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DESIGN AND PROCESS INTEGRATION OF MULTIPLE EFFECTS EVAPORATORS

Amit Meena[*1], **Mukesh Kumar**[2] **& Zelalem Weyuma**[3]
[*1]Assistant Professor, MBM, Engineering College, JNVU, Jodhpur
[2]Lecturer, Assosa University, Ethiopia

ABSTRACT

Evaporators are widely used in process industries for concentrating solutions. Heat supplied to evaporator is principally latent heat of vaporization of solvent. Evaporators are large consumers of energy. Multiple effect evaporation is most frequently used to conserve energy. Mathematical modeling serves as a valuable tool for the detailed thermal and hydraulic design of evaporation system as well as for simulation of existing unit. This report covers the detailed thermal and hydraulic design and performance analysis of multiple effect evaporators. The effect of inclusion of thermo vapor recompressor in multiple effect evaporation system is also studied. A mathematical model together with the concept of heat-path diagram is used to determine optimal design of process integrated multiple effect evaporator. The proposed mathematical model includes the effect of pressure drop on heat transfer area requirement for each effect. Available correlations are used to calculate two-phase pressure drop and corrected temperature is introduced into model equations. A case study is chosen from literature to illustrate the effect of pressure drop on area requirement. To demonstrate the application of proposed methodology, a corn glucose process plant is chosen. The capital energy trade-off for different effect systems is studied and it was found that minimum total cost occurs for process integrated triple effect system. A heat exchanger network to achieve minimum utility requirement of optimal design configuration is also proposed.

Keywords: *Evaporator, Energy, Compressor, evaporation.*

I. INTRODUCTION

Process industries require significant amount of energy in converting raw materials into final desired products. One of the energy intensive operations involved in these industries is evaporation. Process evaporators are energy intensive equipments used for concentrating a variety of solutions. The nature of solution decides the selection of evaporator. The heat supplied to evaporator is mainly latent heat of evaporation. Thus there is need to employ energy conservation techniques to reduce utility requirement and associated operating cost. Several techniques have been applied in process industries to improve economy ratio of evaporator. Multiple effect evaporation is most frequently used energy conservation technique. In multiple effect operation, several evaporators are connected in series such that vapor produced in one effect is utilized as heating medium in next effect, operating at lower pressure than the previous one. The net result of this arrangement is the multiple re-use of heat and a marked increase in the steam economy of the system. Other techniques include heat recovery exchange, condensate recovery, thermo-vapor and mechanical recompression. Traditional design of multiple effect evaporator is based on stand-alone approach in which latent heat of vaporization is supplied by steam. Other heat requirements associated with the evaporation process are sensible heat duties for heating inlet feed stream, heating/cooling of outlet product stream and cooling of condensate and vapor streams. Now that process industries are becoming energy conscious due to steeply rising fuel price, the design of evaporation system with minimum utility must be considered. In this context, process integration technique for evaporator is a valuable tool in minimizing total utility consumption and results in improved overall process efficiency.

II. MATHEMATICAL MODEL, DESIGN AND SIMULATION OF MULTIPLE EFFECT EVAPORATORS

Evaporation

Evaporation is a unit operation and consists of separation of solvent (in most cases, usually it is water) from a solution by boiling it in a suitable vessel, the evaporator. As outlined by Standiford (1963), the requirements for the correct functioning of any evaporator are:

1. Adequate heat transfer: An evaporator must be capable of supplying latent heat of vaporization of the order of 2250 kJ/kg of water evaporated. This factor determines the type, size and the cost of an evaporator.
2. Efficient vapor-liquid separation: An evaporator must separate vapor from the residual liquid in most efficient way. The separation is important on account of value of the product lost, pollution problems or fouling and corrosion on the surface on which the vapor is condensed.
3. Efficient energy use: Evaporation system consumes large amount of energy. In order to minimize the operating cost, it must make full use of the available heat. This is achieved by utilization of hot waste stream to preheat the feed, multiple effect evaporation, where vapor issuing of one effect is used as heating medium in next immediate effect and by compressing the vapor evolved either by mechanical compressor or by thermo-vapor compressor.
4. Product quality: It must be capable of handling feed materials such that its quality remains unchanged.

Types of Evaporators

In practice operating conditions for one particular solution is different from that of the other. Hence, consideration must be given to the characteristics of solution to be evaporated, method of applying heat and method of agitation while selecting a type of evaporator. A simple classification system of evaporators is as follows.

1. Evaporators involving liquid boiling by direct fire
2. Evaporators with heating medium in jackets
3. Evaporators with tubular heating surfaces and heating medium as steam
a. Horizontal tube, steam inside tubes
b. Vertical tubes, steam condensing in shell
4. Evaporators with tubes made up of special shape such as coils and hairpin tubes.

In most cases, the evaporator consists of tubular heating surface and heating medium is steam. These evaporators have high heat transfer coefficient, are easy to clean and provide large contact area for solutions. Other methods such as fire heated evaporators, those with jacket are useful for special applications. Eg., Fire heated evaporator is used in power plants; jacketed kettle is used when quantity of solution to be concentrated is small. The following section covers various types of evaporators with tubular heating surface.

Horizontal tube evaporator

This is the oldest type of evaporator and was built by Norbert Rilliux in 1843. It consists of liquor compartment and it is in the form of a vertical cylinder as shown in Figure 1. In the lower part of body, steam compartments are attached on opposite sides that closed outside by cover plates and on the inside by tube sheets. A number of horizontal tubes are fastened to these tube sheets. As steam is introduced in one steam chest, it flows through the tubes, washing condensate and non condensable, which are withdrawn from the opposite steam chest. This is most important advantage of horizontal tube evaporators that, they do not allow condensate and air blanketing over the useful surface. In addition, they require small headroom. This design didn’t survive long because of its inability to produce circulation and turbulence in liquid pool and is least satisfactory for solutions, which form scale or deposits and crystallize (Badger, 1955).

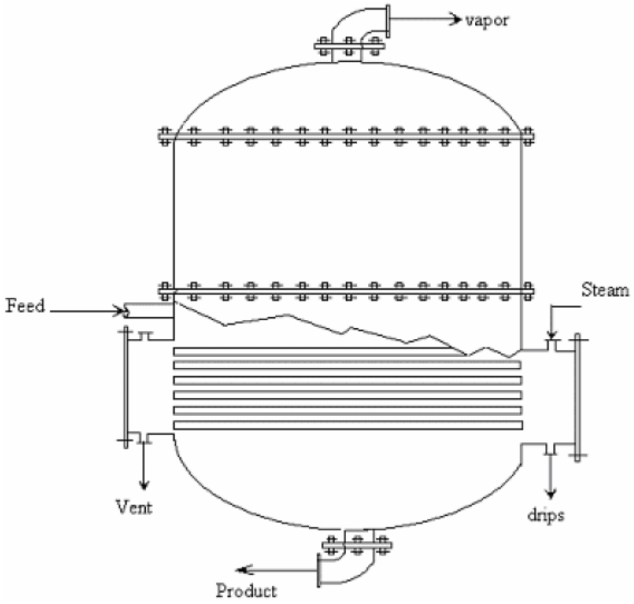

Figure 1 Horizontal tube evaporator

Effect of Operating Conditions on Evaporator Performance

Effect of feed temperature

The solution inside an evaporator will be at the final concentration and at the boiling temperature. Therefore feed rate should be adjusted such that the average temperature of the boiling solution in the evaporator is not appreciably affected. If the feed were introduced below its boiling point, there would be probability of areas in the evaporator where the solution temperature is below at its boiling point. If the feed is extremely cold then it is desirable to have an external heater.

Effect of superheat and condensate temperature

If the steam or vapor used as heating medium contains moderate amount of superheat then it has no effect on the mean temperature of the steam or vapor. The amount of heat transferred as superheat is usually fraction of the total heat that superheat in the steam is neglected. In practice, the sub cooling of condensate is only a few degrees. The sensible heat recovered from cooling the condensate is so small compared to the latent heat of the steam that this sensible heat is usually neglected.

Choice of steam pressure

The true temperature difference (ΔT) in capacity equation of an evaporator is the difference between the saturation temperature of the condensing steam and the boiling point temperature of the solution. It is possible to use high-pressure steam (high saturation temperature) and thus decrease size of the evaporator. However, high-pressure steam is more valuable as source of power in steam power plants than it is as a source of heat. Another fact is that high-pressure steam requires more expensive material of construction. The sum of the above consideration is that low-pressure steam for the evaporator would be cheap and would contain more latent heat as compared to that of high-pressure steam.

Effect of fouling factor

'Fouling' is a general term that includes any kind of deposition of material upon the heat transfer area during the operation of evaporator. Fouling offers an additional resistance to heat transfer and reduces operational capacity of an evaporator considerably. If the deposits are heavy enough, it may interfere the fluid flow and increase the pressure drop.

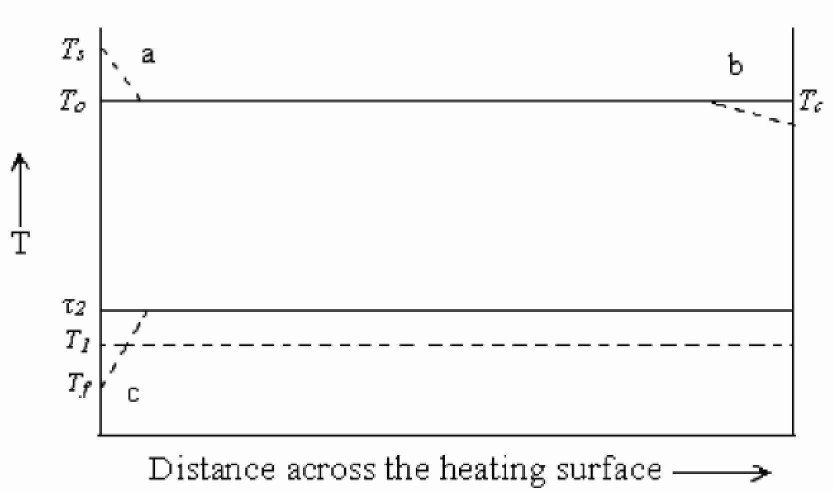

Figure 2 Effects of operating conditions (Badger, 1955).

The feed enters at Tf and the boiling point of pure water corresponding to the pressure in the vapor space is $T1$. Because of *BPR*, the solution boils at $\tau 2$. The saturation temperature of steam is To with some superheat at Ts. The condensate is cooled to few degrees up to Tc. The true temperature difference will be, $\Delta T = Ts - \tau 2$. The triangles a, b and c represents effect of superheat, sub-cooling and feed temperature respectively (Badger, 1955).

Multiple Effect Evaporator

Multiple effect evaporation systems are widely used because of their ability to use the energy in most efficient way. The general principle is that, the effects are interconnected by piping, such that the vapor evolved in one evaporator serves as the heating medium for the next one. If the feed to the effect is at a temperature near the boiling point temperature in the first effect, 1 kg of steam will evaporate almost 1 kg of water. The first effect operates at a higher pressure so that the vapors generated can be used as heating medium in the next effect. The performance of multiple effect evaporator is evaluated by defining steam economy, which is the ratio of quantity of water evaporated to the quantity of steam consumed. As number of effects increases, steam economy improves, however, at the expense of increased heat transfer area of evaporator.

Operation of multiple effect evaporator

Considering Figure 2.6, imagine that the whole system is cold, at atmospheric pressure and that each evaporator body is filled with the liquid to be evaporated. Now imagine that the vacuum pump is started and that the valves CV1, CV2, CV3 in the non-condensable vent lines are open. Let it be assumed that vacuum to be carried out during operation be 26 in. Hg. All the other valves are closed. It follows that through the non-condensing gas lines and through the steam lines the whole of the apparatus will be evacuated down to 26 in. Hg. Now assume that the steam valve S1 and the condensate valve D1 are opened until the desired pressure *Po* is built up in the steam space of evaporator-1. Let *To* be the temperature of saturate steam at the pressure *Po*. The steam will displace any residual air in the steam space of evaporator-1 through the vent valve CV1.when the air is displaced vent, valve CV1 is closed. Since the liquid surrounding the tubes is cold, steam will condense. The trap allows the condensate to escape as fast as it collects. The liquid becomes warmer until it reaches the temperature at which it boils at vacuum of 26 in. The vapor so generated will gradually displace the air in the upper part of the evaporator-1, in the connecting steam line, and in the steam space of evaporator-2. When this vapor is filled in steam chest of evaporator-2, vent valve CV2 is closed. The steam that is coming off from evaporator-1 will transmit its heat to the liquid in evaporator-2 and be condensed. Condensate valve D2 will be opened so that this condensate will be removed as fast as it is formed. In condensing, however, it gives up its heat to the liquid in evaporator-2, which then becomes warmer. As the liquid becomes warmer, the temperature difference between it and the steam becomes less, the rate of condensation becomes less, and therefore the pressure in the vapor space of evaporator-1 will gradually build up, increasing $\tau1$(boiling point of the solution in effect) and cutting down the temperature difference $To- \tau1$. This will continue till the liquid in evaporator-2 reaches a temperature corresponding to vacuum of 26 in Hg. The same process will be repeated in evaporator-3. As the liquid in evaporator-3 becomes warmer and finally begins to boil, the temperature drop between it and the steam from the second evaporator becomes less and pressure begins to build up in the second evaporator and raises $\tau2$, so that the temperature difference $T1- \tau2$ becomes less. This decreases the rate of condensation and build up the pressure in the vapor space of the first evaporator still more, until finally the evaporator comes to a steady state with the liquid boiling in all three bodies. The result of boiling will be decrease in the liquid levels. As soon as the level begins to come down in evaporator-1, the feed valve F1 to keep level constant. As the liquid in evaporator-2 begins to boil, feed valve F2 will be adjusted, and, as the liquid in evaporator-3 boils, feed valve F3 will be adjusted. When the liquid in evaporator-3 reaches desired concentration, the thick solution is removed through valve T. The evaporator is now in continuous operation with a continuous flow of liquid through it, and all the various temperature and pressures are in balance (Badger, 1955).

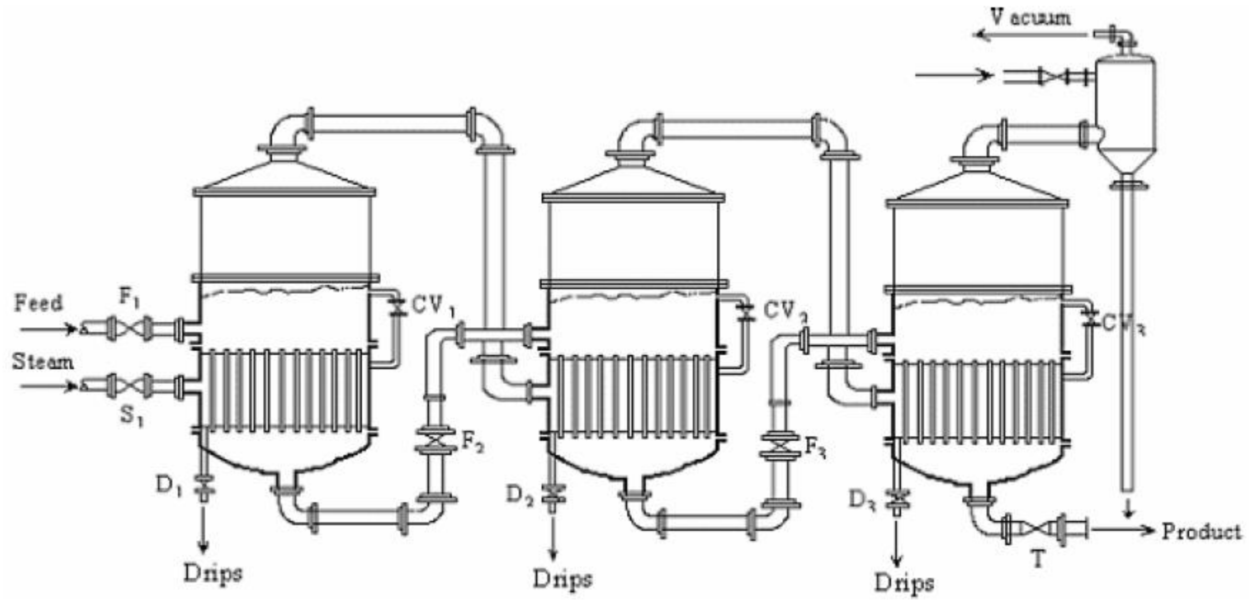

Figure 3 Operation of multiple effect evaporator

Mathematical Model for Multiple Effect Evaporator

In diagram an individual effect in a multiple effect evaporation system is shown, The liquid product stream, $Li-1$, is available from the (i-1)th effect and this is feed to the ith effect. It may be noted that Lo denotes the external feed flow rate to the first effect. The vapor product stream, $Vi-1$, is available from the ($i-1$)th effect and this is fed to the ith effect for heating. For the first effect, external utility such as steam is provided to transfer heat for evaporator. The vapor condenses at its saturation temperature corresponds to its pressure of ($Pi-1-\Delta Pi-1$). The vapor from the last effect is fed to a condenser and liquid product stream is withdrawn as a desired product.

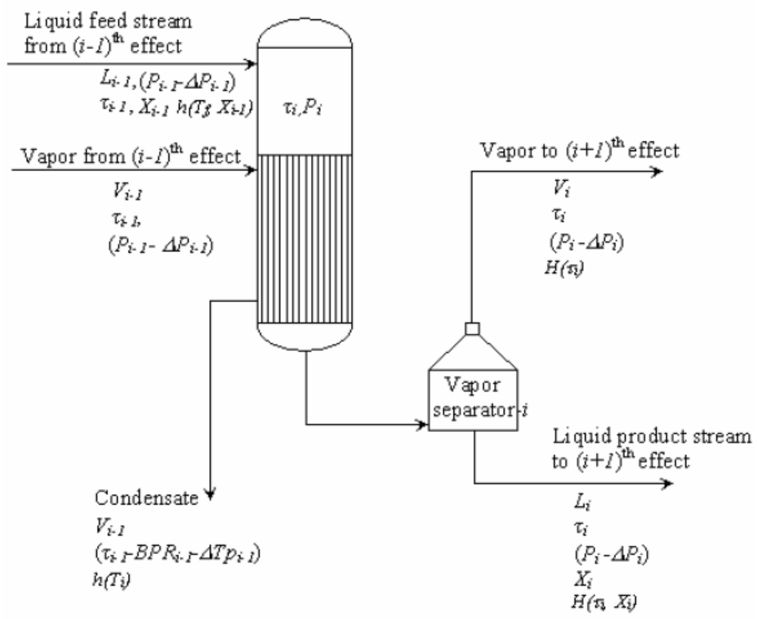

Figure 4 An ith effect evaporator

The following assumptions are made while deriving model equations (Holland, 1975).
1. Solute concentration in vapor stream is negligible.
2. Condensate leaves at its saturation temperature.
3. The degree of superheat (*BPR*) available in condensing vapor stream is negligible.
The overall material balance yields,

$$L = L + V \qquad (1)$$

Solute balance is,

$$L X = L X - 1 - 1 \qquad (2)$$

Case Study-1: Caustic Soda Triple Effect Forward Feed Evaporator

Problem definition: It is required to design a triple effect, feed forward evaporation system which can concentrate 5.04 kg/s of a 20% concentrated caustic soda solution to a final concentration of 50%. The feed enters at 93.33 °C and saturated steam is available at 176.66 °C. The last effect operates at saturation temperature of 37.46 °C.

The variables associated with the model equations can be represented by constitutive relationships. These are described below and pertain to the caustic soda solution. The correlations for determining various properties as well as the error are taken from literature.

1. Boiling point of caustic soda solution (Holland, 1975)

$$\tau = (1.0 + 0.1419526X)T + 150.75706X\ 2 - 2.7095138X \qquad (3)$$

2. Overall heat transfer coefficient (Zain and Kumar, 1996)

$$U = 977.66(\tau / X)0.2823 \text{ ; Error } \pm 3.53\% \qquad (4)$$

3. Latent heat of vaporization of steam (Zain and Kumar, 1996)

$$\lambda = -80.345T - 21035.87 / T + 2049.123\ T - 4213.519\ln(T) + 0.0918T\ 2$$
$$-1.04\times10-04T3 + 8597.953 \text{ ; Error } \pm 0.85\% \qquad (5)$$

4. Enthalpy of saturated and superheated steam (Zain and Kumar, 1996)
$H = 4.154T + 2.0125\times10-04T + 1.62(\tau - T) + 2.0285\times10-04\ (\tau\ 2 - T\ 2)$
$-0.3747\times10-07\ (\tau\ 3 - T3) + \lambda$; Error ± 1.2% (6)

5. Enthalpy of condensate at its saturation temperature (Zain and Kumar, 1996)
$h = 0.103527 + 4.18625T$; Error ± 0.66% (7)

6. Enthalpy of caustic soda solution (Zain and Kumar, 1996)
$h = 2.596971 + 158.896827X + 3.745764\tau - 2594.5098X\ 2 - 3.758577X\tau +$
$0.004723\tau\ 2 + 9164.489089X\ 3 + 11.005268X\ 2\tau - 0.002463X\tau\ 2 -$
$0.000031\tau\ 3 - 5913.313486X\ 4 - 12.344381X\ 3\tau - 0.010289X\ 2\tau\ 2$
$+0.000046X\tau\ 3$; Error ± 2.2 % (8)

The specified variables for design of caustic soda triple effect forward feed evaporator are listed in Table 1 (Holland, 1975).

Table 1. Input data for design of forward feed triple effect evaporator

Feed rate kg/h	18144
Feed concentration	0.2
Feed temperature ^{o}C	93.33
Steam temperature ^{o}C	176.66
Final desired concentration	0.5
Last effect saturation temperature ^{o}C	37.46
Number of effects	3
Liquid flow pattern	Forward feed

The scaled variables are,
1. Steam consumption (Vo) = *Vo/F*
2. Boiling point of solution in first effect (uu1) = *τ1/To*
3. Saturation temperature in first effect (u1) = *T1/To*
4. Solute concentration at first effect evaporator outlet = *X1*
5. Liquid flow rate at first effect outlet (L1) = *L1/F*
6. Boiling point of solution in second effect (uu2) = *τ2/To*
7. Saturation temperature in second effect (u2) = *T2/To*
8. Solute concentration at second effect outlet (X2)
9. Liquid flow rate at second effect outlet (L2) = *L2/F*
10. Area of each effect (a) = *A/ (F*40)*
11. Boiling point of solution in third effect (uu3) = *τ3/To*
12. Liquid flow rate at third effect outlet (L3) = *L3/F*

The model equations are solved by Newton Raphson technique. MATLAB programming is used to solve these sets of model equations. The convergence criteria used is norm and a norm of 10-9 resulted convergence in six iterations. A numerical differentiation of the variables is carried out with an increment of 10-5 to compute Jacobian. If we change the order of the variables (for e.g. Vo, uu1, X1, u1, L1, uu2, u2, X2, L2, a, uu3, L3), it doesn't affect the convergence. The initial guess used for each scaled variable is 0.5 and solution of simultaneous equations is shown in Table 2. The results obtained are comparable with those obtained by Holland (1975).

Table 2. Input data for design of forward feed triple effect evaporator

Scaled variable	Design results	Results of Holland (1975)
V_o	0.3037	0.3046
uu_1	0.8708	0.8690
u_1	0.7954	0.7959

X_1	0.2455	0.2436
L_1	0.8143	0.8207
uu_2	0.6937	0.6967
u_2	0.5802	0.5867
X_2	0.3275	0.3250
L_2	0.6105	0.6152
a	0.3927	0.3913
uu_3	0.4327	0.4327
u_3	0.4	0.4

The scaled variables are now descaled to obtain the design parameters.
1. Steam consumption (*Vo*) = Vo* *F* = 5510.67 kg/h
2. Boiling point of solution in first effect ($\tau 1$) = uu1 * *To* = 153.84 oC
3. Saturation temperature in first effect (*T1*) = u1 * *To* =140.52 oC
4. Solute concentration at first effect outlet (*X1*) = X1 = 0.2455
5. Liquid flow rate at first effect outlet (*L1*) = L1 * *F* =14776 kg/h
6. Boiling point of solution in second effect ($\tau 2$) = uu2 * *To* = 122.56 oC
7. Saturation temperature in second effect (*T2*) = u2 * *To* = 102.58 oC
8. Solute concentration at second effect outlet (*X2*) = X2 =0.327
9. Liquid flow rate at second effect outlet (*L2*) = L2 * *F* = 11067 kg/h
10. Area of each effect (*A*) = a * *F* *40 = 79.174 m2
11. Boiling point of solution in third effect ($\tau 3$) = uu3 * *To* = 76.66 oC
12. Liquid flow rate at third effect outlet (*L3*) = L3 * *F* = 7257.6 kg/h
13. Steam economy = 1.97

The steam economy, which is the ratio of quantity of water evaporated to the steam consumed by first effect, is poor (1.97) and is mainly due to lower temperature (93.33 oC) of the entering feed than first effect temperature (153.84 oC). A portion of steam is utilized in raising the feed temperature to its boiling point. The boiling point rise (*BPR*) continues to increase from first effect (13.3 oC) to last effect (39.4 oC) and this is because *BPR* is a function of concentration of solute alone. The design results obtained by solving model equations for case study-1 using MATLAB programming matched with those obtained by Holland (1975). This validates the MATLAB code.

Pressure Drop Consideration

The effect of pressure drop on available temperature difference was neglected in the mathematical model proposed by Holland (1975). However, the evolved vapor from each effect experience acceleration, gravity and static pressure loss that must be accounted in designing the evaporation system. Increase in pressure drop results in lowering of saturation temperature of vapor condensing in the steam chest of next effect, which in turn reduces the driving force available for heat transfer and increases the area requirement. Lockhart and Martinelli (1949) have proposed correlations for calculating pressure drop in evaporator and condensers (see Appendix-A). The pressure drop calculated is deducted from the saturation pressure of the vapor issued from the effect and the saturation temperature of vapor corresponding to this corrected pressure is used in capacity equation for calculating heat transfer area. To study the effect of pressure drop on heat transfer area requirement, the model equations are solved with the inclusion of corrected saturation temperature of condensing vapor in model equations. The scaled variables are descaled and results are tabulated in Table 3.

Table 3. Design results after pressure drop consideration

Design variables	Design results without pressure drop consideration	Design results with pressure drop consideration
Steam consumption (V_o) kg/h	5510.67	5525.13
Boiling point of solution in first effect (τ_1) °C	153.84	154.22
Saturation temperature in first effect (T_1) °C	140.52	140.86
Solute concentration at first effect outlet (X_1)	0.2455	0.2456
Liquid flow rate at first effect outlet (L_1) kg/h	14776	14771
Boiling point of solution in second effect (τ_2) °C	122.56	123.48
Saturation temperature in second effect (T_2) °C	102.58	103.48
Solute concentration at second effect outlet (X_2)	0.3275	0.3277
Liquid flow rate at second effect outlet (L_2) kg/h	11067	11080
Area of each effect (A) m2	79.174	82.186
Boiling point of solution in third effect (τ_3) °C	76.66	76.66
Liquid flow rate at third effect outlet (L_3) kg/h	7257.6	7257.6

The pressure drop calculated for each effect is given below.

1. Pressure drop in first effect = 0.02024 bar
2. Pressure drop in second effect = 0.06343 bar
3. Pressured drop in third effect = 0.0022326 bar

From Table 3 it is clear that, the steam consumption increases by 14.46 kg/h and is mainly due to increase of boiling point in first effect. The concentration at the outlet of first and second effect are improved, though in small quantity, is due to the consideration of pressure drop which results in thin film at the walls of tube and thus improved heat transfer coefficient. It can be observed from the design results that pressure drop have resulted in 3.5% increase in area requirement than that of without pressure drop consideration.

Performance Analysis of Forward Feed, Multiple Effect Evaporator

Steady state mathematical model is also used for simulation of multiple effect evaporator. In this case, heat transfer area is treated as specified variable and it is required to find out the product concentration.

Specification: F, X_f, T_f, P_o, T_o, P_3 (or T_3), U_1, U_2, U_3, L_3, A (or A_1, A_2, A_3), forward feed flow pattern.
To find: V_o, τ_1, T_1, X_1, L_1, τ_2, T_2, X_2, L_2, X_3, τ_3, and L_3

For evaluating the performance of the caustic soda, triple effect, forward feed evaporator, the input data is taken from the same case study-1 except that area is specified instead of final desired concentration. The specified variables for simulation case are listed in Table 4

Table 4. Input data for simulation of triple effect forward feed evaporator

Feed rate kg/h	18144
Feed concentration	0.2
Feed temperature °C	93.33
Steam temperature °C	176.66
Area of each effect m^2	82.186
Last effect saturation temperature °C	37.46
Number of effects	3
Liquid flow pattern	Forward feed

The results of simulation after descaling the simulation variables are listed in the following Table 5.

Table 5. Simulation results for triple effect forward feed evaporator

Simulation variables	Simulation results
Steam consumption (V_o) kg/h	5524.84
Boiling point of solution in first effect (τ_1) °C	154.22
Saturation temperature in first effect (T_1) °C	140.86
Solute concentration at first effect outlet (X_1)	0.2456
Liquid flow rate at first effect outlet (L_1) kg/h	14771
Boiling point of solution in second effect (τ_2) °C	123.578
Saturation temperature in second effect (T_2) °C	103.49
Solute concentration at second effect outlet (X_2)	0.3277
Liquid flow rate at second effect outlet (L_2) kg/h	11080.5
Final desired concentration	0.5
Boiling point of solution in third effect (τ_3) °C	76.66
Liquid flow rate at third effect outlet (L_3) kg/h	7257.6

The final desired concentration of 0.5 which was used as an input for design case is calculated in simulation case and found exactly the same. Thus, given the area of the multiple effect evaporator, the performance of the existing system can be evaluated.

Effect of Operating Conditions on Evaporator Design

Effect of feed temperature

If the feed to the evaporator system is below its boiling point then additional heat must be supplied as sensible heat to raise its temperature to its boiling point. If the feed enters at temperature above its boiling point, some flashing occurs in the effect to which it is fed and results in improved steam economy. Therefore it is advantageous to preheat the feed up to its boiling point before feeding it into an effect. The area requirement also reduces as feed enters at its boiling point. Following Table 6 shows the effect of feed temperature on steam temperature and area requirement.

Table 6 Effect of feed temperature

Temperature °C	Steam consumption kg/h	Area requirement m^2
93.33	5525.132	82.18
100	5326.313	81.09
110	5032.64	79.47
120	4745.25	77.88
130	4465.26	76.33
140	4193.77	74.83
154	3830.06	72.82

From Table 6 it is clear that 30.67% saving in steam consumption and 11.38% saving in area requirement is possible if feed enters at its boiling point. The cost involved in providing additional area required by heat exchanger which will be of shell and tube type will be less as compared to savings obtained from saved steam quantity and saved area. Since, area of evaporator will be of calendria type which is about four times expensive than shell and tube heat exchanger, feed preheating helps to minimize the total cost of evaporator system. The feed preheating using heat integration with background process will be a good option to minimize the total cost. Following Figure 6 shows the variation of steam consumption and area with feed temperature.

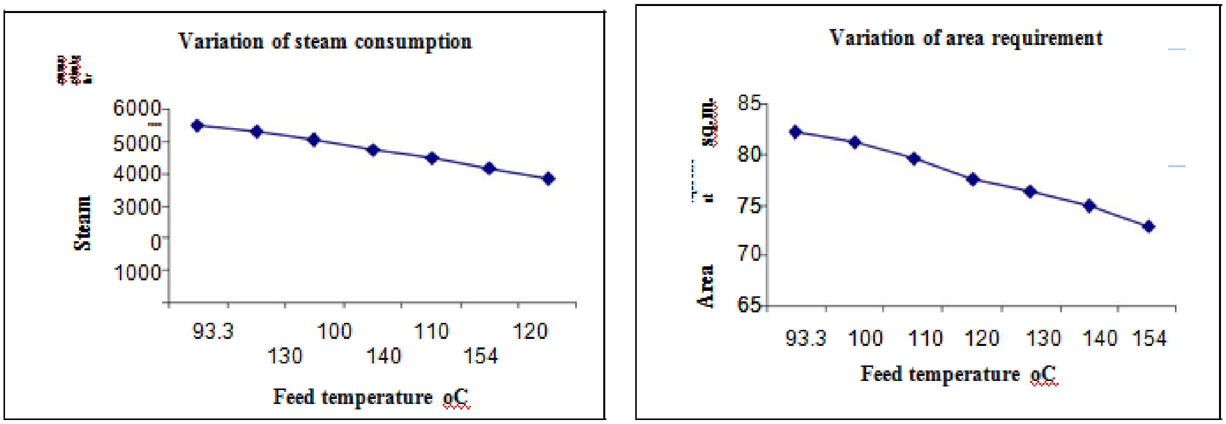

Figure 4 Variation of steam consumption and area with feed temperature

III. PROPOSED METHODOLOGY AND RESULT

The proposed methodology is shown in the following Figure 6. First we choose the number of effects. The input data for design of evaporation system is specified. The specified variables are feed rate, feed concentration, feed temperature, steam pressure or temperature, final desired concentration and last effect temperature. For initial guess $q^{+}_{sen,i}$ and $q^{-}_{sen,i}$ terms are assumed as zeroes and mathematical model is solved for utility consumption, intermediate liquid flow rates, intermediate concentrations, effect temperatures and corresponding saturation temperatures and heat transfer requirement. This provides a set of evaporator streams which are to be process integrated with the background streams. This stream data is used to generate a heat path diagram to compute $q^{+}_{sen,i}$ and $q^{-}_{sen,i}$. The latest $q^{+}_{sen,i}$ and $q^{-}_{sen,i}$ values are substituted in model equations and the procedure is repeated until utility consumption converges. The final iteration provides utility and evaporator area requirement. Countercurrent area targeting and unit targeting is carried out to determine the heat exchange area and the number of units. Total cost comprising capital and operating cost is calculated. The same procedure is carried out by varying the number of effects. The total cost is plotted against number of the effects to arrive at the optimum number of effects.

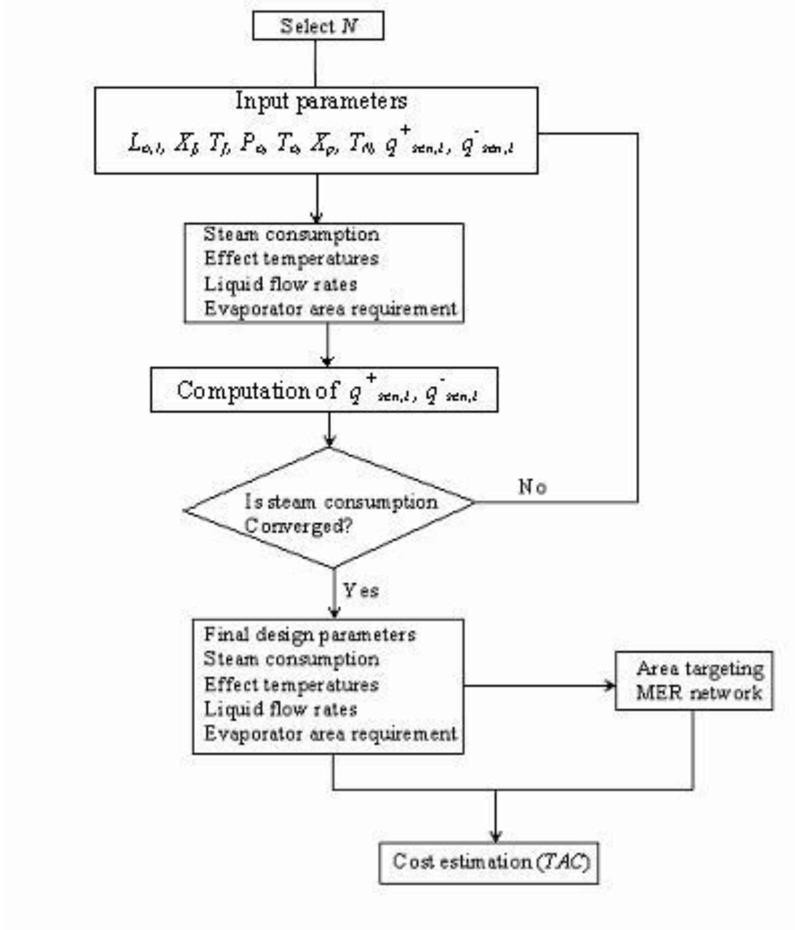

Figure 5 Algorithm for proposed methodology

Optimal Design of Process Integrated Evaporation System

The optimum design of multiple effect evaporation system refers to determination of optimum number of effects satisfying capital-energy trade-off. The capital cost of the process integrated evaporation system consists of evaporator area cost and heat recovery exchanger cost. The utility costs like steam and cooling water cost constitutes operating cost. As we increase the number of effects, operating cost decreases at the expense of additional evaporator area cost. The optimum number of effects then can be found by plotting total annualized cost (comprising both capital and operating cost) against number of effects.

A corn glucose manufacturing process is chosen as a case study to illustrate the proposed methodology. The process description and flow sheet is shown in Figure 7. The raw material used for producing corn syrup is starch slurry. The starch slurry of concentration 36%, at 30 °C and 6 bar is adjusted to a pH of 1.8 and is fed to converter for acid hydrolysis. High-pressure steam at 180 °C (8 bar) is used to provide the heat requirement of the converter. The hydrolysate from converter is fed to a flash chamber operating at 85 °C where water vapor is separated. Liquid syrup from the bottom of the flash tank is then fed to a carbon treatment unit at 85 °C to decolorize the syrup and then filtered. The syrup is passed through ion exchange units at 55 ºC to remove Ca^{+2} and Na^{+2} ions. The outlet of the ion exchange unit is a clear syrup which is again carbon treated at 70 ºC and filtered. The treated syrup is fed to falling film type multiple effect evaporator which concentrates liquid syrup from 40.75% to a final concentration of 82%. The product from third effect is stored and packed in containers. There are three process hot streams (H1, H2, and H3) and three process cold streams (C1, C2, and C3) available for process integration.

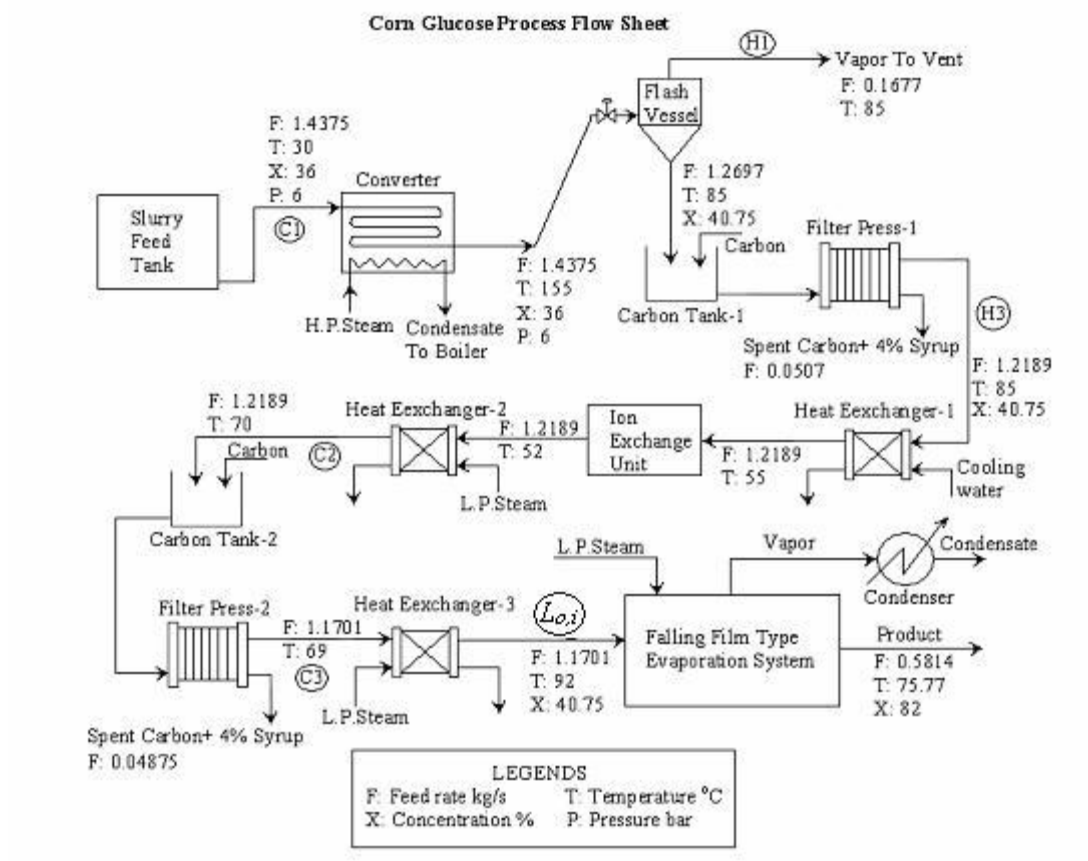

Figure 6 Corn glucose process flow sheet

The input data for evaporation system is extracted from Figure 7 and is listed in Table 7. The computation of total annualized cost for process integrated triple effect system is shown here to illustrate the proposed methodology.
Input data: $L_{o,1}$, X_f, T_f, P_o, T_o, P_3 (*or* T_3), X_3, equal areas, forward feed flow pattern.
To find: $V_{o,1}$, τ_1, T_1, X_1, $L_{1,2}$, τ_2, T_2, X_2, $L_{2,3}$, A, τ_3, and $L_{product}$

There are twelve equations (four equations per effect) and are solved for twelve unknowns i.e. $V_{o,1}$, τ_1, T_1, X_1, $L_{1,2}$, τ_2, T_2, X_2, $L_{2,3}$, A, τ_3, and $L_{product}$. For evaluating overall heat transfer coefficients in falling film type evaporators, Chen and Seban (1962) correlations are used. The constitutive relationships for evaluating properties of corn glucose syrup are listed in Appendix-E. Before solving these equations, it is necessary to scale the variables appearing in them in order to reduce the magnitude of the terms. The scaling methodology as proposed by Holland (1975) is adopted for computation purpose.

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Table 7. Input data for design of evaporation system

Feed rate kg/h	4212.36
Feed concentration %	40.75
Feed temperature °C	92
Steam temperature °C	127.4
Final desired concentration %	82.00
Last effect saturation temperature °C	67
Number of effects	3
Liquid flow pattern	Forward feed

The methodology explained so far is applied by varying number of effects. The steam consumption, cooling water consumption, evaporator area and heat exchanger area is calculated for each case. The total annualized cost comprising operating and capital cost is then determined. Following Table 8 shows cost data for different utilities and exchangers (Westphalen and Maciel, 2000).

Table 8. Cost data for different utilities and exchangers

L.P. Steam cost $/ton	5.29
H.P. Steam cost $/ton	7.00
Cooling water cost $/1000 m^3	20.0
Heat exchanger cost $/$m^2$	$1525.35+(327.79A_H^{0.73})$
Evaporator cost $/$m^2$	$9215.36A^{0.54}$
Operating hours per year	8500
Life time of equipment	10
Interest rate %	12

Following Table 9 lists the utility and heat transfer area requirement for single, double, triple, quadruple and penta effect evaporator which is integrated with the corn glucose process.

Table 9. Utility and heat transfer area requirement for different effect systems

Effects	L.P.Steam tons/year	H.P.Steam tons/year	Cold utility m^3/year	Evaporator area per effect m^2	Heat exchanger area m^2
1	17943	2895	239347	11.89	178.65
2	9997	2895	248264	12.42	235.52
3	7463	2895	250968	13.21	256.22
4	6251	2895	252283	14.23	268.92
5	4810	2981	276693	15.62	308.28

The total annualized cost is for different effect system is shown in Table 10

Table 10 Total annualized cost for different effect systems

Effects	Annualized capital cost $/year	Operating cost $/year	Total annualized cost $/year
1	16256	119979	136235
2	26502	78118	104621
3	36757	64769	101526

4	47034	58385	105420
5	60296	51849	112146

It is clear that minimum total cost occurs when number of effects is three. Following Figure 8. shows capital energy trade-off for process integrated evaporation system.

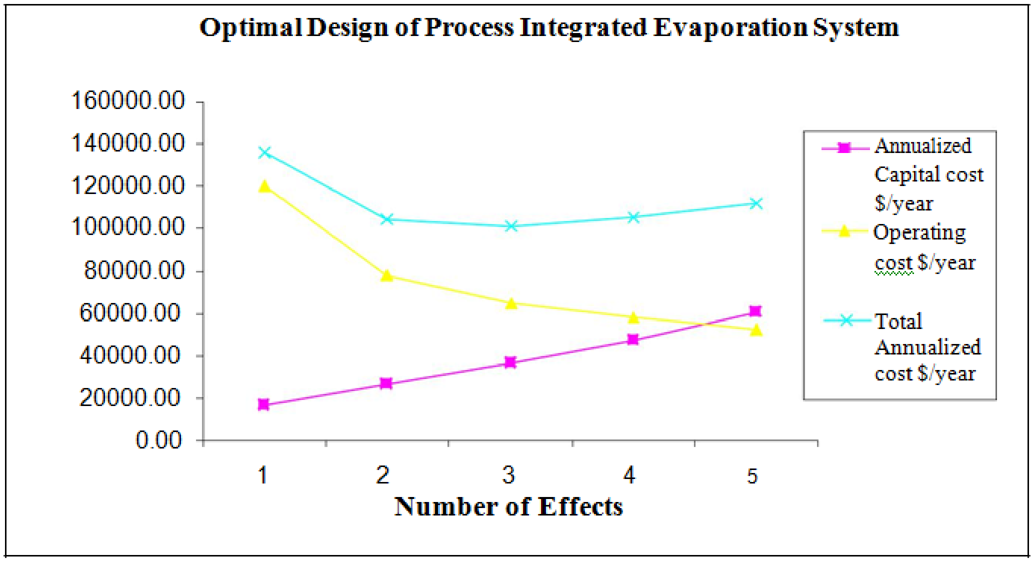

Figure 7 Optimum number of effects

IV. CONCLUSION AND FUTURE SCOPE

Steady state mathematical model of evaporation system serves as a valuable tool to carry out thermal design of a new evaporation system as well as to evaluate the performance of existing unit. The design case for both forward feed and backward feed pattern were studied. It is found that the forward feed pattern results in better steam economy as compared to that backward feed pattern when the feed temperature is near its boiling point. The effect of pressure drop on available temperature difference, which was neglected in the model equations, was considered. For Case study-1 it is found that pressure drop results in an increase of 3.5% in area requirement. For multiple effect evaporator-TVR configuration, the optimization of vapor bleed fraction was studied and it was found that thermo vapor compressor results in energy savings of in L.P. steam. The mathematical model together with the concept of heat-path diagram is used to determine optimal design of process integrated multiple effect evaporator. The capital energy trade-off for different effect systems is studied for Case study-1 and it was found that minimum total cost occurs for process integrated triple effect system. A heat exchanger network to achieve minimum utility requirement of optimal design configuration is also proposed.

There is a need to study the energy savings possible by incorporating mechanical vapor recompressor, condensate flashing and heat recovery exchangers into multiple effect evaporation system. The principles of process integration technique can be applied to retrofit type of problems where the area of each evaporator specified. It is then required to find out the additional evaporator and heat exchanger area of network required for achieving minimum utility target. In retrofit case, an economic analysis can be carried to study the effect of energy savings possible on overall total annualized cost.

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