# Steady State Design of Triple-effect Evaporator

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Abstract

Evaporation is the removal of a volatile solvent as vapor from a solution. It is commonly used to concentrate solutions. This process is achieved by a single or, as widely used, multiple-effect evaporators in series. Operation of evaporators involves simultaneous heat and mass transfer. Modeling these systems, therefore, results in a set of nonlinear algebraic equations. This paper presents a case study which is applied to a triple-effect evaporator system used to produce 40,000 tons/year of 80% by weight sodium chloride solution from a 40% by weight fresh feed sodium chloride solution. The product is further dried and packed as table salt. Feed forward operation with equal heat transfer areas of the effects is employed. A computer program using **FORTRAN** language is employed to solve the set of non-linear algebraic equations which involves a trial and error procedure. The convergence of the steady state solution is speeded up by a proper pre-calculation of the initial data required to run the program. The results show that the heat transfer area of each effect, the fresh steam consumption rate, and the steam economy are 24.0 $m^2$, 1762.4 kg/hr, and 2.87, respectively.

**Keywords:** triple-effect evaporator, steam consumption, steam economy.

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## Introduction

The separation of a volatile solvent from a solution to obtain a more concentrated solute is effected by an operation known as evaporation. This is carried out by a single or most often multiple-effect evaporators. The desired product in an evaporation process is usually the concentrated solution, but occasionally the evaporated solvent is the primary product as, for example, the evaporation of sea water to produce potable water. Typical industrial application includes concentration of dilute solutions such as sodium chloride, sodium hydroxide, fruit juices, and other chemicals. Basically, an evaporator consists of a heat transfer unit capable of boiling the solution and a device to separate the vapor from the boiling liquid. Almost always, the solution to be evaporated flows inside the tubes of the heat transfer unit and the heating medium is a low pressure, below 3 atmosphere absolute, steam. Evaporators are designed in different types and shapes. These include horizontal-short-tube evaporators, and vertical-long-tube evaporators with natural or forced circulation. They come also in different feeding patterns such as forward, backward, and mixed feeding. The selection of the appropriate evaporator type is a matter of economics. However, some properties of the solution being evaporated may limit these choices, such as concentration, viscosity, temperature sensitivity, foaming, scaling tendency, and corrosive nature of the solution which may require a special material of construction (McCabe, W., Smith, J., Hariott, P., (1993), pp 427-458). Figure 1 shows a typical triple-effect evaporator with forward-feed system. The fresh dilute solution and fresh steam are fed in parallel to the first effect. This system has an advantage over other patterns that, except for the fresh dilute solution and the final concentrated solution (product liquor), no pumps are needed to move the solution from one effect to the other due to availability of pressure drop between the effects in the direction of flow. Connections are made so that vapor from one effect is used to boil the solution in the next. Boiling in the first effect is done by the fresh steam that is supplied from an external steam supply. In order to reduce the boiling point temperature in the three effects the system is connected to an air ejector to establish a vacuum spread across the effects. In steady state operation the flow rates and evaporation rates are such that neither solvent nor solute accumulates or depletes in any effect. This ensures that all internal concentrations, temperatures, and pressures are kept constant (Holland, c., (1975), pp 10-22).

## 2 System Modeling

The steady state model of the triple-effect evaporator is derived by applying energy and mass balances around each effect as follows:

**First effect:**

Total mass balance:  $F = L_1 + V_1$  (1)

Solute (NaCl) mass balance $Fx_f = L_1x_1$  (2)

Energy balance:  $Fh_f + Q_1 = L_1h_1 + V_1H_1$ (3)

Heat transfer rate equation:  $Q_1 = V_0\lambda_1 = U_1A_1\Delta T_1$  (4)
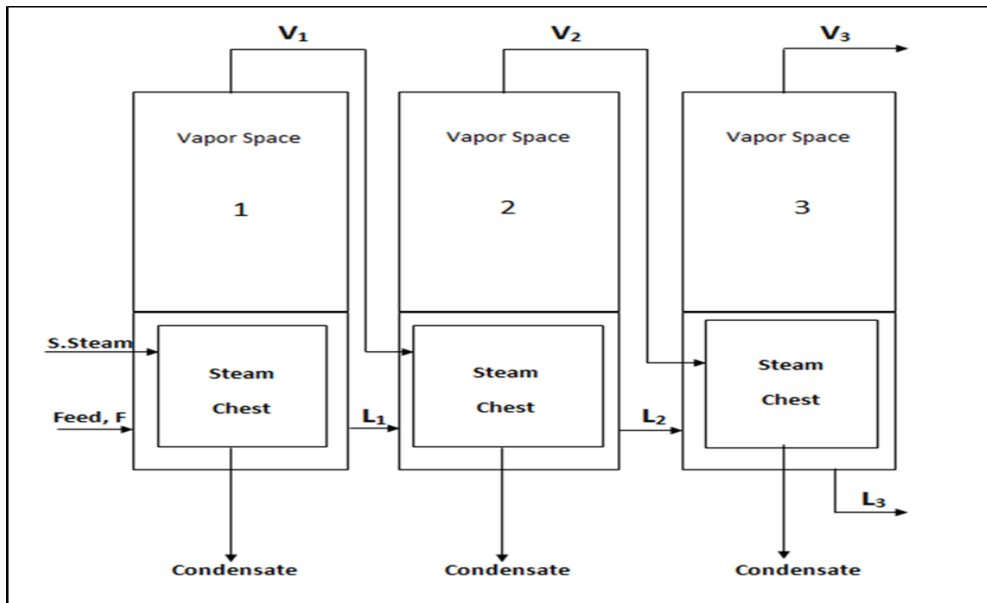
Where, $\Delta T_1 = T_0 - T_1$



Figure 1: Triple-effect Evaporator with Forward Feed

**Second effect:**

Total mass balance: $L_1 = L_2 + V_2$  (5)

Solute (NaCl) mass balance: $L_1x_1 = L_1x_2$  (6)

Energy balance:  $L_1h_1 + Q_2 = L_2h_2 + V_2H_2$ (7)

Heat transfer rate equation  $Q_2 = V_2\lambda_2 = U_2A_2\Delta T_2$  (8)

Where, $\Delta T_2 = T_1 - T_2$

**Third effect:**

Total mass balance: $\mathbf{L_2 = L_3 + V_3}$ (9)

Solute (NaCl) mass balance: $\mathbf{L_2 x_2 = L_3\, x_3}$ (10)

Energy balance: $\mathbf{L_2 h_2 + Q_3 = L_3\, h_3 + V_3 H_3}$ (11)

Heat transfer rate equation: $\mathbf{Q_3 = V_3 \lambda_3 = U_3 A_3 \Delta T_3}$ (12)

Where, $\mathbf{\Delta T_3 = T_2 - T_3}$

The enthalpy of the salt solutions, namely, $h_1$, $h_2$, and $h_3$ are calculated from the following equations:

$$h = \int_{Tref}^{T} CpdT \qquad (13)$$

$$\mathbf{Cp = \Sigma\, x_i\, Cp_i = x_1 Cp_1 + x_2 Cp_2} \quad (14)$$

Where, $x_1$ and $x_2$ are the mass fraction of the solute and the solvent and $Cp_1$ $Cp_2$ are the heat capacity of pure solute (NaCl) and pure solvent ($H_2O$), respectively. Since $V_1$, $V_2$, and $V_3$ are pure solvent ($H_2O$) vapor (steam), steam Table is used to obtain enthalpies and latent heat of condensation (Foust, A., et.al., 1960, pp 361-368 and Himmelblau, D., 1974, pp 99-635).

## 3 Calculation Procedure

Some common assumptions are applied to simplify the simultaneous solution of the equations above in order to get a set of preliminary design parameters of this system. The assumptions employed in this study are (Holland, c., (1975), pp 10-22):

Negligible boiling point rise (BPR).

The effects have equal areas, i.e. $A_1 = A_2 = A_3 = A$.

Equal evaporation rates in each effect, I.e. $V_1 = V_2 = V_3 = V$.

Equal rates of heat transfer, I.e. $Q_1 = Q_2 = Q_3 = Q$.

Constant latent heat of condensation, i.e. $\lambda_1 = \lambda_2 = \lambda_3 = \lambda$.

Considering the above assumptions and applying the data given in Table1. The computer program is designed to execute the following steps:

**Step 1.** From an overall material balance the total evaporation rate is calculated and equally divided among the effects.

**Step 2.** $\mathbf{\Delta T}$ in each effect is initially estimated as follows: as assumed $Q_1 = Q_2 = Q_3$, and

$A_1=A_2=A_3$, then from the heat transfer rate equations (4, 8, and 12) it follows that;

$U_1\Delta T_1=U_2\Delta T_2=U_3\Delta T_3$ and since $\Delta T=\Delta T_1+\Delta T_2+\Delta T_3=T_0-T_3=150-52=98^oC$, then $\Delta T_1= 98/ [1+ (U_1/U_2) + (U_1/U_3)]$, $\Delta T_2=\Delta T_1 (U_1/U_2)$, and $\Delta T_3=\Delta T_1 (U_1/U_3)$.

**Step 3.** Calculate the evaporation rate in each effect by means of the mass and enthalpy balances.

**Step 4.** Calculate the heat transfer area for each effect by means of the heat transfer rate equation.

**Step 5.** If the areas of the effects are unequal correct the $\Delta T$ in each effect as follows:

$\Delta T_i$ **(corrected) = $(A_i/A_m)$ $\Delta T_i$ (estimated),** where, **i = 1, 2, 3**.

And **$A_m= (A_1+A_2+A_3)/3$,** then repeat step 3, 4 and 5 until the areas differ by a specified small tolerance.

### 4 Results

The component mass balance equation is used to calculate the required salt solution as a feed to the first effect, namely; **$Fx_F = L_3x_3$**

**Table 1. Specification Data for the Triple Effect Evaporators [2]**

| Parameter | Value |
|---|---|
| Total no. of effect | 3 |
| Product solution from third effect, kg/hr. | 4566.2 |
| Mass fraction of feed | 0.4 |
| Mass fraction of product | 0.8 |
| Feed temperature, $^oC$ | 27 |
| Fresh saturated steam temperature, $^oC$ | 150 |
| Temperature of third effect, $^oC$ | 52 |
| $U_1$, W/m$^2$.$^oC$ | 1500 |
| $U_2$, W/m$^2$.$^oC$ | 1300 |
| $U_3$, W/m$^2$.$^oC$ | 1200 |

**F (0.4) = 40,000(0.8)**

**F = 80,000 tons/year = 10101.0 kg/hr.**

The overall material balance is used to calculate the total vapor generated in the three effects as follows:

**$F = L_3 + V$**, then

**$V = V_1 + V_2 + V_3 = 80,000 - 40,000 = 40,000$ tons/year = 5050.5 kg/hr.**

The capacity of the triple effect is the sum of the vapor generated in each effect. The present case study this value is equal to the sum of $V_1$, $V_2$, and $V_3$ which is **5050.5 kg/h**. The steam economy of the system is equal to **(5050.5/1762.4) = 2.87**.

**Table 2. Summarizes the main results of the FORTRAN computer program**

| $L_1$,kg/h | $L_2$, kg/h | $V_0$, kg/h | A, m² | $\Delta T_1$, ºC | $\Delta T_2$,ºC | $\Delta T_3$,ºC |
|---|---|---|---|---|---|---|
| 7704.8 | 6177.6 | 1769.3 | 23.3 | 14.9 | 12.5 | 17.7 |
| 7698.5 | 6173.5 | 1762.0 | 23.8 | 14.6 | 12.8 | 17.6 |
| 7698.5 | 6173.4 | 1762.5 | 23.9 | 14.7 | 12.7 | 17.4 |
| 7698.5 | 6173.5 | 1762.4 | 24.0 | 14.8 | 12.8 | 17.5 |
| 7698.5 | 6173.5 | 1762.4 | 24.0 | 14.8 | 12.8 | 17.5 |

## 5  Discussion of Results

The method outlined here for calculating the temperature drop in each effect and used as initial values to run the program gave a fast convergence, i.e. shortens the number of trials to reach the solution of the problem as can be seen in Table 2. Furthermore, the assumptions listed above simplified the solution. The existing of BPR would not complicate the solution greatly, however, BPR have to be pre-assigned in each effect. BPR is function of solute concentration and the boiling points of solution and pure solvent, usually available in the so called Duhring charts. If the BPR is significant the temperature drop in each effect will be reduced and as a result the capacity of vapor generation is reduced, and the economy is also reduced. The feeding temperature of the dilute solution to the first effect can also reduce the steam economy if it is below the boiling point of the solution in the effect. This is because part of the heating energy provided by the fresh steam is consumed to preheat the dilute feed to its boiling point. The assumption of equal areas of

the effects has to do with the economy of construction only. This assumption, however, justifies the assumption of equal vapor generation in each effect (Shah, D. and Bhagchandani, C., 2012).

## 6 Conclusion

Although the method of feeding in multiple effect evaporators comes in a variety of ways, the most common are feed-forward and feed-backward. Feed-forward has the advantage of lower capital cost since pumping between effects is not required due to the availability of pressure drop in the direction of flow. However, it has the disadvantage of relatively low steam economy when compared to the backward feeding which requires pumping between effects. Therefore, cost analysis has to be undertaken before choosing between these two systems. In addition, the number of effects has to be included in the cost analysis to determine the optimum number of effects (usually not more than five effects) which achieves the lowest operating and capital costs.

### *Nomenclature*

| | |
|---|---|
| A | Heat transfer area, $m^2$. |
| $C_P$ | Specific heat capacity, cal/kg. °C. |
| F | Feed mass flow rate to the first effect, kg/h. |
| $h_f$ | Enthalpy of feed, cal/kg. |
| $h_1, h_2, h_3$ | Enthalpy of solution in effect: 1, 2, 3, cal/kg. |
| $H_1, H_2, H_3$ | Enthalpy of vapor in effect: 1, 2, 3, cal/kg. |
| $L_1, L_2, L_3$ | Mass flow rate of solution from effect: 1, 2, 3, kg/h. |
| $Q_1, Q_2, Q_3$ | Heat transfer rate in effect: 1,2,3 , cal/h. |
| $T_0$ | Saturation temperature of fresh steam, °C. |
| $T_1, T_2, T_3$ | Temperatures in effect: 1, 2 ,3 °C. |
| $U_1, U_2, U_3$ | Overall heat transfer coefficients, $W/m^2$.C |
| $V_0$ | Mass flow rate of fresh steam, kg/h. |
| $V_1, V_2, V_3$ | Mass flow rate of vapor from effect: 1,2,3, kg/h. |
| $x_f$ | Mass fraction NaCl in the feed. |
| $x_1, x_2, x_3$ | Mass fraction NaCl from effect: 1, 2, 3. |

| | |
|---|---|
| $\Delta T$ | Temperature drop, °C. |
| $\lambda_0$ | Latent heat of condensation of fresh steam, cal/kg. |
| $\lambda_1, \lambda_2$ | Latent heat of condensation of vapor in effect: 2, 3, cal/kg. |

**References**

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