Optimization of a multiple Effect Evaporator System

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CERTIFICATE

This is to certify that the thesis entitled "Optimization of a Multiple Effect Evaporator", submitted by V.Jaishree for the requirements of bachelor's degree in Chemical Engineering Department of National Institute of Technology, Rourkela is an original work to the best of my knowledge, done under my supervision and guidance.

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Date-07/05/10 **V.Jaishree**

CONTENTS

ABSTRACT

A septuple effect flat falling film evaporator system for the concentration of black liquor is studied and a generalized cascade algorithm is developed for the different operating strategies. The amount of live steam consumption in the system is evaluated for the given base case parameters. Then the amount of auxiliary vapour produced due to the use of one feed flash tank and seven condensate flash tanks was determined. It was found that the presence of flash tanks helps in recovering heat from the used vapour and thereby reduces the overall live steam consumption of the system and improves the overall steam economy of the system. Thus it helps in making the system more economical.

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NOMENCLATURE

The following nomenclature is used for the development of modeling equations

Symbol used	Parameter
L	Liquor flow rate (kg/s)
CO	Condensate flow rate (kg/s)
V	Rate of vapour produced in evaporator (kg/s)
x_i	Mass fraction of solid in liquor in i^{th} effect
x_f	Mass fraction of solid in feed
h	Specific enthalpy of liquid phase (J/kg)
H	Specific enthalpy of vapour phase(J/kg)
h_l	Specific enthalpy of liquor (J/kg)
U	Overall heat transfer coefficient (W/m^2 K)
A	Heat transfer area of an effect (m^2)
T	Vapour body temperature in an effect (K)
T_L	Liquor temperature in an effect (K)
τ	Boiling point rise
n	Total number of effects
n_s	Number of effects supplied with live steam
$C_1 – C_5$	Constants in mathematical model
P	Pressure of steam in vapour bodies (N/m^2)

k	Iteration number
PI	Performance index
$a_1 - a_4$	Coefficients of cubic polynomial
C_{PP}	Specific heat capacity of black liquor

Chapter 1

Introduction

Chapter 1

INTRODUCTION

Evaporators are kind of heat transfer equipments where the transfer mechanism is controlled by natural convection or forced convection. A solution containing a desired product is fed into the evaporator and it is heated by a heat source like steam. Because of the applied heat, the water in the solution is converted into vapour and is condensed while the concentrated solution is either removed or fed into a second evaporator for further concentration. If a single evaporator is used for the concentration of any solution, it is called a single effect evaporator system and if more than one evaporator is used for the concentration of any solution, it is called a multiple effect evaporator system. In a multiple effect evaporator the vapour from one evaporator is fed into the steam chest of the other evaporator. In such a system, the heat from the original steam fed into the system is reused in the successive effects.

1.1 Application of evaporators

Evaporators are integral part of a number of process industries namely Pulp and Paper, Chlor-alkali, Sugar, pharmaceuticals, Desalination, Dairy and Food processing, etc (Bhargava et al., 2010). Evaporators find one of their most important applications in the food and drink industry. In these industries, evaporators are used to convert food like coffee to a certain consistency in order to make them last for considerable period of time. Evaporation is also used in laboratories as a drying process where preservation of long time activity is required. It is also used for the recovery of expensive solvents and prevents their wastage like hexane. Another important application of evaporation is cutting down the waste handling cost. If most of the wastes can be vapourized, the industry can greatly reduce the money spent on waste handling (Bhargava et al., 2010).

The multiple effect evaporator system considered in the present work is used for the concentration of weak black liquor. It consists of seven effects. The feed flow sequence considered is backward and the system is supplied with live steam in the first two effects.

In the system, feed and condensate flashing is incorporated to generate auxiliary vapour to be used in vapour bodies in order to improve the overall steam economy of the system.

1.2 Problems associated with multiple effect evaporators

The problems associated with a multiple effect evaporator system are that it is an energy intensive system and therefore any measure to reduce the energy consumption by reducing the steam consumption will help in improving the profitability of the plant. In order to cater to this problem, efforts to propose new operating strategies have been made by many researchers to minimize the consumption of live steam in a multiple effect evaporator system in order to improve the steam economy of the system. Some of these operating strategies are feed-, product- and condensate- flashing, feed- and steam-splitting and using an optimum feed flow sequence.

One of the earliest works on optimizing a multiple effect evaporator by modifying the feed flow sequence was by Harper and Tsao in 1972. They developed a model for optimizing a multiple effect evaporator system by considering forward and backward feed flow sequence. This work was extended by Nishitani and Kunugita (1979) in which they considered all possible feed flow sequences to optimize a multiple effect evaporator system for generating a non inferior feed flow sequence. All these mathematical models are generally based on a set of linear or non- linear equations and when the operating strategy was changed, a whole new set of model equations were required for the new operating strategy. This problem was addressed by Stewart and Beveridge (1977) and Ayangbile, Okeke and Beveridge (1984). The developed a generalized cascade algorithm which could be solved again and again for the different operating strategies of a multiple effect evaporator system.

In the present work, in extension to the modeling technique proposed by Ayangbile et al,(1984) feed and condensate flashing has also been included and it also considers the variations in the boiling point elevation and overall heat transfer coefficient.

1.3 Objectives

- To study the seven effect evaporator system for the concentration of black liquor.
- To developed a generalized algorithm which can be used for different operating strategies.
- To incorporate the effect of feed and condensate flashing to enhance the steam economy of the system.
- To compare the results with the published models.

Chapter 2

Literature Review

Chapter 2

LITERATURE REVIEW

Evaporation is a process of removing water or other liquids from a solution and thereby concentrating it. The time required for concentrating a solution can be shortened by exposing the solution to a greater surface area which in turn would result in a longer residence time or by heating the solution to a higher temperature. But exposing the solution to higher temperatures and increasing the residence time results in the thermal degradation of many solutions, so in order to minimize this, the temperature as well as the residence time has to be minimized. This need has resulted in the development of many different types of evaporators.

2.1 Different types of evaporators

Evaporators are broadly classified to four different categories:

1. Evaporators in which heating medium is separated from the evaporating liquid by tubular heating surfaces.
2. Evaporators in which heating medium is confined by coils, jackets, double walls etc.
3. Evaporators in which heating medium is brought into direct contact with the evaporating fluid.
4. Evaporators in which heating is done with solar radiation.

Out of these evaporator designs, evaporators with tubular heating surfaces are the most common of the different evaporator designs. In these evaporators, the circulation of liquid past the heating surfaces is induced either by natural circulation (boiling) or by forced circulation (mechanical methods).

Evaporators may be operated as either once through units or the solution which has to be concentrated may be recirculated through the heating element again and again. In an once through evaporator, the feed passes through the heating element only once, it is heated, which results in vapour formation and then it leaves the evaporator as thick liquor. This results in a limited ratio of evaporation to feed. Such evaporators are especially useful for heat sensitive materials.

In circulation evaporators, a pool of liquid is held inside the evaporator. The feed that is fed to the evaporator mixes with this already held pool of liquid and then it is made to pass through the heating tubes.

The different types of evaporators are

2.1.1 Horizontal tube evaporators

These were the first kind of evaporators that were developed and that came into application. They have the simplest design of all evaporators. It has a shell and a horizontal tube such that the tube has the heating fluid and the shell has the solution that has to be evaporated. It has a very low initial investment and is suitable for fluids which have low viscosity and which do not cause scaling. The use of this kind of evaporator in the present day is very less and limited to only preparation of boiler feedwater.

2.1.1.1 Horizontal spray film evaporators

This evaporator is a modification of horizontal tube evaporator. It is a kind of horizontal falling film evaporator and in thos evaporator, the liquid is distributed by a spray system. This sprayed liquid falls from one tube to another tube by gravity. In such evaporators, the distribution of fluid is easily accomplished and the precise leveling of fluid is not required.

2.1.2 Short tube vertical evaporators

These evaporators were developed after the horizontal tube evaporators and they were the first evaporators that came to be widely used. These evaporators consist of tubes which are 4 to 10 feet long and which are 2 to 3 inches in diameter. These tubes are enclosed inside a cylindrical shell. In the centre a downcomer is present. The liquid is circulated in the evaporator by boiling. Downcomers are required to permit the flow of liquid from the top tubesheet to the bottom tubesheet.

2.1.2.1 Basket type evaporators

These evaporators have construction similar to short tube vertical evaporators. The only difference between the two is that basket type evaporators have annular downcomer. This makes the arrangement more economical. These evaporators have an easily installed deflector which helps in reducing entrainment.

2.1.2.2 Inclined tube evaporators

These evaporators have tubes that are inclined at an angle of 30 to 45 degrees from the horizontal.

2.1.3 Long tube vertical evaporators

This kind of evaporator system is seen in more evaporators because it is more versatile and economical. This kind of evaporator has tubes which have 1 to 2 inch diameter and a length of 12 to 30 feet. When long tube evaporators are used as once through evaporators, no liquid level is maintained in the vapour body and the liquor has a residence time of only few seconds. When long tube vertical evaporators are used as recirculation type evaporators, a particular level has to be maintained in the vapour body and a deflector plate is provided in the vapour body. The liquor temperature in the tube is not uniform and is difficult to predict. Because of the length of the tubes, the effect of hydrostatic head is very pronounced.

2.1.3.1 Rising or climbing film evaporators

The working principle behind rising or climbing film evaporators is that the vapour traveling faster than the liquid flows in the core of the tube causing the liquid to rise up the tube in the form of a film. When such a flow of the liquid film occurs, the liquid film is highly turbulent. Since in such evaporators, the residence time is also low, therefore it can be used for heat sensitive substances too.

2.1.3.2 Falling film evaporators

In this kind of evaporator, the liquid is fed at the top of long tubes and allowed to fall down under the effect of gravity as films. The heating media is present inside the tubes. The process of evaporation in such evaporators occurs on the surface of the highly turbulent films. In such an arrangement, vapour and liquid are usually separated at the bottom of the tubes. In some cases the vapour is allowed to flow up the tubes, in a direction opposite to the flow of liquor. The main application of falling film evaporators is for heat sensitive substances since the residence time in case of falling film evaporators is less. It is also useful in case of fouling fluids as the evaporation takes place at the surface of the film and therefore any salt which deposits as a result of vaporization can be easily removed. These kind of evaporators are suitable for handling viscous fluids since they can easily flow under the effect of gravity. The main problem associated with falling film evaporators is that the fluid which has to be concentrated has to be equally distributed to all the tubes i.e all the tubes should be wetted uniformly.

2.1.3.3 Rising falling film evaporators

When both rising film evaporator arrangement and falling film evaporator arrangement is combined in the same unit, it is called a rising falling film evaporator. Such evaporators have low residence time and high heat transfer rates.

2.1.4 Forced circulation evaporators

This kind of evaporator is used in those cases when we have to avoid the boiling of the product on heating surface is to be avoided because of the fouling characteristics of the liquid. In order to achieve this, the velocity of the liquid in the tubes should be high and so high capacity pumps are required.

2.1.5 Plate evaporators

These evaporators are constructed of flat plates or corrugated plates. One of the reasons of using plates is that scales will flake off the plates more readily than they do so from curved surfaces. In some flat evaporators, plate surfaces are used such that alternately one side can be used as the steam side and liquor side so that when a side is used as liquor side and scales are deposited on the surface, it can then be used as steam side in order to dissolve those scales.

2.1.6 Mechanically aided evaporators

These evaporators are primarily used for two reasons

The first reason is to mechanically scrap the fouling products from the heat transfer surface

The second reason is to help in increasing the heat transfer by inducing turbulence.

They are of different types like

- Agitated vessels
- Scraped surface evaporators
- Mechanically agitated thin film evaporators

2.2 Black liquor

Black liquor is the spent liquor that is left from the Kraft process. It is obtained when pulpwood is digested to paper pulp and lignin, hemicelluloses and other extractives from the wood is removed to free the cellulose fibres. The black liquor is an aqueous solution of lignin residues, hemicelluloses, and the inorganic chemicals used in the process and it contains more than half of the energy of wood fed to the digester.

One of the most important uses of black liquor is as a liquid alternative fuel derived from biomass.

2.2.1 Properties of black liquor

Some of the properties of black liquor are as follows (Ray et al, 1992)

1. Black liquor is distinctly alkaline in nature with its pH varying from 10.5 to 13.5 but it is not caustic in nature. The reason behind this is that most of the alkali in it is present in the form of neutral compounds.

2. The lignin has an intence black colour and the colour changes to muddish brown, when it is diluted with water and even when it is diluted to 0.04 % with water, it still retains yellow colour.
3. Black liquor is foamy at low concentrations and the foaming of black liquor increases with the increase in resin content in it.
4. The amount of total solids in black liquor depends on the quantity of alkali charged into the digester and the yield of the pulp. Under average conditions, black liquor contains 14 – 18 % solids.
5. The presence of inorganic compounds in black liquor tend to increase the specific heat, thermal conductivity, density, specific gravity, viscosity but it has no effect on the surface tension of the black liquor.

2.2.2 Composition of black liquor in the current study

The composition of weak kraft black liquor that is used in the current study is given in table 2.1 and table 2.2 (Bhargava et al., 2010).

Table 2.1 Organic constituents of black liquor

S.no.	Organic constituent
1.	Alkali lignin and thiolignins
2.	Iso-saccharinic acid
3.	Low molecular weight polysaccharides
4.	Resins and fatty acid soaps
5.	Sugars

Table 2.2 Inorganic constituents of black liquor

S.no.	Inorganic compound	Gpl
1.	Sodium hydroxide	4-8
2.	Sodium sulphide	6-12
3.	Sodium carbonate	6-15
4.	Sodium thiosulphate	1-2
5.	Sodium polysulphides	Small
6.	Sodium sulphate	0.5-1
7.	Elemental sulpher	Small
8.	Sodium sulphite	Small

2.3 Methods of modeling of multiple effect evaporator systems

Multiple effect evaporator systems can be modeled in 2 ways

1. In equation based model, equations are written for each effect separately and for each operating condition separately and it is solved. On changing the operating conditions

like the feed flow sequence, or incorporating additional flash tanks, the original equations fail to hold true.

For a mathematical model of a five effect evaporator system, the following equations are written for each evaporator (Radovic et al, 1979)

i. The enthalpy balance equation
ii. The heat transfer rate
iii. The phase equilibrium relationship
iv. The mass balance equation

Other such equation based models were developed by Itahara and Stiel in 1966 which used dynamic programming for the optimization of stagewise processes. It was used for the optimal design of chemical reactors, cross current extractors and mass transfer separation processes.

Lambert, Joye and Koko in 1987 presented a model which was based on boiling point rise and the non linear enthalpy relationships. These relationships were obtained by curve fitting and interpolation.

Other similar equation based models were developed by Holland (1975), Mathur (1992), Bremford and Muller-Steinhagen (1994), El-Dessouky, Alatiqi, Bingulac,

and Ettouney (1998), El-Dessouky, Ettouney, and Al-Juwayhel (2000) and Bhargava (2004).

2. In cascade algorithm model, generalized equations for each effect is written in which the liquor flow rate into each effect is taken as the sum of the fraction of feed entering into that effect and the fraction of feed entering from the previous effect to that effect. So on changing the operating condition like introduction of vapour bleeding or addition of flash tanks or changing the feed flow sequence will not require a change in the algorithm and the same program can be used for all operating conditions. (Bhargava et al, 2010)

   Another generalized model has been proposed by Stewart and Beveridge which attempts to incorporate the best available information on pressure drop and heat transfer in two-phase flow and on the physical and thermodynamic properties of the evaporating mixture. This model was intended to provide a realistic low level effect model for use in general simulation approach.(Stewart and Beveridge, 1977)

Similar generalized model was also developed by Ayangbile, Okeke and Beveridge in 1984.

Chapter 3

Problem Statement

Chapter 3

PROBLEM STATEMENT

The multiple effect evaporator system that has been considered in the work is a septuple effect flat falling film evaporator operating in an Indian Kraft pulp and paper mill (Bhargava et al., 2010). The system is used in the mill for concentrating non wood (straw) black liquor which is a mixture of organic and inorganic chemicals. The schematic diagram of the system is shown in Fig 3.1. The feed flow sequence followed in the multiple effect evaporator system is backward that is the feed is initially fed to the seventh effect, from there it goes to the sixth effect and so on and finally the concentrated product is obtained from the first effect. Live steam is fed to the first and second effect. Feed and condensate flashing is employed in the system to generate auxiliary vapour which is then used to enhance the overall steam economy of the system. The base case operating parameters of the system are as given in Table 3.1. The geometrical data are presented in Table 3.2.

Table 3.1 Base case operating parameters

S. no.	Parameter(s)	Value(s)
1.	Total number of effects	7
2.	Number of effects supplied with live steam	2
3.	Live steam temperature in effect 1	140˚C
4.	Live steam temperature in effect 2	147˚C
5.	Inlet concentration of black liquor	0.118
6.	Inlet temperature of black liquor	64.7˚C
7.	Feed flow rate of black liquor	56,200 kg/hr
8.	Vapour temperature of last effect	52˚C
9.	Feed flow sequence	Backward

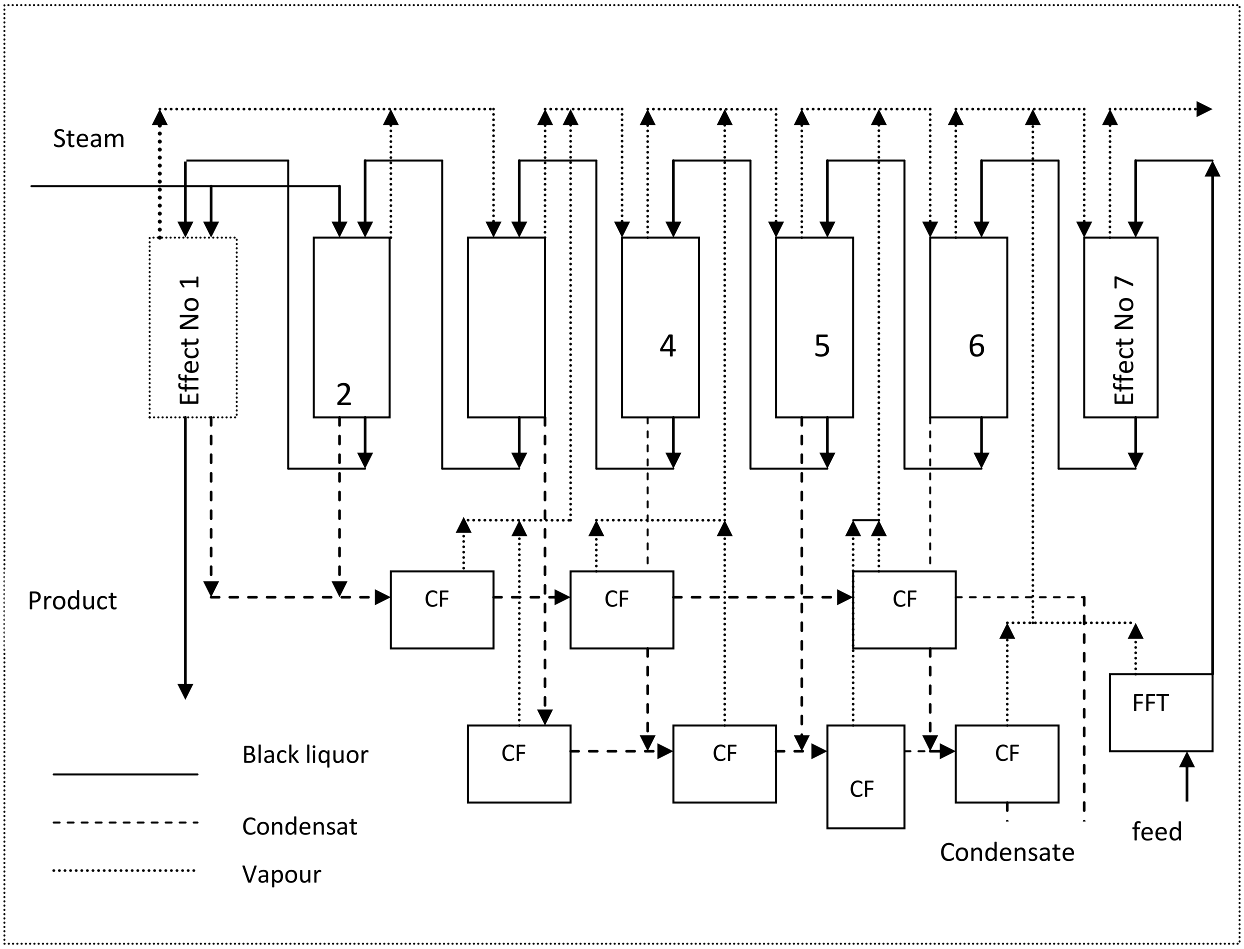
10.	Position of feed and condensate flash tanks	As shown in fig 1

The parameters given in Table 3.1 are considered as base case parameters. From these values it is observed that the live steam fed to the second effect is at a temperature of 7 ˚C higher than that fed to the first effect. Since the problem statement considered is an actual scenario, therefore the base case parameters have been considered as it is for simulation. The reason for unequal steam temperature in both the effects could be attributed to the unequal distribution of steam from the header to these effects and thereby resulting in two different pressures in these effects.

Table 3.2.Geometrical parameters of the evaporator

S.No.	Parameter	Value
1.	Area of first effect	540 m^2
2.	Area of second effect	540 m^2
3.	Area of third effect	660 m^2
4.	Area of fourth effect	660 m^2
5.	Area of fifth effect	660 m^2
6.	Area of sixth effect	660 m^2
7.	Area of seventh effect	690 m^2
8.	Size of lamella	1.5m (W) x 1.0m (L)

Fig 3.1 Schematic diagram of the system



The schematic diagram of the system shows that it has seven effects. Live steam is supplies to the first and the second effect and the black liquor flows in the backward direction. The feed initially enters the feed flash tank (FFT) and after undergoing flashing, it enters the seventh effect. Seven condensate flash tanks are present. Out of these, first, second and third flash tanks are primary condensate flash tanks and the fourth, fifth, sixth and seventh flash tanks are secondary flash tanks. The final concentrated product comes out of the seventh effect.

Chapter 4

Development of a Model & Solution Technique

Chapter 4

DEVELOPMENT OF A MODEL AND SOLUTION TECHNIQUE

4.1 Mathematical model for a particular effect

The block diagram, shown in Fig. 4.1, indicates the schematic representation of ith effect of the evaporator. In the steam section, inlet vapour flow rate is given by V_{i-1} and the outlet condensate flow rate is given by C_{i-1}. In the evaporation section, the inlet liquor flow rate is given by L_{i+1} having a concentration of x_{i+1} and a temperature of T_{Li+1} and the outlet liquor flow rate is given by L_i, having a concentration of x_i. The vapour flow rate coming out of the evaporation section is given by V_i.

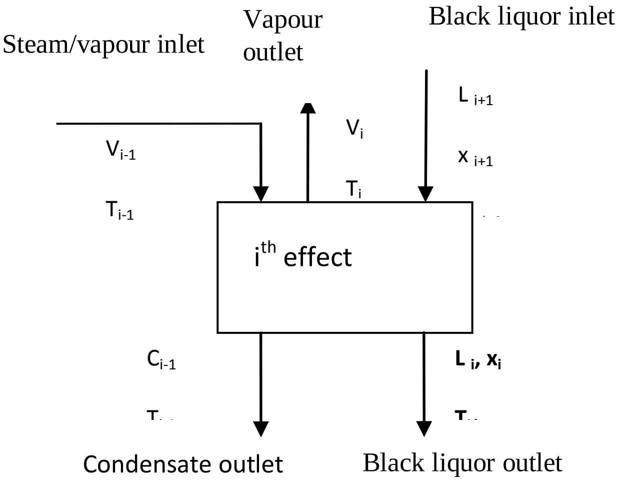


Fig. 4.1 Block Diagram of ith effect of an evaporator

If we consider mass and energy balance over the ith effect, the following equations can be obtained

The overall mass balance equation over the evaporation section

$$L_{i+1} = L_i + V_i \tag{4.1}$$

The overall mass balance equation over the steam chest

$$V_{i-1} = CO_{i-1} \tag{4.2}$$

Component mass balance

$$L_{i+1}\, x_{i+1} = L_i\, x_i = L_F\, x_F \tag{4.3}$$

Overall energy balance

$$L_{i+1}\, h_{i+1} = L_i\, h_{Li} + V_i\, H_{vi} + \Delta H_i \tag{4.4}$$

Here,

$$\Delta H_i = U_i\, A_i\, (T_{i-1} - T_{Li}) \tag{4.5}$$

Energy balance on steam side

$$V_{i-1} = \Delta H_i / (H_{vi-1} - h_{Li-1}) \tag{4.6}$$

In order to determine the enthalpy of the black liquor being used, the following correlation is used

$$h_L = C_{PP}\, (T_L - C_5) \text{ J/kg} \tag{4.7}$$

here,

$$C_{PP} = C_1\, (1 - C_4\, x)$$

$$T_L = T + \tau$$

The values of the coefficients used are given by

$C_1 = 4187$

$C_4 = 0.54$

$C_5 = 273$

To determine the boiling point rise, the functional relation is taken from TAPPI correlation (Ray et al, 1992)

$$\tau_i = C_3 (C_2 + x_i)^2 \tag{4.8}$$

the values of the coefficients are taken from Ray et al, (1992)

$C_2 = 0.1$

$C_3 = 20$

The following cubic polynomial is used to determine the outlet liquor flow rate from each effect

$$a_1L_i^3 + a_2L_i^2 + a_3L_i + a_4 = 0 \tag{4.9}$$

Here, the empirical relations of the coefficients is given by

$$a_1 = H_{Vi} – C_1T_i – C_1C_2^2C_3 + C_1C_5 \tag{4.9a}$$

$$a_2 = L_{i+1} h_{i+1} + U_iA_i (T_{i-1} – T_i – C_3C_2^2) + L_{i+1} x_{i+1} (C_1C_4T_i – 2C_1C_2C_3 + C_1C_3C_2^2C_4 – C_1C_4C_5) – L_{i+1} H_{Vi} \tag{4.9b}$$

$$a_3 = (L_{i+1} x_{i+1})^2 (2C_1C_2C_3C_4 - C_1C_3) – 2 C_2C_3U_iA_i L_{i+1} x_{i+1} \tag{4.9c}$$

$$a_4 = (C_1C_3C_4 L_{i+1} x_{i+1} – C_3U_iA_i) (L_{i+1} x_{i+1})^2 \tag{4.9d}$$

4.2 Model for liquor flash tank

The block diagram show in fig 4.2 is a schematic representation of a liquor flash tank. In this, liquor having an inlet flow rate of L_i, composition of x_i and an inlet temperature of T_{Li} enter the flash tank. It is then flashed to a temperature of T_{Le}. The outlet liquor has a flow rate of L_e and an outlet concentration of x_e. The flow rate of vapour generated in the process is given by V_e.

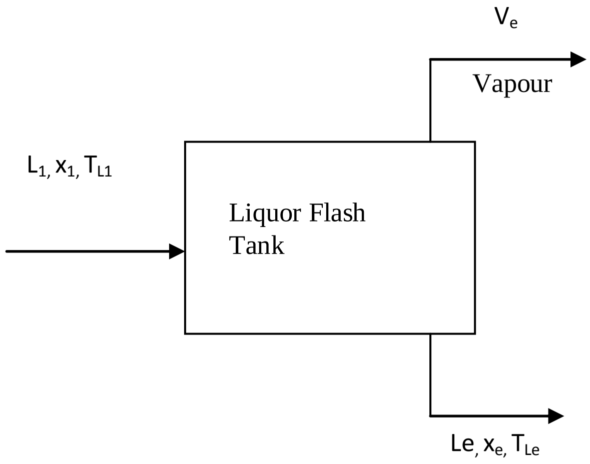


Fig 4.2 Block diagram of a flash tank

For calculating the outlet liquor flow rate from a liquor flash tank for a given inlet inlet liquor flow rate, similar cubic equation is used to determine. The modified values of the coefficients are given as under:

$a_1 = H_{Vout} – C_1 T_{out} – C_1C_2^2C_3 + C_1C_5$

$a_2 = L_{in} h_{in} + L_{in} x_{in} (C_1C_4T_{out} – 2C_1C_2C_3 + C_1C_2^2C_3C_4 – C_1C_4C_5) – L_{in} H_{vout}$

$a_3 = (L_{in} x_{in})^2 (2C_1C_2C_3C_4 – C_1C_3)$

$a_4 = (L_{in} x_{in})^2 C_1C_3C_4$

Equation number 4.9 is solved for each effect to get the outlet liquor flow rate. Out of the three values obtained, that value is selected which has a value less than or equal to the feed flow rate. This value is then used to determine the vapour outlet flow rate and the outlet feed concentration using mass balance and component balance respectively.

For example for ith effect,

$L_{i+1} – L_i = V_i$ (mass balance equation)

$L_{i+1} x_{i+1} = L_i x_i$ (component balance equation)

4.3 Model for condensate flash tank

In order to determine the outlet condensate flow rate from a condensate flash tank for an inlet condensate flow rate, mass and energy balance is performed over condensate flash tank. Considering a condensate flash tank in which the flow rate of condensate entering the tank is given by CO_i, entering at a temperature of T_i and having a specific enthalpy of h_i, being flashed to a temperature T_j, with the condensate flowing out of the flash tank at a rate of CO_j and producing V_j amount of vapour

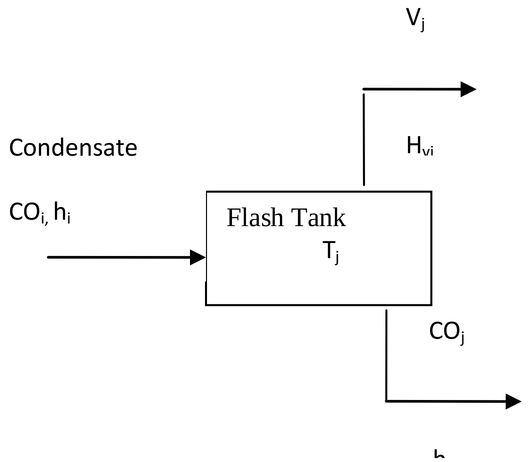


Fig. 4.3 Block Diagram of a Condensate Flash Tank

From overall mass balance equation over condensate flash tank

$$V_j = CO_i - CO_j \qquad (4.10)$$

From overall energy balance equation over condensate flash tank

$$CO_j = CO_i\,(H_{vj} - h_i)/(H_{vj} - h_j) \qquad (4.11)$$

4.4 Empirical relation for overall heat transfer coefficient

The correlation given in equation 4.12 is used to evaluate the overall heat transfer coefficient of each effect of the evaporator. It is considered from Bhargava et al. (2008). From the correlation it can be seen that the overall heat transfer coefficient of each effect is a function of the temperature gradient and the average values of concentration and liquor flow rate obtained from the input and output parameters.

$$U/2000 = a\,(\Delta T/40)^b\,(x_{avg}/0.6)^c\,(F_{avg}/25)^d \qquad (4.12)$$

Here a, b, c, d are empirical constants. These values are assumed to be same for the first and second effect and same for rest of the five effects. Their values are as given in the Table 4.1.

Table 4.1 Values of the constants

Effect no	a	b	c	d
1 & 2	0.0604	-0.3717	-1,227	0.0748
3,4 5,6 & 7	0.1396	-0.7949	0.0	0.1673

4.5 Representation of flow sequence

In order to cater to the changing feed flow sequences, a boolean matrix can be used to indicate the feed flow sequence so that the same code can be used for simulation for all feed flow sequences depending upon the position of 1’s and 0’s.

For example for a backward feel flow sequence, the following Boolean matrix is obtained

$$\begin{vmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

The 8 x 8 matrix shown above is the Boolean matrix for backward feed arrangement.the columns represent the source effect and the rows represent the sink effect. In this the first column represents feed and the successive columns represent the seven effects respectively. Similarly, the first row to seventh row represent the seven effects and the eighth row represents the product respectively.

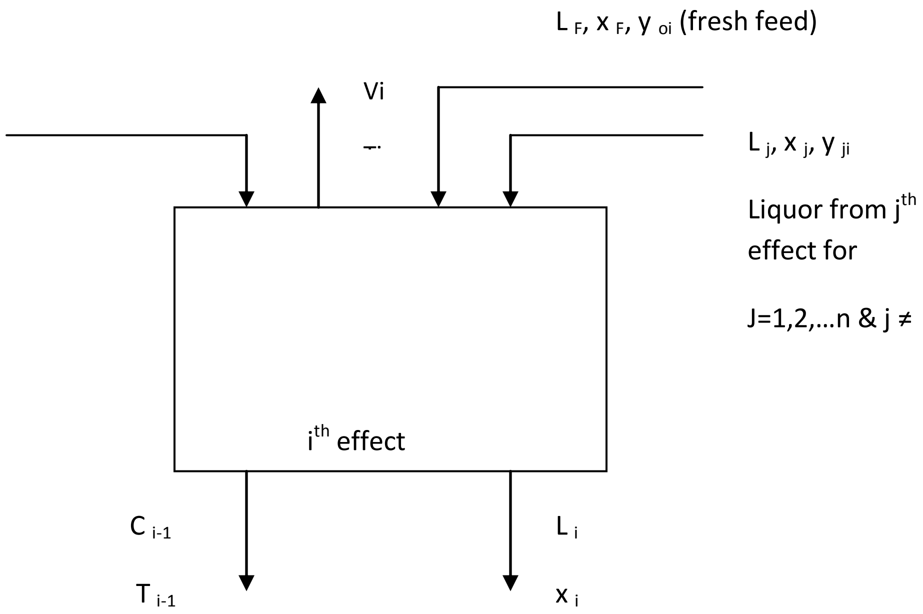
In order to construct the matrix, first the position where the feed is fed is identified, in case of a backward flow, the feed is fed into the last effect. So for the case considered, the feed is fed to the seventh effect. Therefore 1 appears in the matrix in the position corresponding to feed column and seventh effect row. From the seventh effect, the feed goes to the sixth effect, therefore 1 is written in the matrix in a position corresponding to seventh effect in the column and sixth effect in the row. Similarly the rest on the Boolean matrix is constructed.

A matlab code is written with the given base case parameters for the given system to find out the amount of live steam required. The feed and condensate flash tanks are also incorporated and the amount of auxiliary steam produced by them is calculated to find out the reduction in steam consumption by the use of flash tanks.

4.6 Generalized model of an effect

In order to simplify the calculation, a generalized model is developed which can be applied for different operating parameters, for different feed flow sequences and feed, product and condensate flashing. Fig 4.4 shows the block diagram of i^{th} effect for cascade simulation.(Bhargava et al. ,2008)

Fig 4.4 Block diagram of an effect for cascade simulation



The block diagram shown if fig 4.4 shows the generalized diagram of an effect and it can accommodate any feed flow sequence and can also accommodate the effect of liquor splitting. Accommodating the effect of flow sequencing and feed splitting the feed flow rate, the black liquor feed rate to the i^{th} effect can be expressed by the relation given in equation number 4.13

$$y_{oi}\, L_F + \sum y_{ji} Lj \tag{4.13}$$

In this correlation,

y_{oi} refers to the fraction of feed after feed flashing which enters into the i^{th} effect.

y_{ji} refers to fraction of black liquor which comes out from the j^{th} effect and enters into the i^{th} effect.

Taking these parameters into account, the total mass balance around i^{th} effect can be represented by equation number 4.14

$$y_{o,i}\, L_F + \sum_{j=1}^{n} y_{j,i} L_j = L_i + V_i \tag{4.14}$$

Extending the equation developed for i^{th} effect (equation number 4.14) to an evaporator of n effects, the matrix representation is as given in fig 4.5

Fig 4.5 Matrix representation of toal mass balance of n effect evaporator

$$\left\{\begin{matrix} y_{11}-1 & y_{21} & y_{31} & \cdots & y_{n1} \\ y_{12} & y_{22}-1 & y_{32} & \cdots & y_{n2} \\ y_{13} & y_{23} & y_{33}-1 & \cdots & y_{n3} \\ : & : & : & \cdots & : \\ y_{1n} & y_{2n} & y_{3n} & \cdots & y_{nn}-1 \end{matrix}\right\} \begin{bmatrix} L_1 \\ L_2 \\ L_3 \\ : \\ L_n \end{bmatrix} = \begin{bmatrix} V_1 - y_{o1}L_F \\ V_2 - y_{o2}L_F \\ V_3 - y_{o3}L_F \\ : \\ V_n - y_{on}L_F \end{bmatrix}$$

This can be represented by

$$\mathbf{YL = VL_F} \tag{4.15}$$

or $$\mathbf{L = Y^{-1}\, VL_F = AVL_F} \tag{4.16}$$

Here **Y** matrix is called flow fraction matrix and the matrix A is the inverse of this matrix.

From equation number 4.16 the exit liquor flow rate from the ith effect can be expresses as given in equation number 4.17

$$L_i = \sum_{j=1}^{n} a_{ij}V_j - L_F \sum_{j=1}^{n} y_{oj}a_{ij} \tag{4.17}$$

The solid mass balance around an effect I can be represented bt the relation given in equation number 4.18

$$y_{oi}L_F x_F + \sum_{j=1}^{n} y_{ji}L_j x_j = L_i x_i \tag{4.18}$$

Rearranging this equation we get

$$\sum_{j=1}^{n} y_{ji}L_j x_j - L_i x_i = -y_{oi}L_F x_F$$

$\mathbf{Y}\ \mathbf{LX} = -\ \mathbf{Y_0}\, L_F\ x_F$

Simplifying this the following relation can be obtained

$\mathbf{LX} = \mathbf{Y}^{-1}\ (-\ \mathbf{Y_0}\, L_F x_F) = -\ \mathbf{A}(-\ \mathbf{Y_0}\, L_F x_F)$

So, the expression for the total solids coming out of ith effect can be represented by equation number 4.19

$$L_i x_i = \left(\sum_{j=1}^{n} y_{oj}a_{ij} \right) L_F x_F \tag{4.19}$$

Combining equation 4.18 and equation 4.19, an expression for the concentration of liquor coming out of the ith effect can be determined as given in equation 4.20

$$\theta_i = \frac{\sum_{j=i}^{n} (y_{oj}a_{ij}) L_F x_F \sum_{j=i}^{n} a_{ij}}{\left[\sum_{j=1}^{n} (y_{oj}a_{ij}) L_F - \sum_{j=i}^{n} a_{ij}V_j \right]^2} \tag{4.20}$$

We rename the theoretical vapour requirement of each effect V_{i-1} as V_{bi} and then modify the vapour produced by each effect (V_{i-1}) by adding to it the vapour produced by feed and condensate flashing. In order to arrive at the exact solution, we have to iterate V_{i-1} and V_{bi} till their values become equal. In order to satisfy this condition we define an index called Performance Index which can be defined by the equation 4.21 which is a measure of the difference between V_{i-1} and V_{bi}

$$PI = \Sigma\left(\left(V_{i-1} - V_{bi}\right) / V_{bi}\right)^2 \tag{4.21}$$

The summation is done for the effects in which live steam is not fed, that is for the given case from third to seventh effect.

The various parameters of an effect like Ti , TLi , Vi , xi of an effect change with the pressure (Pi) of the effect bt the change in these parameters is not linear. But assuming the range of the parameters to be linear, we can approximate these changes to be linear.

As proposed by Stewart and Beveridge (1977) and Ayangbile, Okeke and Beveridge (1984), it is assumed that vapour produced in a effect V_i is a function of temperature difference (ΔT_i) across the film where ΔT_i is given by equation number 4.22

$$\Delta T_i = T_{i-1} - T_{Li} \tag{4.22}$$

So writing the relation for the change in V_i with the change in temperature difference we get,

$$\delta V_i = \frac{\partial V_i}{\partial(\Delta T_i)}(\delta \Delta T_i) \tag{4.23}$$

In this equation, assuming a new variable α such that the expression for α is given by

$$\frac{\partial V_i}{\partial(\Delta T_i)} = \alpha_i$$

Equation number 4.23 can be rewritten as equation number 4.24

$$\delta V_i = \alpha_i\ \delta(\Delta T_i) \ = \alpha_i(\delta T_{i-1} - \delta T_{Li}) \tag{4.24}$$

To determine the relation between the change in T_i with the change in P_i

$$\delta T_i = \frac{\partial T_i}{\partial P_i}\delta P_i \tag{4.25}$$

Here defining a variable γ such that the expression for γ is given by

$$\gamma i = \frac{\partial T_i}{\partial P_i}$$

we can rewrite equation 4.25 as equation 4.26

$$\partial T_i = \gamma_i \partial P_i \tag{4.26}$$

From the knowledge that the temperature of the black liquor is a function of the pressure and the concentration of solids the change in temperature of black liquor can be expressed as equation 4.27.

$$\delta T_{Li} = \frac{\partial T_{Li}}{\partial P_i} \delta P_i + \frac{\partial T_{Li}}{\partial x_i} \delta x_i$$

$$\delta T_{Li} = \gamma_i' \, \delta P_i \; + \gamma_i'' \, \delta x_i \tag{4.27}$$

from equation 4.20, we can get

$$\delta x_i = \frac{\sum_{j=i}^{n} (y_{oj} a_{ij}) L_F x_F \sum_{j=i}^{n} a_{ij} \delta V_j}{\left[\sum_{j=1}^{n} (y_{oj} a_{ij}) L_F - \sum_{j=i}^{n} a_{ij} V_j \right]^2}$$

$$\delta xi \;= \theta_i \sum_{j=1}^{n} \delta V_j \tag{4.28}$$

where, $$\theta_i = \frac{\sum_{j=i}^{n} (y_{oj} a_{ij}) L_F x_F \sum_{j=i}^{n} a_{ij}}{\left[\sum_{j=1}^{n} (y_{oj} a_{ij}) L_F - \sum_{j=i}^{n} a_{ij} V_j \right]^2}$$

Combining equation number 4.27 and 4.28, we get

$$\delta T_{Li} = \gamma_i' \, \delta P_i + \theta_i \sum_{j=i}^{n} \delta V_j \tag{4.29}$$

Defining $\Delta V_i = V_{i-1} - V_{bi}$ for $i = n, n\text{-}1, \ldots, n\text{-}n_s$ (4.30)

The changes in V_{i-1} and V_{bi} for the kth iteration can be given by equation 4.31 and 4.32

$$\delta V_{i-1} = V_{i-1}^{k} - V_{i-1}^{k-1} \tag{4.31}$$

$$\delta V_{bi} = V_{bi}^{k} - V_{bi}^{k-1} \tag{4.32}$$

In order to arrive at the solution of the flat falling film evaporator system, the vapour required for heating by an effect should be equal to the sum of vapour coming out of the previous effect and the auxiliary vapour added to it from condensate flashing.

$$V_{i-1} \approx V_{bi} \tag{4.33}$$

From equation 4.30, 4.31, 4.32 and 4.33 we can obtain

$$\Delta V_i = \delta V_{bi} - \delta V_{i-1} \tag{4.34}$$

The vapour required for heating in an effect is a function of vapour produced in that effect, so on linearization we get relation represented by equation 4.35

$$\delta V_{bi} = \frac{\partial V_{bi}}{\partial V_i} \delta V_i$$

$$\delta V_{bi} = \beta_i \, \delta V_i \tag{4.35}$$

Combining equations 4.24, 4.26, 4.29, 4.34 and 4.35 and rearranging equation number 4.36 and equation number 4.37 are obtained

$$\delta V_i - \beta_{i+1} \, \delta V_{i+1} = -\Delta V_{i+1} \qquad \text{where, } i = 1,2,\ldots, n - n_s \tag{4.36}$$

$$(1 + \alpha_i \theta_i a_{ii}) \delta V_i + \alpha_i \theta_i \sum_{j=1}^{i-1} a_{ij} \, \delta V_j + \alpha_i \theta_i \sum_{j=i+1}^{n} a_{ij} \, \delta V_j - \alpha_i \gamma_i \, \delta P_{i-1} + \alpha_i \gamma_i' \, \delta P_i = 0$$

$$\text{where, } i = 1,2,\ldots,n-n_s+1 \tag{4.37}$$

From equation 4.36 and equation 4.37,a set of $(2(n-n_s)+1)$ linear algebraic equations with the same number of unknowns, namely, δV_i, where, $i = 1,2,\ldots, n-n_{s+1}$ and δP_i where, $i = 1,2,\ldots, n-n_s$ is obtained.

The matrix representation of equation 4.36 and 4.37 can be represented by table 4.2

Table- 4.2 Matrix representation of set of linear algebraic equations given by equation 36 and 37

$$
\left|\begin{array}{ccccccccccc}
1 & -\beta_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & -\beta_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & -\beta_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & -\beta_5 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & -\beta_6 & 0 & 0 & 0 & 0 & 0 \\
1+b_{11} & b_{12} & b_{13} & b_{13} & b_{15} & b_{16} & \alpha_1\gamma'_1 & 0 & 0 & 0 & 0 \\
b_{21} & 1+b_{22} & b_{23} & \alpha_2 a_{24}\theta_2 & \alpha_2 a_{25}\theta_2 & \alpha_2 a_{26}\theta_2 & -\alpha_2\gamma_2 & \alpha_2\gamma'_2 & 0 & 0 & 0 \\
\alpha_3 a_{31}\theta_3 & \alpha_3 a_{32}\theta_3 & 1+\alpha_3 a_{33}\theta_3 & \alpha_3 a_{34}\theta_3 & \alpha_3 a_{35}\theta_3 & \alpha_3 a_{36}\theta_3 & 0 & -\alpha_3\gamma_3 & \alpha_3\gamma'_3 & 0 & 0 \\
\alpha_4 a_{41}\theta_4 & \alpha_4 a_{42}\theta_4 & \alpha_4 a_{43}\theta_4 & 1+\alpha_4 a_{44}\theta_4 & \alpha_4 a_{45}\theta_4 & \alpha_4 a_{46}\theta_4 & 0 & 0 & -\alpha_4\gamma_4 & \alpha_4\gamma'_4 & 0 \\
\alpha_5 a_{51}\theta_5 & \alpha_5 a_{52}\theta_5 & \alpha_5 a_{53}\theta_5 & \alpha_5 a_{54}\theta_5 & 1+\alpha_5 a_{55}\theta_5 & \alpha_5 a_{56}\theta_5 & 0 & 0 & 0 & -\alpha_5\gamma_5 & \alpha_5\gamma'_5 \\
\alpha_6 a_{61}\theta_6 & \alpha_6 a_{62}\theta_6 & \alpha_6 a_{63}\theta_6 & \alpha_6 a_{64}\theta_6 & \alpha_6 a_{65}\theta_6 & 1+\alpha_6 a_{66}\theta_6 & 0 & 0 & 0 & 0 & -\alpha_6\gamma_6
\end{array}\right|
\left|\begin{array}{c}
\delta V_1 \\ \delta V_2 \\ \delta V_3 \\ \delta V_4 \\ \delta V_5 \\ \delta V_6 \\ \delta P_1 \\ \delta P_2 \\ \delta P_3 \\ \delta P_4 \\ \delta P_5
\end{array}\right|
=
\left|\begin{array}{c}
-\Delta V_2 \\ -\Delta V_3 \\ -\Delta V_4 \\ -\Delta V_5 \\ -\Delta V_6 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0
\end{array}\right|
$$

The values for α_i, β_i, γ_i and γ_i' for the different iteration number, denoted by k, are defined as

For the first iteration, k=1

$$\alpha_i = V_i / \Delta T_i$$

For the successive iterations, k=2,3…..

$$\alpha_i = (V_i^k - V_i^{k-1}) / (\Delta T_i^k - \Delta T_i^{k-1})$$

For the first iteration,k=1

$$\beta_i = V_{bi} / V_i$$

For the successive iterations, k=2,3…..

$$\beta_i = (V_{bi}^k - V_{bi}^{k-1}) / (V_i^k - V_i^{k-1})$$

The values of γ and γ' are given by

$$\gamma_i' = \frac{\partial T_{Li}}{\partial P_i} = \frac{\partial (T_i + BPR_i)}{\partial P_i} = \frac{\partial T_i}{\partial P_i}$$

$$\gamma_i = \frac{\partial T_{i-1}}{\partial P_{i-1}}$$

These values can be obtained from the following correlation

$P=0.206-9.89*10^{-3}*T+2.304*10^{-4}*T^2-2.03*10^{-6}*T^3+1.521*10^{-8}*T^4$

4.7 Solution technique

Considering the steam pressure in the first and seventh effect and assuming equal pressure drop across all effects, we will find the pressure in the individual effects. Based on this pressure, we will calculate the steam and condensate properties for each effect. Using cubic equation 4.9 and finding out its coefficients from equations 4.9a, 4.9b, 4.9c and 4.9d, the liquor outlet from each effect is found out and from that the concentration of liquor from each effect and the steam requirement of each effect is also evaluated by material balance and mass balance respectively. After this the auxiliary vapour produced due to condensate flashing is evaluated and the modified values of vapour produced from each effect is found out which is the sum of the vapour produced in the effect and the addition vapour produced due to flashing. A parameter known as performance index is evaluated, which is the difference between the steam requirement of each effect and the vapour supplied by the preceding effect (including the flash vapour). The entire process is iterated till these two values become equal.

4.8 Algorithm

The following algorithm is followed for the matlab code

1. First the following data are read.
    - Total number of effects.
    - Number of effects in which live steam is supplied
    - Inlet concentration of feed
    - Feed flow rate
    - Temperature of live steam in the first and second effects
    - Pressure of steam in the first and last effect
    - Boolean for the feed flow sequence
    - Geometrical parameters of the evaporators
2. Assuming equal pressure drop across each effect, the vapour pressure of each effect is computed from the pressure values of the first and the seventh effect. These pressure values are used for the initial computation of physical properties of steam and condensate in each effect.
3. The effect of feed flashing is then evaluated from the inlet concentration and the feed flow rate. The cubic equation is generated, the coefficients are evaluated and the outlet liquor flow rate from the feed flash tank is obtained. The outlet liquor concentration is obtained from component balance. We will set the value of k at 1.
4. Enthalpy of liquor in each effect is evaluated from the empirical relation.
5. The flow rate of liquor from each effect is then evaluated from the cubic equation and from that the vapour generated from each effect and the outlet concentration of liquor from each effect is evaluated by mass balance and component balance

respectively. Here the vapour generated due to condensate flashing is not taken into account.

6. New values of x_{avg} and F_{avg} is determined for each effect based on the input and output parameters of each effect.
7. Then Δx_{avg} and ΔF_{avg} values are determined.
    - $\Delta x_{avg} = x_{avg,new} - x_{avg}$
    - $\Delta F_{avg} = F_{avg,new} - F_{avg}$

8. If the value of Δx_{avg} & $\Delta F_{avg} \leq 0.0005$, we will proceed to next step. If the inequality is not satisfied, the concentration values of each effect is replaced by the x_{avg} values and the entire algorithm from step 2 to step 8 is repeated till the inequality is satisfied.
9. The modified values of overall heat transfer coefficient are found from the empirical relation given in equation 4.12.
10. The effect of the three primary condensate flash tanks and the four secondary flsh tanks is evaluated from equations 4.10 & 4.11 and the auxiliary vapour generated from them is found out. The vapour requirement of each effect is termed as V_{bi} and the sum of vapour generated from previous effect and the flash vapour together is designated as V_{i-1} .
11. The performance index of each effect is evaluated which is given by

$$PI = \Sigma \left((V_{i-1} - V_{bi}) / V_{bi} \right)^2$$

If the PI > 0.001, we will calculate the modified pressure values and repeat steps 2 to 11. If PI < 0.001 , we will end the program.

Chapter 5

Results & Discussion

Chapter 5

RESULTS AND DISCUSSION

After following the algorithm as per previous chapter and writing a MATLAB code, the following simulation results are obtained.

Table 5.1 gives the pressure values of each effect assuming equal pressure drop across each effect. These pressure values are used for the initial evaluation for the steam and condensate parameters. The specific vapour enthalpy for each effect corresponding to the initially assumed pressure values of the effect are given in Table 5.2. These values have been derived from steam table.

Table 5.1 Initial pressure difference values of each effect

S.no.	Effect number	Pressure value (bar)
1.	First effect	3.6160
2.	Second effect	3.1189
3.	Third effect	2.6217
4.	Fourth effect	2.1246
5.	Fifth effect	1.6274
6.	Sixth effect	1.1303
7.	Seventh effect	0.6331

Table 5.2 specific enthalpy of vapour of each effect

S.no	Effect number	Specific enthalpy(J/kg)*10^{-6}

1.	First effect	2.7335
2.	Second effect	2.7267
3.	Third effect	2.7187
4.	Fourth effect	2.7090
5.	Fifth effect	2.6968
6.	Sixth effect	2.6804
7.	Seventh effect	2.6551

The feed flow rate is considered from Table 3.1 as 15.55 kg/s with an initial composition of 0.118. Applying the feed flashing on this, the modified liquor flow rate and concentration are evaluated as

L_{mod} = 15.2766 kg/s

x_{mod} = 0.1201

Temperature of feed after flashing is given by 53.1˚C

For further calculations, these modified values of inlet liquor flow rate and feed concentration are considered.

Table 5.3 gives the specific enthalpy of vapour in each effect as evaluated from the empirical relations

$$h_L = C_{PP} (T_L - C_5) \text{ J/kg}$$

where,

$C_{PP} = C_1 (1- C_4 x)$

$T_L = T + \tau$

$\tau_i = C_3 (C_2 + x_i)^2$

Table 5.3 Specific enthalpy of liquor from each effect

S.no.	Effect number	Specific enthalpy(J/kg)*10^{-5}
1.	First effect	2.5364
2.	Second effect	4.9040
3.	Third effect	4.7908
4.	Fourth effect	4.6279
5.	Fifth effect	4.3870
6.	Sixth effect	4.0293
7.	Seventh effect	3.4566

Table 5.4 gives the liquor flow rate from each effect as determined from the cubic equation given by

$a_1L_i^3 + a_2L_i^2 + a_3L_i + a_4 = 0$

where the coefficients are given by

$a_1 = H_{Vi} - C_1T_i - C_1C_2^2C_3 + C_1C_5$

$a_2 = L_{i+1} h_{i+1} + U_iA_i (T_{i-1} - T_i - C_3C_2^2) + L_{i+1} x_{i+1} (C_1C_4T_i - 2C_1C_2C_3 + C_1C_3C_2^2C_4 - C_1C_4C_5) - L_{i+1} H_{Vi}$

$a_3 = (L_{i+1} x_{i+1})^2 (2C_1C_2C_3C_4 - C_1C_3) - 2 C_2C_3U_iA_i L_{i+1} x_{i+1}$

$a_4 = (C_1C_3C_4 L_{i+1} x_{i+1} - C_3U_iA_i) (L_{i+1} x_{i+1})^2$

The real root of the cubic equation is given by

$L = -a_2/(3a_1) + ((P_1^3 + Q_1^2)^{1/2} - Q_1)^{1/3} - ((P_1^3 + Q_1^2)^{1/2} + Q_1)^{1/3}$

Where,

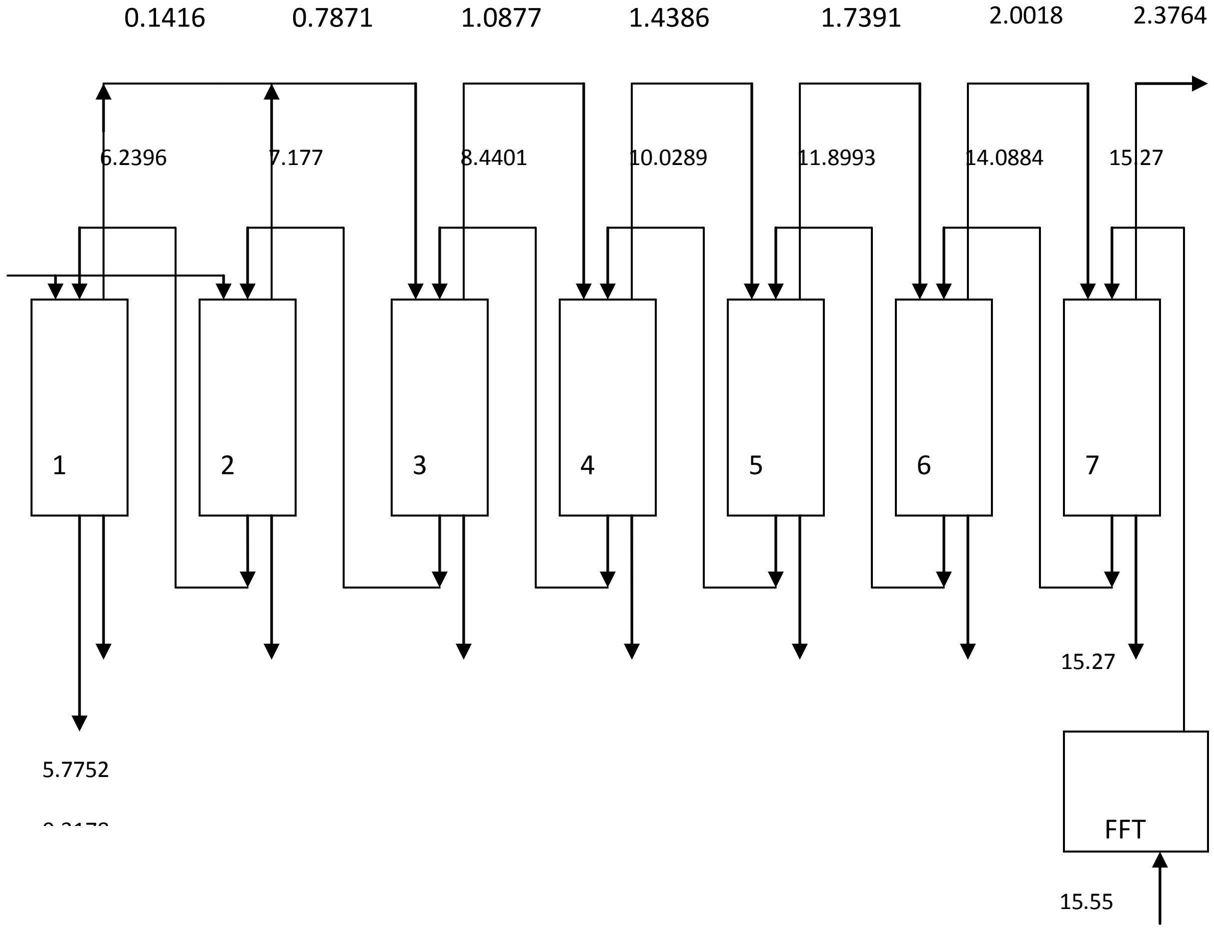
$P_1 = a_3/(3a_1)-(a_2/(3a_1)^2$

$Q_1 = (a_4 - a_2^3/(27a_1^2) - a_2 P_1)$

It also gives the liquor composition as obtained from component balance and the outlet vapour flow rate from each effect as obtained from mass balance. Since the multiple effect evaporator system considered is of backward flow arrangement, therefore the values are tabulated in reverse order. After obtaining the initial values, the check condition of Δx_{avg} & ΔF_{avg}. After satisfying the condition, the final values obtained are as follows.

Table 5.4 liquor flow rate, concentration and vapour flow rate from each effect

S.no.	Effect number	Liquor flow rate (kg/s)	Liquor Concentration	Vapour flow rate (kg/s)
1.	Seventh effect	14.0884	0.1312	2.3764
2.	Sixth effect	11.8993	0.1553	2.0018
3.	Fifth effect	10.0289	0.1843	1.7391
4.	Fourth effect	8.4401	0.2190	1.4386
5.	Third effect	7.1770	0.2571	1.0877
6.	Second effect	6.2396	0.2953	0.7871
7.	First effect	5.7752	0.3178	0.1416



The value of steam from each effect given in table 5.4 does not include the effect on condensate flashing. After incorporating the effect of three primary flash tanks and four secondary flash tanks, the modified values of vapour produced from each effect is evaluated. These values are the sum of the values of vapour produced from the preceding effect and the vapour generated from the condensate flash tanks.

Table 5.5 gives the amount of vapour generated from each of the condensate flash tanks

Table 5.5 Vapour generated from flash tanks

S.no.	Flash tank number	Amount of vapour (kg/s)
1.	CF V1	0.0063
2.	CF V2	0.0103
3.	CF V3	0.0153
4.	CF V4	0.0029
5.	CF V5	0.0083
6.	CF V6	0.0182
7.	CF V7	0.0369

These values of vapour generated from the condensate flash tanks are added to the respective streams of vapour generated from each of the effects and the modified values of vapour generated from each effect is evaluated in table 5.6

Table 5.6 Modified values of vapour from each effect

S.no.	Effect number	Vapour flow rate (kg/s)
1.	First effect	0.1416
2.	Second effect	0.7871
3.	Third effect	1.0969
4.	Fourth effect	1.4572
5.	Fifth effect	1.7726
6.	Sixth effect	2.0387
7.	Seventh effect	2.3764

Comparing table 5.4 and table 5.6, we can see the effect of using condensate flash tanks. Due to the presence of condensate flash tanks, auxiliary vapour is generated, which may be used in the respective effects to reduce the actual steam consumption.

After calculation of performance index, the modified pressure values are evaluated. The values of α, β, γ, γ’ and θ are as given in the table 5.7

Table 5.7 Values of parameters to obtain set of linear equations in table 4.2

S.no	α	β	γ	γ'	θ
1.	0.0396	1.0000	9.7950	8.3765	0.3716
2.	0.3411	1.0000	11.0364	9.7950	0.3037
3.	0.3057	0.9916	12.7060	11.0364	0.1979

4.	0.2885	0.9872	15.0803	12.7060	0.1175
5.	0.2578	0.9811	18.7592	15.0803	0.0628
6.	0.2129	0.9819	25.3314	18.7592	0.0296

The matrix A is the inverse of matrix Y

$$A = \begin{vmatrix} -1 & -1 & -1 & -1 & -1 & -1 & -1 \\ 0 & -1 & -1 & -1 & -1 & -1 & -1 \\ 0 & 0 & -1 & -1 & -1 & -1 & -1 \\ 0 & 0 & 0 & -1 & -1 & -1 & -1 \\ 0 & 0 & 0 & 0 & -1 & -1 & -1 \\ 0 & 0 & 0 & 0 & 0 & -1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 \end{vmatrix}$$

The modified pressure values as obtained by solving the set of linear equations given in table 4.2, after the first iteration is as given in table 5.8. These values of pressure are used in the successive iteration for the calculation of steam and condensate properties.

Table 5.8 Modified pressure values after first iteration

S.no.	Effect number	Pressure (bar)
1.	First effect	2.9773
2.	Second effect	2.3751
3.	Third effect	1.9155
4.	Fourth effect	1.5676
5.	Fifth effect	1.3047
6.	Sixth effect	1.1303
7.	Seventh effect	0.6331

The amount of vapour required by each effect before flashing and after flashing is given by table 5.9

Table 5.9 Amount of vapour required by each effect befor flashing and after flashing

S.no.	Effect number	Vapour flow rate (kg/s) (Before flashing)	Vapour flow rate (kg/s) (after flashing)
1.	First effect	0.1416	0.0630
2.	Second effect	0.7871	0.7501
3.	Third effect	1.0969	1.3846
4.	Fourth effect	1.4572	1.4362
5.	Fifth effect	1.7726	1.4398
6.	Sixth effect	2.0387	1.2911

7.	Seventh effect	2.3764	2.3061

The final steam consumption for the given system of seven effect evaporators is given by 7056.0 kg/hr after flash tanks are incorporated and the steam consumption before the flash tanks are incorporated is given by 7488.0 kg/hr.

Chapter 6

Conclusion

Chapter 6

CONCLUSION

In the present work, cascade simulation of a flat falling film seven effect evaporator system is done in order to optimize the system in terms of live steam requirement of the system. A generalized solution technique is used so that the same algorithm and code could be used and there be no need for a separate code for the different feed flow sequences or when additional flash tanks are used. Taking the results into account, the conclusions that can be drawn from the work are that the presence of flash tanks in a multiple effect evaporator system helps in reducing the live steam requirement of the system by deriving heat from the vapour as well. In the present work, initially the live steam requirement of the system is evaluated without the presence of any flash tanks and it is found out to be and the live steam requirement of the system is evaluated in the presence of seven condensate flash tanks and one feed flash tank.

The live steam requirement of the system without the use of flash tanks is found to be 7488.0 kg/hr

And with the use of flash tanks is found to be 7056.0 kg/hr .

The reduction in the consumption of live steam is because of the derivation of heat from the vapour coming out of each effect and it is found to be 432 kg/hr. This reduces the live steam consumption of the multiple effect evaporator system and hence the process is economized in terms of live steam consumption.

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