 * \lambda s5 = L5 * Cp5 * (T5 - 0) + V5 * H5$$

- Calculations of Heat Rate (W)

$$Q = s * \lambda s$$

- Calculation for Area (m²)

$$A = \frac{Q}{U * \Delta T}$$

- Calculation for Number of Tubes

a = surface area of tube = $\pi d_0 L$

$$Nt = \frac{A}{a}$$

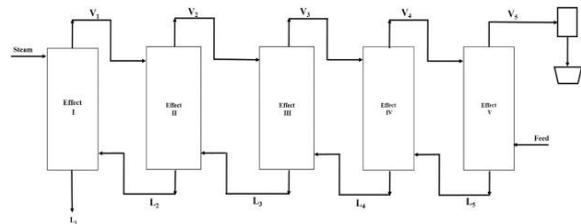
- Steam Economy

$$\text{Steam Economy} = \frac{V1+V2+V3+V4+V5}{S}$$

- Steam Consumption

$$\text{Steam Consumption} = F * x * Cp * (T1 - T2) / \lambda s$$

2. Design of Backward Feed



- Heat Balance equation

$$L2Cp2 (T2+BPR2)+ V_0\lambda_0 - (L2 - L1)H1 - L1Cp1 (T1+ BPR1)=0$$

$$L3 Cp3 (T3 +BPR3) + (L2 - L1)\lambda_1 - (L3 -L2) H2 - L2Cp2(T2+ BPR2)=0$$

$$L4 Cp4 (T4 +BPR4) + (L3 -L2) \lambda_2 - (L4 - L3) H3 - L3Cp3(T3 +BPR3)=0$$

$$L5 Cp5 (T5 +BPR5) + (L4 -L3) \lambda_3 - (L5 - L4) H4 - L4Cp4(T4 +BPR4)=0$$

$$F Cp f Tf + (L5 -L4) \lambda_4 - (F - L5) H5 - L5Cp5(T5 +BPR5)=0$$

III. SIMULATION



Fig. Component Selection

Forward Feed:

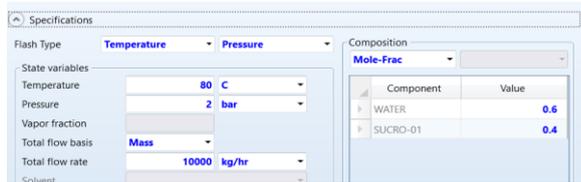


Fig. Feed Conditions

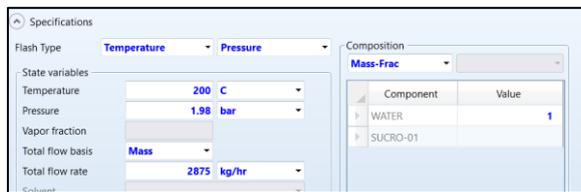


Fig. Steam Inlet Conditions

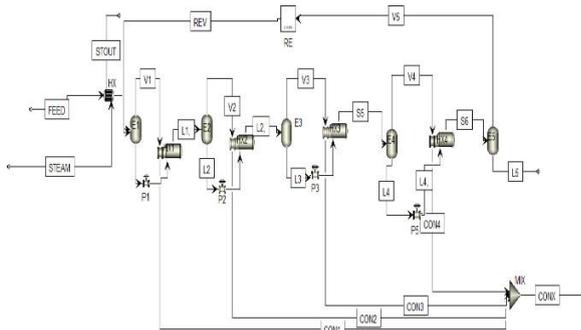


Fig. Forward Feed Flowsheet

Table: Evaporator Streams

No. of Effect	Effect - 1		Effect - 2		Effect - 3		Effect - 4		Effect - 5	
	L1	V1	L2	V2	L3	V3	L4	V4	L5	V5
Flowrate (Kg/hr)	9348.18	663.18	9457.99	46.56	9364.37	93.61	9341.36	23.01	9329.99	11.36

Table: Heat Exchanger Streams

No. of Heat Exchangers	HE - 1		HE - 2		HE - 3		HE - 4		HE - 5	
	Inlet	Outlet								
Liquid Temperature (C)	80	105.79	98.42	98.63	80.30	84.58	78.59	80.25	70.95	70.96
Vapour Temperature (C)	200	121.44	105.79	103.46	89.84	106.61	82	88.11	75	78.23
Heat Duty (kW)	319.68		0.816		21.135		7.287		0.0630	

Table: Valves

No. of Valves	P-1	P-2	P-3	P-4
Pressure Drop (bar)	0.8	0.6	0.2	0.2

Backward Feed:

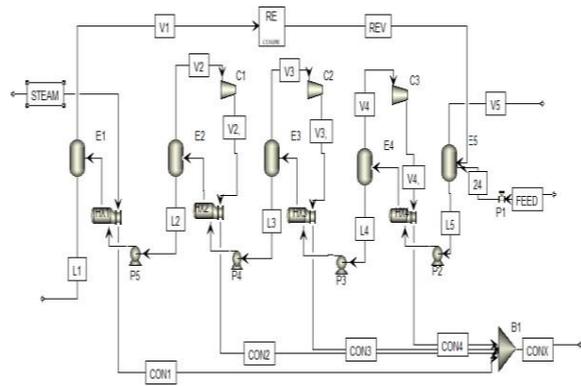


Fig. Backward Feed Flowsheet

Table: Evaporator Streams

No. of Effect	Effect - 1		Effect - 2		Effect - 3		Effect - 4		Effect - 5	
	L1	V1	L2	V2	L3	V3	L4	V4	L5	V5
Flowrate (Kg/hr)	9370.25	0.38	9370.63	18.74	9389.37	78.89	9468.27	110.09	9578.36	422.01

Table: Heat Exchanger Streams

No. of Heat Exchangers	HE - 1		HE - 2		HE - 3		HE - 4	
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
Liquid Temperature (C)	85.00	115.40	79.00	81.68	65.5	74.15	55.00	64.43
Vapour Temperature (C)	120	86.00	110.97	80.00	105.09	66.50	91.20	56.00
Heat Duty (kW)	125.16		12.79		54.96		77.35	

Table: Valve And Pumps

No. of Pressure Changers	P-1 (Valve)	Pumps	P-2	P-3	P-4	P-5
	Pressure Drop (bar)	0.6	Pressure Increase (bar)	0.05	0.015	0.015

Table: Compressors

No. of Compressors	C-1	C-2	C-3
Pressure Increase (bar)	0.2	0.2	0.2

IV. VARIOUS CONDITIONS

1. Condensate Flashing

The condensate (water in present case), which exits from steam/vapor chest of an effect, contains sufficient amount of sensible heat which can be put to use. This sensible heat can be extracted by means of flashing which will produce low pressure vapor. This vapor can be used as a heating medium in vapor chests of appropriate effects and thereby can improve steam economy of the whole system.

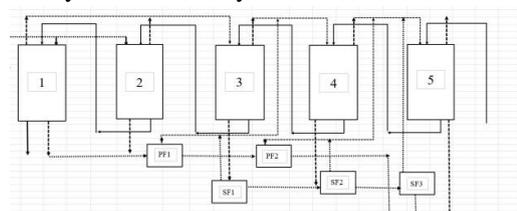


Fig. Condensate Flashing

2. Vapour Bleeding

Vapor bleeding in multiple-effect evaporators is a technique used to enhance the overall efficiency and performance of the evaporation process. This method involves the strategic removal or "bleeding" of vapor from certain points within the evaporator system to utilize its latent heat for preheating the feed or for other purposes. By doing so, the process maximizes energy usage, reduces operational costs, and improves thermal efficiency.

Calculations for Liquid:

$$L2Cp2 (T2+BPR2) + V\lambda_0 - (L2 - L1) H1 - L1Cp1 (T1+ BPR1) =0$$

$$L3 Cp3 (T3 +BPR3) + (L2 - L1) \lambda_1 - (L3 -L2) H2 - L2Cp2(T2+ BPR2) =0$$

$$L4 Cp4 (T4 +BPR4) + (L3 -L2) \lambda_2 - (L4 - L3) H3 - L3Cp3(T3 + BPR3) =0$$

$$L5 Cp5 (T5 +BPR5) + (L4 -L3) \lambda_3 - (L5 - L4) H4 - L4Cp4(T4 + BPR4) =0$$

$$F Cpf Tf + (L5 -L4) \lambda_4 - (F - L5) H5 - L5Cp5(T5 + BPR5) =0$$

Calculations for vapour:

$$Vb5 \lambda_5 - FCpf(T5-10-30) =0$$

$$Vb4 \lambda_4 - L5Cp5(T4-5-(T5 + BPR5)) =0 \quad Vb3 \lambda_3 - L4Cp4 (T3-5-(T4 + BPR4)) =0 \quad Vb2 \lambda_2 - L3Cp3 (T2-5-(T3 + BPR3)) =0 \quad Vb1 \lambda_1 - L2Cp2 (T1-5-(T2 + BPR2)) =0$$

3. Vapour Splitting

Vapor splitting in a multiple effect evaporator is a technique used to optimize the efficiency and performance of the evaporation process. This method involves strategically dividing the vapor produced in one effect and distributing it to subsequent effects, thereby improving the overall energy efficiency and heat transfer rates within the system. The key objective is to maximize the utilization of the available thermal energy and minimize energy consumption, which is critical in processes where large quantities of water or solvents need to be evaporated.

Calculations:

$$[L2Cp2(T2+BPR2)] + [0.5V\lambda_0] - [L1Cp1(T1+BPR1)] - [(L2-L1) (\lambda_1+(4.2T1))] =0$$

$$[L3Cp3(T3+BPR3)] + [0.5V\lambda_0] - [L2Cp2(T2+BPR2)] - [(L3-L2) (\lambda_2+(4.2T2))] =0$$

$$[L4Cp4(T4+BPR4)] - [L3Cp3(T3+BPR3)] + (L2- L1) \lambda_1 + (L3-L2) \lambda_2 - [(L4-L3) (\lambda_3+(4.2T3))] =0$$

$$[L5Cp5(T5+BPR5)] - [L4Cp4(T4+BPR4)] + (L4- L3) \lambda_3 - [(L5-L4) (\lambda_4+(4.2T4))] =0$$

$$[FCpTf] - [L5Cp5(T5+BPR5)] + (L5-L4) \lambda_4 - [(F- L5) (\lambda_5+(4.2T5))] =0$$

V. RESULTS

Forward Feed Calculations:

Effect	1	2	3	4	5
Solid Balance	0.176	0.214	0.273	0.375	0.6
BPR, °C	0.508	0.667	0.948	1.542	3.307
ΔT, °C	9.47	10.33	11.37	12.63	14.21
T, °C	110.525	99.6807	57.6435	74.062	58.3072
Ts, °C	110.01	99.01	86.69	72.51	55
P, bar	1.98498	1.4338	0.97931	0.61938	0.34847
Cp, KJ/Kg.k	3.77	3.36	3.54	3.30	2.78
H, KJ/Kg	2962.26	2675.36	2654.89	2632.41	2604.53
λs, KJ/Kg	2202.42	2230.92	2260.52	2294.77	2331.02
L, Kg/hr	8748.300	7349.581	5823.694	4195.979	2500
V, Kg/hr	1251.699	1398.718	1525.887	1627.715	1695.979
Q, watt	1526005	775677	878285	972654	1053953
A, m2	178.95	90.9611	102.994	114.06	123.594
Steam Consumption, Kg/hr	32.8037	42.6225	58.155	85.1863	131

Backward Feed Calculations

Effect	1	2	3	4	5
Solid Balance	0.6	0.375	0.272	0.214	0.176
BPR, °C	3.3072	1.5421	0.9480	0.6670	0.5078
ΔT, °C	14.2126	12.6334	11.3701	10.3364	9.47507
T, °C	105.787	89.8468	76.9345	65.6499	55.5078
Ts, °C	102.48	88.3046	75.9864	64.9829	55
P, bar	1.98414	1.10675	0.65856	0.403	0.2501
Cp, KJ/Kg.k	2.78	3.30	3.54	3.68	3.75
H, KJ/Kg	2685.13	2659.31	2636.39	2617.06	2600.96
λs, KJ/Kg	2250.18	2287.52	2318.99	2346.34	2370.52
L, Kg/hr	2500	4263.2	6912.4	9379.8	9892.5
V, Kg/hr	8500	2763.18	2649.24	2467.37	512.74
Q, watt	6470153.254	19443944.56	6407808.909	6216017.905	5848939.358
A, m2	785.733	2280.128	751.422	728.93	685.88
Steam Consumption, Kg/hr	118.1638	70.0378	47.1009	34.1457	43.5844

VI. CONCLUSION

Based on the design and simulation of multiple effect evaporator systems using Aspen for the sugar industry, it is evident that the backward feed arrangement yields the most effective results compared to the forward feed arrangement. The utilization of steam as the heating medium for the first effect, followed by the sequential use of vapours from each effect as heating mediums for subsequent effects, coupled with the recompression of vapours from the last effect to the first, demonstrates efficient energy utilization and

optimal evaporation performance. The consistency between simulated results and design calculations further reinforces the effectiveness of the backward feed arrangement. Therefore, it can be concluded that employing a backward feed arrangement in multiple effect evaporator design for the sugar industry is a viable and efficient approach, offering significant advantages in terms of energy efficiency and process optimization.

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