**Design and simulation of a multiple-effect evaporator using vapor bleeding**

A thesis submitted in partial fulfillment of the requirements for the degree of

Bachelor of Technology

In

Chemical Engineering

By

MonalishaNayak

Roll No. 108CH001

Under the guidance of

Dr. ShabinaKhanam

DEPARTMENT OF CHEMICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

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MonalishaNayak

Roll No. 108CH001

DEPARTMENT OF CHEMICAL ENGINEERING,

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

# CERTIFICATE

This is to certify that the project entitled "Design and simulation of a Multiple effect evaporator using Vapor bleeding" is an original work done by MonalishaNayak, Roll No. 108CH001, under my guidance and supervision.

Dr.ShabinaKhanam

Assistant Professor

Department of Chemical Engineering

National Institute of Technology, Rourkela

Date-
07.05.2012

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# NOMENCLATURE

The following nomenclature is used in the development of model equations:

| Symbol | Parameter | Unit |
|---|---|---|
| F | Feed flow rate | Kg/s |
| xf | Concentration of feed by weight | - |
| Tf | Feed temperature | ˚C |
| $T_i$ | Temperature of ith effect | ˚C |
| $L_i$ | Liquor flow rate from ith effect | Kg/s |
| $x_i$ | Concentration of liquor coming out of ith effect | - |
| $Cp_i$ | Specific heat capacity of liquor leaving ith effect | KJ/Kg K |
| $ʈ_i$ | Boiling point elevation of liquor in $i^{th}$ effect | ˚C |
| $h_i$ | Film heat transfer coefficient of liquor in $i^{th}$ effect | $KW/m^2K$ |
| $Ø_i$ | Heat flux in $i^{th}$ effect | $KW/m^2$ |
| $л_i$ | Linear velocity of liquid on tubes in $i^{th}$ effect | Kg/m.s |
| $V_i$ | Flow rate of vapor coming out of ith effect | Kg/s |
| $V_0$ | Steam flow rate | Kg/s |
| $T_0$ | Steam temperature | ˚C |
| $\lambda_0$ | Latent heat capacity of steam | KJ/Kg |
| $\lambda_i$ | latent heat capacity of vapor leaving ith effect | KJ/Kg |
| $V_{bi}$ | Flow rate of bleed stream from $V_i$ | Kg/s |
| h | Specific enthalpy of liquid phase | KJ/Kg |
| H | Specific enthalpy of vapor phase | KJ/Kg |
| $A_i$ | Heat transfer area of ith effect | $m^2$ |

# ABSTRACT

The objective of this report is to develop a model for a five-effect evaporator system. Vapor bleeding is incorporated in the model as a means to reduce the amount of steam consumed in the evaporator. Since evaporation is the most energy-intensive stage in any industrial operation, measures to reduce energy consumption in the evaporator-house are greatly beneficial towards making an operation cost-effective. Other energy reduction schemes like condensate, feed and product flashing, vapor compression etc. are also available. Vapor bleeding brings about an increase in the steam economy of the process, but at the added cost of the required heat exchangers.

A model for an evaporator used for the concentration of sugar solution is developed using a set of non-linear equations derived from the mass and energy balance relations. These equations are then solved using the Newton-Raphson method by developing a matlab code for the same. For the present system steam requirement without vapor bleeding is computed first. Other variables like effect temperatures and liquor flow rates are also a result of the modeling procedure. The same system is then modeled by incorporating vapor bleeding for which steam requirement is also found. Additionally, the purchase and installation cost of the heat exchangers required are computed.

Vapor bleeding brings an improvement in the steam economy of a process by 26% but at the added cost $1,50,291 of the five heat exchangers. Annual savings of $43,200 in the cost of steam is achieved. The payback period of the modified design of five effect evaporator system is found as 2 years 5 months and 12 days.

# CONTENTS

# CHAPTER ONE: INTRODUCTION

Evaporators are used in a process industry to concentrate solutions consisting of a non-volatile solute and volatile solvent, like foods, chemicals, etc. In a majority of the processes, the solvent is water. Dilute solutions contain a large amount of water, and the cost of processing such solutions involves a high equipment cost. The evaporation process proceeds by evaporating a part of the solvent from the solution to increase its concentration. This evaporation is carried out by using steam as the heating medium. Normally, the thick liquor obtained is the valuable product. The material of construction of an evaporator may be any kind of steel. Special materials like copper, stainless steel, nickel, aluminium may be used depending upon the specific properties of the solution to be concentrated.

When a single evaporator is used for concentration, the vapor issuing out of it is condensed and discarded. This type of operation is called single-effect evaporation. When a number of effects are used in series, such that the vapor coming out of one effect is used as a heating medium in the steam chest of the next effect, it is called multiple effect evaporation. Single effect evaporation is simple but fails to utilize the steam effectively, while multiple effect evaporators evaporate more quantity of water per kilogram of steam consumed in the evaporation process. This brings about a saving in the steam cost, but at the same time, the cost of material and installation of the evaporator system increases because of the large number of effects involved. There has to be trade-off between the material cost and the steam cost and the number of effects giving the minimum total cost is the most thermo-economic solution. The maximum number of effects in a multiple effect evaporator usually should not exceed seven, because beyond this, the material and installation cost of the evaporator effects offset the saving achieved in the steam cost.

The various process industries where evaporation plays a pivotal role are food and pharmaceuticals, pulp and paper, sugar, chlor-alkali, desalination of water etc. The most important application of evaporators is in the food and beverage industry. Evaporation of water from foods and beverages like milk products, fruit juices, various extracts, enables them to last for a longer period of time or helps in maintaining the required consistency, like in case of coffee. Evaporation eliminates excess moisture from pharmaceutical products, thereby improving product stability and enabling easy handling of the product. Preservation of long-term activity and stabilization of enzymes is brought about by evaporating excess moisture. In the pulp and paper industry, sodium hydroxide is recovered in the Kraft process by evaporation.

In an air-conditioning process, evaporation is used to allow the coolant, Freon, to evaporate from liquid to gas while absorbing heat. All industries must dispose off any waste after processing and methods for waste-handling are costly. By removing moisture through vaporization, there is a reduction in the amount of waste to be handled and thus the waste-handling cost incurred by any industry.

Evaporation is a highly energy-intensive process. It consumes a considerable portion of the energy consumed by the whole process. There is a great scope for cutting down the costs involved in an evaporation operation by reducing the live steam requirement in an evaporation operation. Efforts have been made by many researchers such as Khanam et al.(2010), Jorge et al.(2010), to cut down the steam consumption in a multiple-effect evaporator by different operating strategies like feed, condensate and product flashing, vapor compression, vapor bleeding, feed and steam splitting or using an optimal feed flow sequence.

Harper and Tsao (1972) carried out optimization of multiple effect evaporator and they modified the feed flow pattern. Their work was extended by Nishitani and Kunugita (1979) who considered all possible feed flow sequences to optimize a MEE system. All the mathematical models are solved by developing a set of non-linear equations originating from the corresponding mass and energy balance relations. When the operating strategy of a system is changed, a whole new set of equations results. This problem was addressed by Stewart and Beveridge(1977). They developed a generalized cascade algorithm which could be solved irrespective of the operating strategy involved in the operation.

Many different operating strategies such as flashing, vapor compression, have been studied in literature. In the present work, vapor bleeding as an energy reduction scheme has been elaborated. Vapor bleeding has been applied to three-effect problem first and then to an existing industrial five-effect system both for forward and backward feed flow sequences. Improvement in steam economy, if any, is noted and overall cost computations are made. To meet this target following objectives are to be framed:

- To develop governing equations for the multiple effect evaporator system without vapor bleeding and then for a system with vapor bleeding
- To develop a matlab code for the solution of these equations
- To compute the operating and the capital cost of the original system as well as the modified system.
- To compare the results of different modification to select the best design.

# CHAPTER TWO: LITERATURE REVIEW

Evaporation is a process of concentrating a given solution by heating it to vaporize water. Exposing the solution to a higher surface area or heating it to a higher temperature reduces the time needed to achieve a desired concentration. But increasing the temperature of operation or the residence time in an evaporator might degrade the solution. So, in order to avoid thermal degradation of the solution, the operating temperature, as well as the residence time should be kept as low as possible. This requirement has led to the development of many types of evaporators.

## 2.1. Different types of evaporators

Evaporators are classified into four categories

1. Evaporators in which the heating medium and the evaporating medium are separated by tubular heating surfaces
2. Evaporators in which the heating medium is confined by coils, jackets, double walls etc.
3. Evaporators in which the heating medium is in direct contact with the evaporating fluid.
4. Evaporators that use solar radiation as the heating medium.

The most commonly used evaporators are the tubular heating-surface evaporators. In these evaporators, the liquid flows past the heating surface either by natural circulation(boiling) or by forced circulation(mechanical methods).

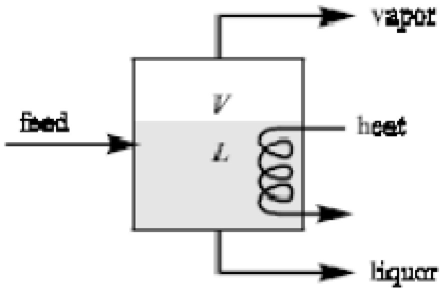


Fig.2.1. Schematic diagram of a single-effect evaporator[1]

The different types of evaporators are :

### 2.1.1.Horizontal tube evaporators

These were the first kind of evaporators that came into use and have the simplest of designs. It contains a shell and a horizontal tube within it, such that the heating medium is confined within the tubes and the liquid to be evaporated is in the shell. They have very limited use in present day applications, they are mostly used for fluids that have low viscosity and are non-scaling. They have a very low initial investment.

### 2.1.2. Horizontal spray-film evaporators

They are modified horizontal tube evaporators in which the liquid is distributed by a spray system and falls down the tubes by the action of gravity.

They give the following advantages:

1. Easy removal of non-condensable vapors
2. Uniform distribution of the liquid
3. Vapor is easily separated from the liquid
4. Convinient operation even with scaling fluids.

### 2.1.3. Short tube vertical evaporators

They are better known as Calandrias. Liquid circulates past the heating surface by boiling,i.e. natural circulation. The first short tube evaporator was built by Robert. They consist of tubes inside a shell. The tubes may be 2 to 3 inches in diameter and 4 to 10 feet long. A downcomer is present at the centre which enables the flow of liquid from the top to the bottom tube sheet.

### 2.1.4. Basket type evaporators

The first basket-type evaporator was built in 1877. These evaporators are similar to the short tube vertical evaporators in all respects, the only difference being that the downcomer, instead of being central, is annular. The annular downcomer is installed to allow removal of the evaporator for cleaning and repair purpose. The presence of the downcomer makes the design more economical. Entrainment losses are caused due to violent boiling in the vertical-tube evaporator. A deflector is provided in order to reduce entrainment from spouting.

### 2.1.5.Long tube vertical evaporators

They are the most versatile and economical evaporator systems. The tubes herein are 1 to 2 inch in diameter and 12 to 30 feet long. They may be operated as once-through or recirculating systems. In once-through evaporators, the liquid has a residence time of few seconds only. Recirculation type evaporators may be batch type or continuos. In a recirculating evaporator, a particular level in the vapor body has to be maintained, and a deflector is provided to prevent entrainment in the vapor body. There is a non-uniform temperature distribution in the tubes and this makes prediction of the tube side temperature difficult. Due to the appreciable length of the tubes, the effect of hydrostatic pressure head cannot be ignored.

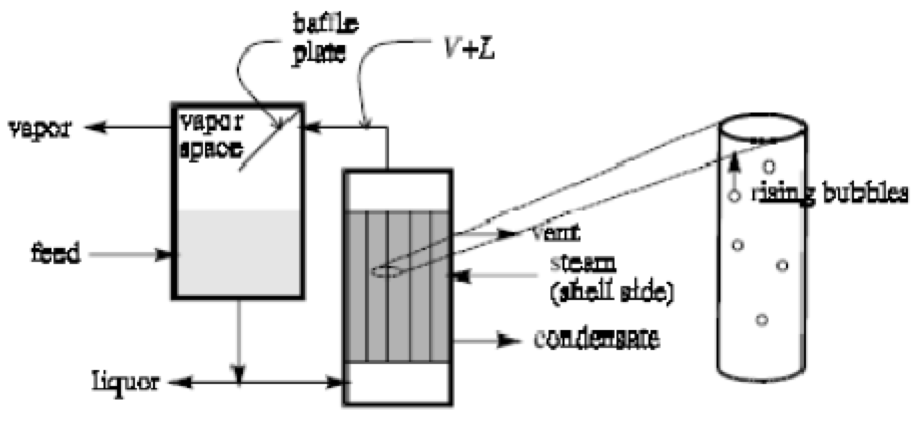


Fig.2.2.Long tube vertical evaporators ( Source: Unit operations in food engineering, www.nzifst.org.nz)

### 2.1.7 Climbing film evaporators

They are mainly used in industry to concentrate a solution. They are operated under vacuum, in order to lower the boiling point of the solution and thus increase the temperature difference driving force. The working principle behind this is the 'thermo-siphon' principle. The liquid rises up in the core of the tube in the form of a thin film, because the liquid flows faster than the vapor. Such a flow of the liquid is against gravity and thus it is highly turbulent. They give high heat transfer rates and have a low contact time. They are most ideal for concentration of heat sensitive materials like juices, pharmaceuticals etc. They provide low cost operation. They have the least cost per unit capacity available.

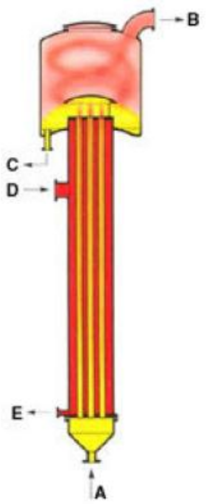


Fig.2.3. Climbing film evaporators

(Source: GEA Process Engineering Inc.)

A: Product

B: Vapor

C: Concentrate

D: Heating steam

E: Condensate

### 2.1.8. Falling film evaporators

In falling film evaporators, the liquid enters the tubes from the top, gets heated and flows downstream as a film, and leaves from the bottom. The tubes in these type of evaporators are about 2 to 10 in. in diameter. The vapor that is evolved from the liquid also moves downward with the liquid and is removed from the bottom of the unit. They have a liquid-vapor separator at the bottom to and a distributor for uniform distribution of the feed liquid at the top. Once-through falling film evaporators have a minimum time of exposure to the heated surface, and thus can be used for concentration of highly heat sensitive liquids. They are also effective in handling highly viscous liquids.

Recirculating evaporators distribute the liquid to the tubes by moderate recycling of the liquid from the bottom to the top of the tubes. Recirculating systems allow larger volume of flow through the tubes as compared to the once-through evaporators.

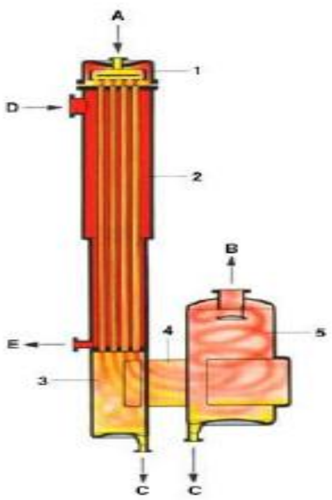


Fig.2.4. Falling-film evaporators (Source: GEA Process Engineering Inc.)

### 2.1.9. Rising falling film evaporators

A high heat transfer rate is obtained by incorporating both the falling film and rising film evaporators in a single unit. Such type of evaporator is called rising-falling film evaporator. They have short residence times for the liquid and are hence suitable for heat sensitive products.

### 2.1.10 Forced circulation evaporators

Natural circulation evaporators give uneconomically low heat transfer coefficients with viscous liquids since the velocity of liquid entering the tubes is low, only about 0.3 to 1.2 m/s.

Forced-circulation evaporators provide for a centrifugal pump which forces the liquid through the tubes at a higher velocity, about 2 to 5.5 m/s. Sufficient static head is provided to the tubes to ensure that the liquid does not boil over the heating surface, in order to avoid the fouling characteristics of the liquid.  It has a shell and tube heat exchanger, with vertical or horizontal tubes. There is a significant reduction in the cost of evaporation of viscous liquids by using forced circulation evaporators, despite the added cost of pumping. Because of the high liquid velocities, they take very short residence times and are good for moderately heat sensitive liquids. Forced circulation evaporators are also used for evaporating salting liquors, or those that have foaming tendency.

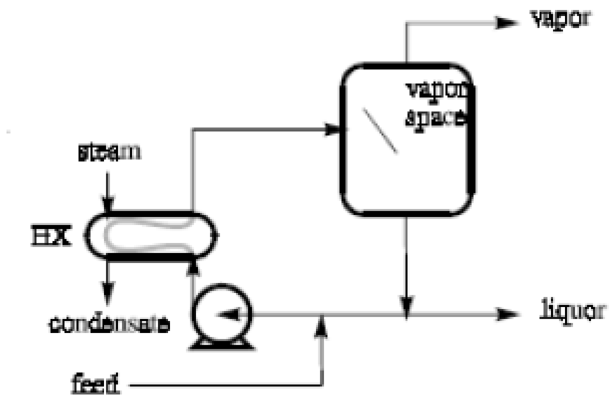


Fig.2.5. Forced-Circulation Evaporators [1]

### 2.1.11. Plate type evaporators

Plate evaporators consist of corrugated and framed plates that are suitable for scaling liquids, since the scales can be easily flaked off the plates. They provide relatively larger surface areas than other type of evaporators. The liquid is pumped between the thin plates, and the heating medium is provided between the mating surfaces. They have a single pass operation and thus a short contact time with the heating surface, making them suitable for heat-sensitive liquids. The product quality is better than other evaporators. They have a low liquid hold-up and produce minimal waste. They can be easily scaled up, and need low installation cost due to their compact size and light weight.

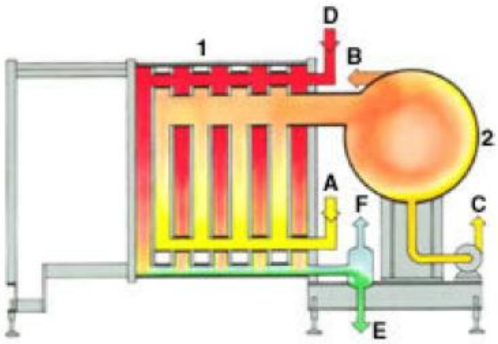


Fig.2.6. Plate type evaporators (Source: GEA Process Engineering Inc.)

## 2.2. Modeling of a multiple effect evaporator system

There are two different ways of modeling a multiple effect evaporator:

**Equation-based model**

In the equation based model, the various operating parameters of the different effects are related by the mass and enthalpy balance relations, the heat transfer rates and the phase equilibrium relationships for the liquid and vapor (Radovic et.al,1979). This results in a set of non-linear equations. The number of variables and equations depends on the operating strategy of the evaporator system. This system of non-linear equations is then solved, iteratively or by developing a code for the Newton-raphson method. Pre-developed solvers are also available for obtaining the solution of non-linear systems.

This model is disadvantageous when the operating strategy of a system changes, like when the feed flow sequence is altered, or when feed or product flashing is incorporated because the original equations now fail to hold true and a completely new set of equations has to be developed again.

Equation based models for the design of chemical reactors and mass transfer separation equipment have been developed in literature by Itahara and Steil (1966) using programming.

A model based on boiling point rise and enthalpy relationships developed by curve fitting procedures was presented by Lambert et al. (1987).

Similar equation based models are previously published in literature by Holland (1975), Mathur (1992), Bremford and Muller-Steinhagen (1994), Bhargava (2004).

**Cascade algorithm**

In cascade algorithm, generalized equations are written for a model which are independent of the operating strategy. This model can handle any feed flow sequence, condensate, feed or product flashing, and vapor bleeding. The liquor flow rate entering each effect is taken as the total of the fraction of feed entering that effect and the fraction of feed entering that effect from the previous effect. On changing the operating condition in any way, the feed flow sequence in the algorithm does not need to be changed, and the same program can be used.(Bhargava et al., 2010)

Other generalized models on similar lines have also been developed by Stewart and Beveridge (1977) and Ayangbile et al. (1984).

## 2.3. Energy Reduction Schemes(ERSs) in evaporators.

### 2.3.1. Flash evaporation

Flash evaporation is the process in which a part of the heated liquid instantly vaporizes when its pressure is suddenly reduced. The reduction in pressure is brought about by passing the liquid through a throttling device. The vessel within which flash evaporation occurs is called as a flash drum. A single component liquid flashes into vapor but a in the case of a multicomponent liquid, the flash vapor contains a greater amount of the more volatile component than the residual liquid.

A flashing liquid utilizes the energy it possesses in excess of the evaporation enthalpy, thus flashing helps in reduction of energy consumption. In a normal evaporation operation, either the feed, the evaporation product, or the condensate can be flashed.

### 2.3.2. Vapor compression

In vapor compression, the pressure of the vapor leaving the evaporator system is increased by using a blower or compressor. The purpose of compression is to make the vapor suitable for heating in the steam chest of the same effect in place of steam. The vapor issuing out of an effect in an evaporator has the same temperature as the effect, and thus is unsuitable for use as a heating medium in the same effect since the temperature difference driving force in this case would be zero. However, if the pressure of this vapor is reduced, the boiling point of the vapor increases and it stays at a higher temperature than the effect temperature, and there is some driving force for heat transfer. But the latent heat of this vapor has been lowered after compression.

### 2.3.3. Vapor bleeding

Vapor bleeding is a scheme in which a part of the vapor coming out of one effect is withdrawn and utilized to preheat the liquor entering any other effect. I a backward feed evaporator, the liquor coming out of any effect is at a temperature lower than the next subsequent effect it is going to enter. Therefore, a part of the heat provided by the heating medium in that effect is first utilized to raise the temperature of the liquor to that of the effect, and the remaining heat is devoted towards evaporating water from the liquor. In an evaporation operation, the goal is to obtain maximum concentration, by evaporating as much water as possible. Therefore, if the heat utilized to achieve the temperature rise is met from somewhere else, the entire amount of heat in the effect could be utilized for evaporation of water only, and we would thus have a higher evaporator economy.

To fulfill this purpose, vapor is bled out of a particular effect and additional heat exchangers are installed to raise the temperature of the liquor entering any effect, using this bled vapor as the heating medium.

There is additional cost incurred in this process, like the capital cost of the heat exchangers, but great savings are brought about in the cost of steam.

## 2.4. Sugarcane juice

Sugarcane is a low-cost agricultural resource, produced mainly in tropical and sub-tropical regions. Sugarcane juice is the juice extracted from pressed sugarcane. It is consumed as a beverage worldwide. Sugarcane is commercially grown in South east Asia, South Asia and Latin America. One of the most important applications of sugarcane juice is in the production of ethanol biofuel. Sugarcane juice is used as a raw material in sugar industry. After some pre-treatment steps, the juice is concentrated in large evaporators to produce sugar. This evaporation removes about 98% of the water in the juice and sugar crystals are formed.

The evaporator house of a sugarcane industry is the most energy-intensive part. In the present study, vapor bleeding as a method to reduce the steam consumption, and thus the cost of operation of the evaporation operation, is studied in various patterns of triple-effect and five-effect evaporators.

Sugarcane juice is composed of combinations of sugars, including glucose and fructose. Some soluble solids like sugars and organic acids are also present. It is alkaline in nature. The rheology and fluid dynamics properties of sugarcane juice were studied by Zailer Astolfi-Filho et al. in February 2011 [15].

# CHAPTER THREE: PROBLEM STATEMENT

## 3.1. Problem I

A triple-effect evaporator is considered which is used for concentrating sugarcane juice. The base-case operating parameters are listed in Table 3.1. The schematic diagram of the system in shown in Fig.3.1. The feed flow sequence is backward, that is the feed is fed to the 3$^{rd}$ effect, from there the liquor moves to the second effect, and from the second to the first effect. Live steam is fed to the 1$^{st}$ effect only.

Table 3.1. Operating parameters for a three-effect backward feed problem

| S.No. | Parameter(s) | Value(s) |
|---|---|---|
| 1 | Total no. of effects | 3 |
| 2 | Number of effects supplied with live steam | 1 |
| 3 | Live steam temperature, To | 121.1˚C |
| 4 | Feed flow rate, F | 22680 kg/hr |
| 5 | Feed temperature, Tf | 22˚C |
| 6 | Feed concentration, xf | 10% by wt. |
| 7 | Area of each effect, A | 100m$^2$ |
| 8 | Temperature of last effect | 52˚C |
| 9 | Feed flow sequence | Backward |
| 10 | Length of evaporator tubes | 4 m |

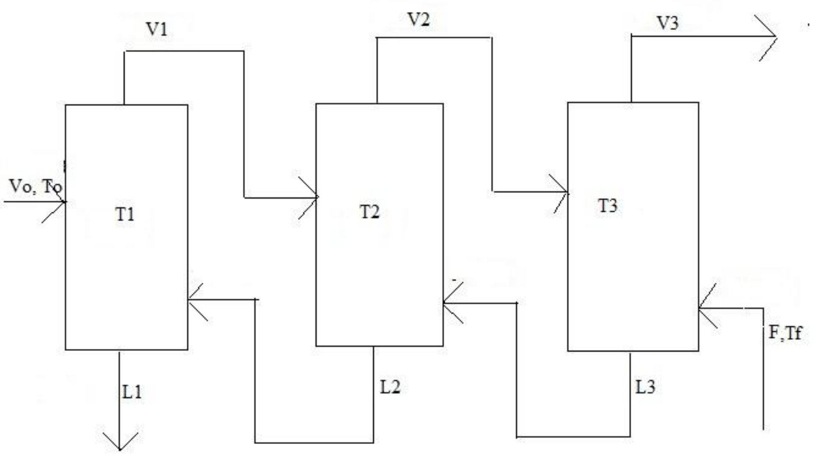


Fig.3.1. Schematic diagram of triple-effect evaporator system

### 3.2. Problem II

In this problem, a five-effect evaporator is considered which is operated in forward feed sequence. The operating parameters and schematic diagram of the system are shown in Table 3.2 and Fig. 3.2, respectively.

Table 3.2. Operating parameters for the five-effect evaporator

| S.No. | Parameter(s) | Value(s) |
|---|---|---|
| 1 | Total no. of effects | 5 |
| 2 | Number of effects supplied with live steam | 1 |
| 3 | Live steam temperature, To | 120˚C |
| 4 | Feed flow rate, F | 37.8 kg/s |
| 5 | Feed temperature, Tf | 108˚C |
| 6 | Feed concentration, xf | 13% by wt. |
| 7 | Area of first effect, A1 | 1800 |
| 8 | Area of second effect, A2 | 1400 |
| 9 | Area of third effect, A3 | 600 |
| 10 | Area of fourth effect, A4 | 300 |
| 11 | Area of fifth effect, A5 | 300 |
| 12 | Temperature of last effect | 62˚C |
| 13 | Length of evaporator tubes | 4 m |

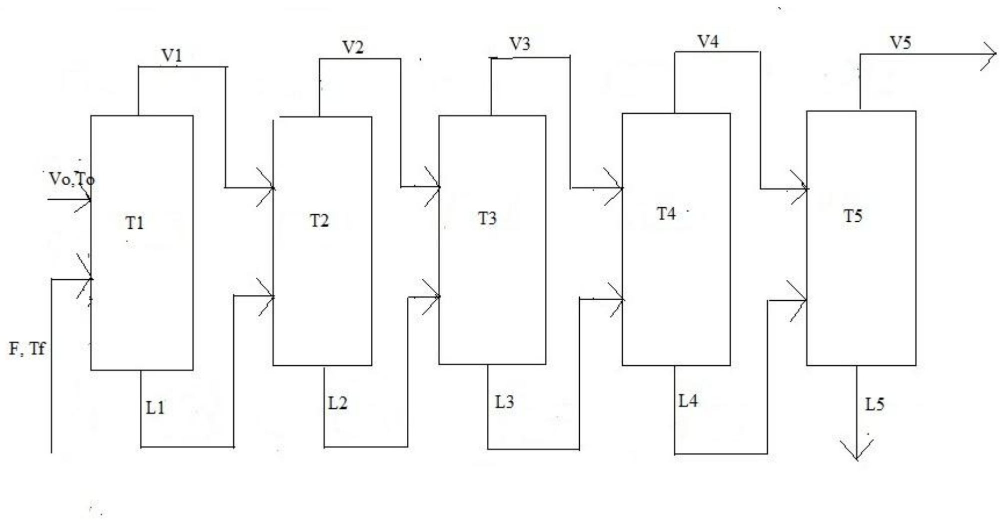


Fig.3.2. Schematic diagram of the five-effect forward feed system with one stage pre-heating

# CHAPTER FOUR : DEVELOPMENT OF THE MODEL AND SOLUTION PROCEDURE

## 4.1. Model development for a particular effect

The block diagram of a single effect is shown in Fig.4.1. The effect belongs to an evaporator being operated in forward feed flow sequence. $T_i$ is the temperature of the $i^{th}$ effect. $L_{i-1}$ is the flow rate of liquor leaving effect i-1 entering effect i and $L_i$ is the flow rate of liquor leaving effect i. $V_{i-1}$ is the vapor flow rate leaving effect i-1, which is used as a heating medium in effect i. $V_i$ is the vapor flow rate leaving effect i, which leaves at the temperature of the effect, i.e., $T_i$.

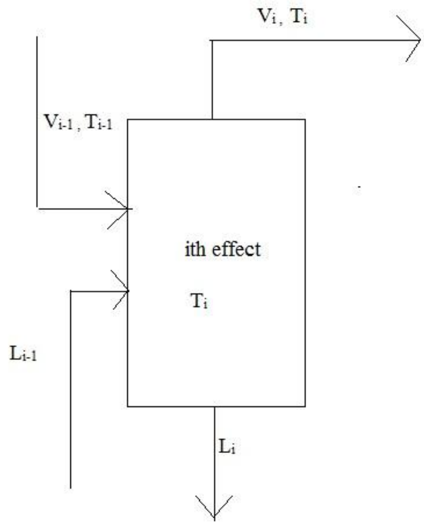


Fig.4.1. Block diagram of a single effect in a multiple effect evaporator operating in forward feed flow

The equation based model is developed by writing the mass and energy balance relations for each effect, as well as the equations for heat-transfer rates[2].

The overall mass balance over ith effect becomes

$L_{i-1} = L_i + V_i$ (4.1)

Component mass balance is written as

$L_{i-1}\, x_{i-1} = L_i\, x_i = L_f\, x_f$ (4.2)

Overall energy balance

$L_{i-1}\, h_{i-1} + Q_i - V_i H_i - L_i h_i = 0$ (4.3)

$Hi = \lambda_i + h_i$ (4.4)

Thus, equation 4.3 becomes

$L_{i-1}\, h_{i-1} - L_i\, h_i + Qi - V_i\, \lambda_i = 0$ (4.5)

The enthalpy balance on the steam chest is given by

$$Q_i = V_{i-1}\lambda_{i-1} \qquad (4.6)$$

And the rate of heat transfer is given by

$$Q_i = U_i A_i (T_{i-1} - T_i) \qquad (4.7)$$

Substituting the relation for $Q_1$ , we finally get two equations for any ith effect

Enthalpy balance: $f_1 = L_{i-1} h_{i-1} - L_i h_i + V_{i-1}\lambda_{i-1} - V_i \lambda_i$

Heat transfer rate : $f_2 = U_i A_i (T_{i-1} - T_i) - V_{i-1}\lambda_{i-1}$

Similar relations are written for all the effects, depending on the operating strategy. The number of equations obtained is equal to the number of variables to be solved for. The set of non-linear equations is solved using Newton-Raphson method to get converged values for all the variables.

### 4.2. Model development for the three effect backward feed evaporator

The following six equations are obtained from the mass and enthalpy balance, and heat transfer rate equations for the three effects. A total of six non-linear equations is to be solved to obtain the variables Vo, $T_1$, $T_2$, $L_1$, $L_2$, $L_3$.

$$f_1 = L_2 C_{p2} T_2' + V_o\lambda_o - (L_2 - L_1)H_1 - L_1 C_{p1} (T_1 + \tau_1) \qquad (4.8)$$

$$f_2 = U_1 A(T_o - T_1) - V_o\lambda_o \qquad (4.9)$$

$$f_3 = L_3 C_{p3} (T_3 + \tau_3) + (L_2 - L_1)\lambda_1 - (L_3 - L_2) H_2 - L_2 C_{p2}(T_2 + \tau_2) \qquad (4.10)$$

$$f_4 = U_2 A(T_1 - T_2) - (L_2 - L_1)\lambda_1 \qquad (4.11)$$

$$f_5 = F C_{pF} T_F + (L_3 - L_2) \lambda_2 - (F - L_3) H_3 - L_3 C_{p3}(T3 + \tau_3) \qquad (4.12)$$

$$f_6 = U_3A(T_2 - T_3) - (L_3 - L_2)\lambda_2 \quad (4.13)$$

**4.3. Model development for the three effect backward feed evaporator with bleeding**

The schematic of the three effect backward feed system with bleeding is shown in Fig 4.2. Here, two bleed streams are withdrawn from the vapor leaving effects 1 and 2 to pre heat the liquor entering effects 2 and 3 respectively. Therefore, we have two additional equations obtained as a result of the enthalpy balance over the bleed streams.

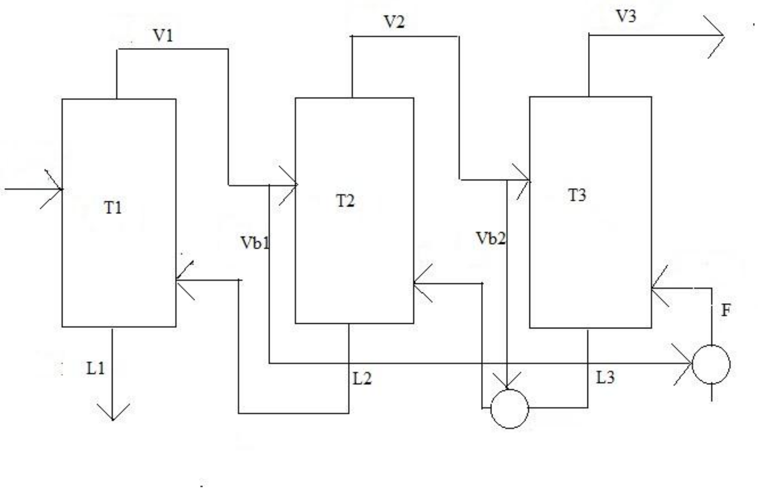


Fig.4.2. Schematic diagram of a three effect backward feed system with bleeding

$$f_1 = L_2C_{p2}T_2' + V_o\lambda_o - (L_2 - L_1)H_1 - L_1C_{p1}(T_1 + \tau_1) \quad (4.14)$$

$$f_2 = U_1A(T_o - T_1) - V_o\lambda_o \quad (4.15)$$

$$f_3 = L_3C_{p3}(T_3 + \tau_3) + (L_2 - L_1 - V_{b1})\lambda_1 - (L_3 - L_2)H_2 - L_2C_{p2}(T_2 + \tau_2) \quad (4.16)$$

$$f_4 = U_2A(T_1 - T_2) - (L_2 - L_1 - V_{b1})\lambda_1 \quad (4.17)$$

$$f_5 = FC_{pF}T_F + (L_3 - L_2 - V_{b2})\lambda_2 - (F - L_3)H_3 - L_3C_{p3}(T3 + \tau_3) \quad (4.18)$$

$$f_6 = U_3A(T_2 - T_3) - (L_3 - L_2 - V_{b2})\lambda_2 \quad (4.19)$$

$$f_7 = V_{b1}\lambda_1 - L_2\,Cp_2\,(T_1 - T_2) \quad (4.20)$$

$$f_8 = V_{b2}\lambda_2 - L_3\,Cp_3\,(T_2 - T_3) \quad (4.21)$$

**4.4. Model development for the five- effect forward feed evaporator without bleeding**

A five-effect system is modeled using the mass and energy balance relations. A total of 10 equations are obtained for the variables $V_0$, $T_1$, $T_2$, $T_3$, $T_4$, $L_1$, $L_2$, $L_3$, $L_4$ and $L_5$. In this system, the inlet temperature of the feed is at 108˚C. Therefore, an additional quantity of steam is consumed in preheating the feed from its normal temperature to the required feed inlet temperature.

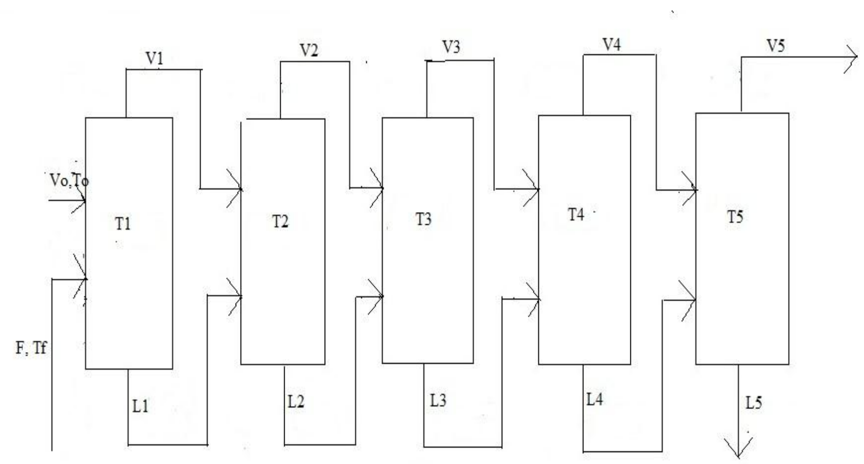


Fig.4.3. Schematic of the five-effect forward feed evaporator without bleeding

$$f_1 = FC_{pf}T_f + V_o\lambda_o - (F - L_1)H_1 - L_1C_{p1}(T_1 + \tau_1) \quad (4.22)$$

$$f_2 = U_1A_1(T_o - T_1) - V_o\lambda_o \quad (4.23)$$

$$f_3 = L_1\,C_{p1}\,(T_1 + \tau_1) + (F - L_1)\lambda_1 - (L_1 - L_2)H_2 - L_2C_{p2}(T_2 + \tau_2) \quad (4.24)$$

$$f_4 = U_2A_2(T_1-T_2) - (F - L_1)\lambda_1 \qquad (4.25)$$

$$f_5 = L_2\, C_{p2}\; (T_2 + \text{ʈ}_2) + (L_1 - L_2)\, \lambda_2 - (L_2 - L_3)\, H_3 - L_3C_{p3}(T_3 + \text{ʈ}_3) \qquad (4.26)$$

$$f_6 = U_3A_3(T_2-T_3) - (L_1 - L_2)\, \lambda_2 \qquad (4.27)$$

$$f_7 = L_3\, C_{p3}\; (T_3 + \text{ʈ}_3) + (L_2 - L_3)\, \lambda_3 - (L_3 - L_4)\, H_4 - L_4C_{p4}(T_4 + \text{ʈ}_4) \qquad (4.28)$$

$$f_8 = U_4A_4(T_3-T_4) - (L_2 - L_3)\, \lambda_3 \qquad (4.29)$$

$$f_9 = L_4\, C_{p4}\; (T_4 + \text{ʈ}_4) + (L_3 - L_4)\, \lambda_4 - (L_4 - L_5)\, H_5 - L_5C_{p5}(T_5 + \text{ʈ}_5) \qquad (4.30)$$

$$f_{10} = U_5A_5(T_4-T_5) - (L_3 - L_4)\, \lambda_4 \qquad (4.31)$$

**4.5. Model development for the five-effect forward feed evaporator with bleeding**

In this case, the temperature of the feed is 108˚C, which is far higher than the normal temperature of 30˚C. Therefore, the feed has to be pre-heated to a temperature of 108˚C from 30˚C. To carry out this pre-heating, vapor is bled from the evaporator effects.

In the forward feed case, the preheating of the feed can be done either by employing additional steam to raise the feed temperature from 30˚C to 108˚C directly, or it may be done in four steps, from 30˚C to 50˚C, 50˚C to 70˚C, 70˚C to 88˚C and finally from 88˚C to 108˚C. The first step, i.e. from 30˚C to 50˚C is met by bleeding vapor coming out of effect 4. The heating from 50˚C to 70˚C is done by bleeding vapor from effect 3. The temperature of the feed is then raised from 70˚C to 88˚C by bleeding a part of the vapor coming out of the 2$^{nd}$ effect. Further preheating from 88˚C to 108˚C is carried out by employing additional steam.

Fig.4.4. shows the schematic of the five-effect forward feed evaporator employing vapor bleeding for four-stage preheating

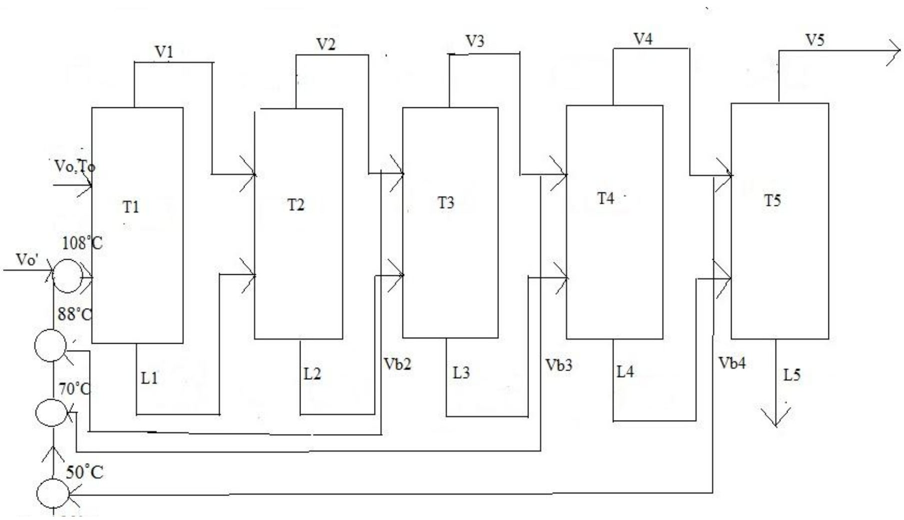


Fig.4.4. Schematic of the five effect forward feed evaporator with four stage pre-heating

$f_1 = FC_{pf}T_f + V_o\lambda_o - (F - L_1)H_1 - L_1C_{p1}(T_1 + \tau_1)$ (4.32)

$f_2 = U_1A_1(T_o - T_1) - V_o\lambda_o$ (4.33)

$f_3 = L_1 C_{p1} (T_1 + \tau_1) + (F - L_1)\lambda_1 - (L_1 - L_2) H_2 - L_2C_{p2}(T_2 + \tau_2)$ (4.34)

$f_4 = U_2A_2(T_1 - T_2) - (F - L_1)\lambda_1$ (4.35)

$f_5 = L_2 C_{p2} (T_2 + \tau_2) + (L_1 - L_2 - V_{b2}) \lambda_2 - (L_2 - L_3) H_3 - L_3C_{p3}(T_3 + \tau_3)$ (4.36)

$f_6 = U_3A_3(T_2 - T_3) - (L_1 - L_2 - V_{b2}) \lambda_2$ (4.37)

$f_7 = L_3 C_{p3} (T_3 + \tau_3) + (L_2 - L_3 - V_{b3}) \lambda_3 - (L_3 - L_4) H_4 - L_4C_{p4}(T_4 + \tau_4)$ (4.38)

$f_8 = U_4A_4(T_3 - T_4) - (L_2 - L_3 - V_{b3}) \lambda_3$ (4.39)

$f_9 = L_4 C_{p4} (T_4 + \tau_4) + (L_3 - L_4 - V_{b4}) \lambda_4 - (L_4 - L_5) H_5 - L_5C_{p5}(T_5 + \tau_5)$ (4.40)

$f_{10} = U_5A_5(T_4 - T_5) - (L_3 - L_4 - V_{b4}) \lambda_4$ (4.41)

$$f_{11} = V_{b2}\,\lambda_2 - FCp_f(88\text{-}70) \quad (4.42)$$

$$f_{12} = V_{b3}\,\lambda_3 - FCp_f(70\text{-}50) \quad (4.43)$$

$$f_{13} = V_{b4}\,\lambda_4 - FCp_f(50\text{-}30) \quad (4.44)$$

$$f_{14} = V_0^{'}\lambda_0 - FCp_f(108\text{-}88) \quad (4.45)$$

**4.6. Model development for the five-effect evaporator operated in backward feed flow without bleeding**

The same five-effect evaporator is now operated in backward-flow, with and without bleeding. In backward flow, the feed temperature can be raised to a maximum of 52˚C in order to maintain a 10˚C temperature approach. This is done by employing additional steam (in the case without bleeding).Fig.4.5. shows the schematic of the five-effect backward flow evaporator without bleeding.

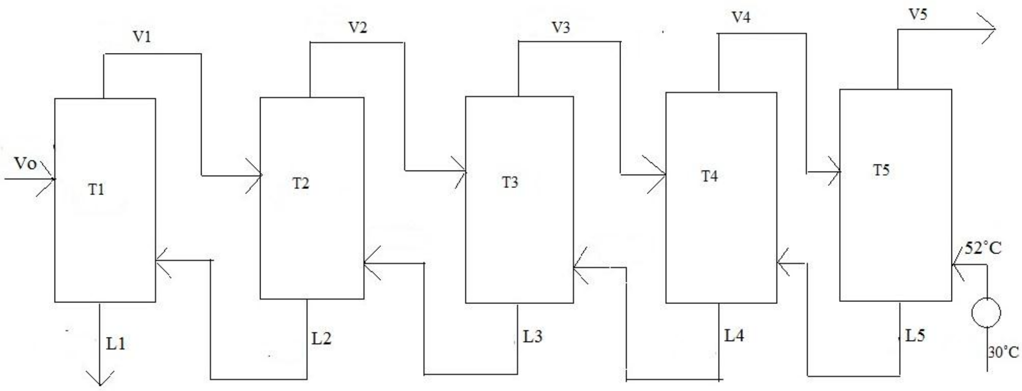


Fig.4.5. Schematic of the five-effect backward feed flow without bleeding

$$f_1 = L2Cp2\,(T2+\tau_2) + V_o\lambda_o - (L_2 - L_1)H_1 - L_1C_{p1}(T_1 + \tau_1) \quad (4.46)$$

$$f_2 = U_1A_1(T_o - T_1) - V_o\lambda_o \quad (4.47)$$

$$f_3 = L_3\, C_{p3}\, (T_3 + \tau_3) + (L_2 - L_1)\lambda_1 - (L_3 - L_2)\, H_2 - L_2C_{p2}(T_2 + \tau_2) \quad (4.48)$$

$$f_4 = U_2A_2(T_1 - T_2) - (L_2 - L_1)\lambda_1 \quad (4.49)$$

$$f_5 = L_4\, C_{p4}\, (T_4 + \tau_4) + (L_3 - L_2)\,\lambda_2 - (L_4 - L_3)\, H_3 - L_3C_{p3}(T_3 + \tau_3) \quad (4.50)$$

$$f_6 = U_3A_3(T_2 - T_3) - (L_3 - L_2)\,\lambda_2 \quad (4.51)$$

$$f_7 = L_5\, C_{p5}\, (T_5 + \tau_5) + (L_4 - L_3)\,\lambda_3 - (L_5 - L_4)\, H_4 - L_4C_{p4}(T_4 + \tau_4) \quad (4.52)$$

$$f_8 = U_4A_4(T_3 - T_4) - (L_4 - L_3)\,\lambda_3 \quad (4.53)$$

$$f_9 = F\, C_{pf}\, T_f + (L_5 - L_4)\,\lambda_4 - (F - L_5)\, H_5 - L_5C_{p5}(T_5 + \tau_5) \quad (4.54)$$

$$f_{10} = U_5A_5(T_4 - T_5) - (L_5 - L_4)\,\lambda_4 \quad (4.55)$$

### 4.7. Model development for the five-effect evaporator operated in backward feed flow with bleeding

With vapor bleeding, the feed temperature is raised by bleeding a part of the vapor leaving the 5$^{th}$ effect. Then a part of the vapor leaving the 4$^{th}$ effect is used to preheat the liquor entering effect 4. Similarly, five bleed streams are taken and the additional cost of five heat exchangers has to be considered Fig.4.6. shows the schematic of the same system with vapor bleeding.

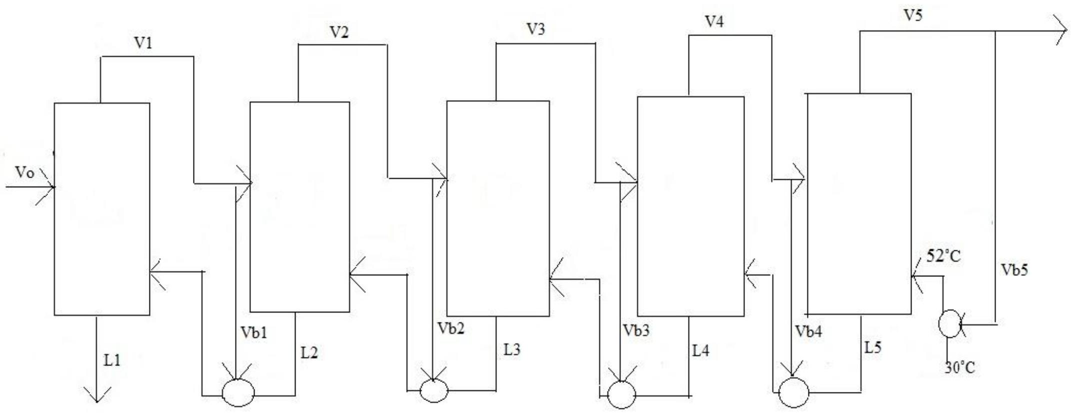


Fig.4.6. Schematic of the five-effect backward flow evaporator with vapor bleeding

$$f_1 = L2Cp2\ ( T2+\text{ɽ}_2)+ V_o\lambda_o - (L_2 - L_1)H_1 - L_1C_{p1}\,(T_1+ \text{ɽ}_1) \quad (4.56)$$

$$f_2 = U_1A_1(T_o - T_1) - V_o\lambda_o \quad (4.57)$$

$$f_3 = L_3\ C_{p3}\ \ (T_3 +\text{ɽ}_3) + (L_2 - L_1)\lambda_1 - (L_3 -L_2)\ H_2 - L_2C_{p2}(T_2+ \text{ɽ}_2) \quad (4.58)$$

$$f_4 = U_2A_2(T_1\text{-}T_2) - (L_2 - L_1)\lambda_1 \quad (4.59)$$

$$f_5= L_4\ C_{p4}\ \ (T_4 +\text{ɽ}_4) + \ (L_3 -L_2)\ \lambda_2 - (L_4 - L_3)\ H_3 - L_3C_{p3}(T_3 + \text{ɽ}_3) \quad (4.60)$$

$$f_6= U_3A_3(T_2\text{-}T_3) - (L_3 -L_2)\ \lambda_2 \quad (4.61)$$

$$f_7 = L_5\ C_{p5}\ \ (T_5 +\text{ɽ}_5) + \ (L_4 - L_3)\ \lambda_3 - (L_5 - L_4)\ H_4 - L_4C_{p4}(T_4 + \text{ɽ}_4) \quad (4.62)$$

$$f_8 = U_4A_4(T_3\text{-}T_4) - (L_4 - L_3)\ \lambda_3 \quad (4.63)$$

$$f_9\ = F\ C_{pf}\ T_f + \ (L_5 - L_4)\ \lambda_4 - (F - L_5)\ H_5 - L_5C_{p5}(T_5 + \text{ɽ}_5) \quad (4.64)$$

$$f_{10} = U_5A_5(T_4\text{-}T_5) - (L_5 - L_4)\ \lambda_4 \quad (4.65)$$

$$f_{11} = V_{b5}\,\lambda_5 - FCp_f(T_5\text{-}10\text{-}30) \quad (4.66)$$

$$f_{12} = V_{b4}\,\lambda_4 - L_5Cp_5(T_4\text{-}5\text{-}(\ T_5 + \text{ɽ}_5)) \quad (4.67)$$

$f_{13} = V_{b3}\,\lambda_3 - L_4 Cp_4\,(T_3\text{-}5\text{-}(\,T_4 + ɽ_4))$ (4.68)

$f_{14} = V_{b2}\,\lambda_2 - L_3 Cp_3\,(T_2\text{-}5\text{-}(\,T_3 + ɽ_3))$ (4.69)

$f_{15} = V_{b1}\,\lambda_1 - L_2 Cp_2\,(T_1\text{-}5\text{-}(\,T_2 + ɽ_2))$ (4.70)

### 4.8. Solution of the model: Newton Raphson method [2]

The obtained equations for the model are written in a compact form as

$J_k \Delta X_k = -f_k$

Where $J_k$ is the jacobian matrix

And $\Delta X_k = X_{k+1} - X_k = [\Delta V_0\ \Delta T_1 \Delta T_2\ \Delta L_1\ \Delta L_2\ \Delta L_3]'$ (for the case of 4.2)

$X_{k+1}$ and $X_k$ are respectively the values of the variables obtained after $(k+1)^{th}$ and $k^{th}$ iterations respectively.

An assumed set of values for all the variables are provided. The initial guess values for temperature are provided by assuming that there is equal driving force in each effect, and the initial values for the liquor flow rates are provided assuming equal vaporization in each effect.

If the functional values $f_1$, $f_2 \ldots . f_6$ and their partial derivatives occurring in the jacobian matrix are continuos, and the determinant of $J_k$ is not equal to zero, the Newton Raphson method will provide a converged solution with a limited number of iterations.

### 4.9. Empirical correlations for specific heat, boiling point rise, latent heat and heat transfer coefficient

The values of specific heat capacity, boiling point elevation of the liquor and latent heat capacity of the vapor are calculated from empirical correlations. Empirical correlations are also used for calculating the film heat transfer coefficient of the liquor.

The correlations given in equations 4.8 to 4.13 are used to calculate the specific heat capacity, boiling point elevation[5] and film heat transfer coefficient [10] respectively for the liquor and equation 4.11 gives the latent heat for the vapor[5] coming out of a particular effect.

$$Cp = 4.19-2.35x, \quad (4.8)$$

$$\tau = 1.78x+6.22(x^2) \quad (4.9)$$

$$hi = 218 + 24\phi - 3700x + 1090\Gamma + 32(T+\tau) \quad (4.10)$$

$$\lambda = 2823.2-4.9783T \quad (4.11)$$

where x is the concentration of the liquor by wt.

Cp is the specific heat capacity in KJ/Kg K.

$\tau$ is the boiling point elevation in the liquor in ˚C

$\phi$ is the heat flux in the effect, $KW/m^2$

$\Gamma$ is the linear velocity of the liquid on the tubes, kg/m.s

T is the temperature of the effect from where the vapor is leaving,˚C

$\lambda$ is the latent heat of the vapor in KJ/Kg.

**4.10. Detailed iterative solution procedure of the three-effect backward feed evaporator**

The model equations are shown in equations 4.8 to 4.13

The jacobian matrix is

$$\begin{vmatrix}
\lambda o & -L_1Cp_1-(L_2-L_1)Cp_1 & L_2Cp_2 & -Cp_1(T_1+\text{ɽ}_1)+Cp_1T_1+\lambda_1 & Cp_2(T_2+\text{ɽ}_2)-(Cp_1T_1+\lambda_1) & 0 \\
-\lambda o & -U_1A & 0 & 0 & 0 & 0 \\
0 & 0 & -L_2Cp_2-Cp_2(L_3-L_2) & -\lambda_1 & \lambda_1-Cp_2(T_2+\text{ɽ}_2)+(Cp_2T_2+\lambda_2) & Cp_3(T_3+\text{ɽ}_3)-(Cp_2T_2+\lambda_2) \\
0 & U_2A & -U_2A & \lambda_1 & -\lambda_1 & 0 \\
0 & 0 & 0 & 0 & -\lambda_2 & \lambda_2-Cp_3(T_3+\text{ɽ}_3)+Cp_3T_3+\lambda_3 \\
0 & 0 & U_3A & 0 & \lambda_2 & -\lambda_2
\end{vmatrix}$$

Given, $T_0$=121.1˚C and $T_3$=51.6 ˚C

Assuming equal temperature drop in each effect,

$$\Delta T_1 = \Delta T_2 = \Delta T_3 = \frac{\text{total } \Delta T}{3} = \frac{121.1-51.6}{3} = 23.17\ ˚C$$

This gives $T_1$ = 97.93 ˚C and $T_2$ = 74.76 ˚C

Let us assume the final concentration is 10% ( $x_1$=0.1) and there is equal vaporization in each effect,

$L_1 = \frac{F*x_f}{x_1}$ = 4536 kg/hr

$\Delta V_1 = \Delta V_2 = \Delta V_3 = \frac{22680-4536}{3}$ = 6048 kg/hr

This gives $L_2$= 10584 kg/hr, $x_2$ = 0.214

and $L_3$= 16632 kg/hr, $x_3$ = 0.136

This problem may be solved iteratively and the results are given in Table 5.1.

**4.11. Detailed iterative solution procedure of the five-effect backward feed evaporator with bleeding**

The model equations for this case are shown through Eqs 4.56 to 4.70

Variables: $V_0$, $T_1$, $T_2$, $T_3$, $T_4$, $L_1$, $L_2$, $L_3$, $L_4$, $L_5$, $Vb_1$, $Vb_2$, $Vb_3$, $Vb_4$, $Vb_5$

The guess values of the variables to be provided for the 1st iteration are calculated in a similar way, i.e. by assuming equal driving force and equal vaporization in each effect. The guess values for the bleed streams are also calculated from the guess values for temperature and liquor flow rates.

This gives the assumed values to be :

$V_{00}$ = 5.7 kg/s

$T_{10}$ = 108.4 ˚C

$T_{20}$ = 96.8 ˚C

$T_{30} = 85.2$ ˚C

$T_{40} = 73.6$ ˚C

$L_{10} = 9.828$ kg/s

$L_{20} = 15.418$ kg/s

$L_{30} = 21.008$ kg/s

$L_{40}=26.598$ kg/s

$L_{50} = 32.188$ kg/s

$Vb_{10} = 0.096$ kg/s

$Vb_{20} = 0.19$ kg/s

$Vb_{30} = 0.25$ kg/s

$Vb_{40} = 0.31$ kg/s

$Vb_{50} = 1.46$ kg/s

A matlab code is developed for solving the system and the converged solution is listed in Table 5.7.

# CHAPTER FIVE: RESULT AND DISCUSSION

The present Chapter shows the results obtained from the theoretical investigation carried out in the present work. The MEE systems considered in this work are three effect and five effect evaporator systems which are utilized for concentrating sugar solution as described in Chapter 3. For this system different models are developed considering vapor bleeding. These models consists of set of non-linear equations is developed in Chapter 4. The results obtained are discussed in the subsequent paragraphs:

### 5.1. Three effect evaporator operated in backward-feed flow sequence

The operating parameters as mentioned in Table 3.1.are used to solve the model developed in Section 4.10.using matlab code. This model is for three-effect evaporator without the use of vapor-bleeding. To solve this model, empirical correlations are used for computing boiling-point elevation and specific heat of liquor and the latent heat capacity of vapor as described through Eqs.4.8-11. Empirical correlations are also used to calculate the film-heat transfer coefficient for the liquor which have been mentioned in equation 4.10 . As temperature and concentration dependent properties are accounted in the model an iterative approach is used to get the final results. The results of all iteration with different parameters are shown in Table 5.1. For this computation, To, λo, ho and hd are considered as 121.1˚C, 2220 kJ/kg, 9000 kW/$m^2$ K and 566 kW/$m^2$ K, respectively[3].

Table 5.1. Iterative results for the simple three effect system

| Itr. no. | Effect no. | T(˚C) | L(kg/h) | x | Cp(kJ/kgK) | ʈ(˚C) | λ(KJ/kgm) | л(kg/m/s) | ø(kW/m2) | hi(kW/m2 K) | U(kW/$m^2$ K) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 97.93 | 4536 | 0.5 | 3.015 | 2.445 | 2336 | 0.315 | 22.82 | 2471 | 438.1 |
| | 2 | 74.76 | 10584 | 0.214 | 3.686 | 0.667 | 2451 | 0.735 | 39.24 | 3581.7 | 463.59 |
| | 3 | 51.59 | 16632 | 0.136 | 3.869 | 0.358 | 2566 | 1.155 | 41.18 | 3623 | 464.27 |
| 2 | 1 | 98.66 | 4291 | 0.528 | 2.947 | 2.679 | 2332 | 0.298 | 39.33 | 2773.8 | 446.75 |
| | 2 | 74.76 | 11120 | 0.204 | 3.711 | 0.622 | 2451 | 0.772 | 44.24 | 3779.1 | 466.74 |
| | 3 | 51.59 | 17441 | 0.13 | 3.884 | 0.337 | 2566 | 1.211 | 43.04 | 3751.6 | 466.32 |
| 3 | 1 | 99.16 | 4023 | 0.564 | 2.865 | 2.980 | 2330 | 0.279 | 39.21 | 2646.1 | 443.3 |
| | 2 | 74.99 | 10988 | 0.206 | 3.705 | 0.632 | 2450 | 0.763 | 45.07 | 3787.6 | 466.87 |
| | 3 | 51.59 | 17398 | 0.130 | 3.884 | 0.338 | 2566 | 1.208 | 43.62 | 3761.3 | 466.47 |
| 4 | 1 | 99.36 | 3917 | 0.579 | 2.829 | 3.116 | 2329 | 0.272 | 38.55 | 2576.6 | 441.3 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2 | 75.11 | 10916 | 0.208 | 3.702 | 0.638 | 2449 | 0.758 | 45.27 | 3785.8 | 466.85 |
| | 3 | 51.59 | 17363 | 0.131 | 3.883 | 0.339 | 2566 | 1.206 | 43.87 | 3763.5 | 466.5 |
| 5 | 1 | 99.43 | 3878 | 0.585 | 2.816 | 3.168 | 2328 | 0.269 | 38.25 | 2548.8 | 440.48 |
| | 2 | 75.15 | 10888 | 0.208 | 3.701 | 0.641 | 2449 | 0.756 | 45.33 | 3784.7 | 466.83 |
| | 3 | 51.59 | 17350 | 0.131 | 3.883 | 0.339 | 2566 | 1.205 | 43.96 | 3764.4 | 466.52 |

The final converged values for all the variables are presented in Table 5.2 and Fig 5.1 which shows steam economy of simple three effect evaporator system is 1.45.

Table 5.2: Values of different variables for three effect evaporator system

| Effect no. | Liquor flow rate L(kg/hr) | Temperatureof effect T(˚C) | Steam consumption Vo(kg/hr) | Steam economy |
|---|---|---|---|---|
| 1 | 4291 | 98.6580 | 3147.7 | 2.3 |
| 2 | 11120 | 74.7649 | | |
| 3 | 17441 | 51.5900 | | |

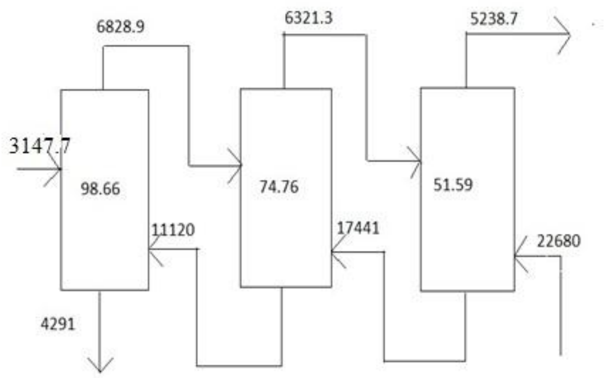


Fig 5.1.Schematic of the three-effect evaporator with specified variables

According to Al-Sahali et al.(1997), the cost of steam is \$0.3 per $m^3$. The steam requirement for this operation is 3147.7 kg/hr. Considering density of steam from the steam tables as 1.157 $kg/m^3$ the cost of this operation per year becomes \$816.

**5.2. Three-effect evaporator system with vapor bleeding**

The model of the three effect evaporator system considered in Section 5.1 is now solved by incorporating vapor bleeding. Two preheaters are used for vapor bleeding. Similar correlations for all the parameters are chosen as in the previous case. The results are iterated to obtain the final converged values as shown in Table 5.3. The schematic diagram of this system is shown in Fig. 5.2.

Table 5.3. Values of different variables in the triple-effect backward feed evaporator with bleeding

| Effect no. | Liquor flow rate L(kg/hr) | Temperature of effect T(˚C) | Bleed stream of vapor (kg/hr) | Steam consumption Vo(kg/hr) | Steam economy |
|---|---|---|---|---|---|
| 1 | 15213 | 87.1413 | 678.5 | 3082 | 2.38 |
| 2 | 21337 | 69.8225 | 1072 | | |
| 3 | 22549 | 51.5900 | | | |

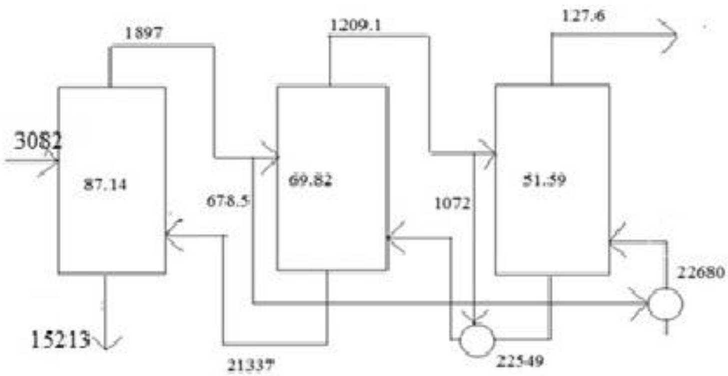


Fig. 5.2. Schematic of triple-effect backward feed evaporator with vapor bleeding showing the different variables

### 5.2.1 Associated costs

Cost of steam for this operation comes out to be $799.Two heat exchangers are to be installed to carry out the pre-heating operation.These exchangers are shell and tube exchangers. The installation cost of these exchangers is to be taken into account.

Area of each heat exchanger handling a particular bleed-stream

= Heat duty/(Overall heat transfer coefficient*temperature driving-force)

The overall heat-transfer coefficient for an exchanger handling steam and organic liquid is 1000 $W/m^2K$ [3].This gives the areas of the two exchangers to be 163.77 $cm^2$ and 240 $cm^2$ respectively. Considering stainless-steel to be the material of construction for the shell and tube heat exchanger, capital cost of heat exchangers is found as $60139 using following expression [4]where A is the area of heat-transfer surface in $m^2$:

Cost ($) = $30000+1650A^{0.81}$

Comparison of results of three effect evaporator with and without vapor bleeding shows that the steam economy of the system increases with bleeding. The increase in steam economy of the evaporator system is 0.08, i.e. per kg of steam consumed, 0.08 kg more liquid is evaporated with bleeding. This is as vapor bleeding is done to preheat the liquor near to the temperature of the effect before it is entering into the effect so that the liquor can quickly attain the boiling temperature inside the effect. Thus, evaporation rate increases in the system. The steam consumption of the system falls from 3147.7 kg/hr to 3082 kg/hr when bleeding is incorporated. The cost of steam for the system thus decreases. The savings brought about in the cost of steam come out to be $1,22,400 per year.

Payback period = $\frac{\text{Total depreciable cost}}{\text{Profit+Depreciation}}$[16]

Assuming the salvage value of both the heat exchangers to be \$ 10000 and the service life to be 10 years, yearly depreciation = $\frac{\$(60139-10000)}{10}$ =\$5014

Total depreciable cost=60139-10000=\$50139

This gives the payback period to be $\frac{50139}{1,22,400+5014}$ = 4 months 22 days.

**5.3. Five-effect forward feed evaporator**

A model is developed for a five-effect evaporator system with forward-feed and solved using the Newton-Raphson method. Operating parameters have been mentioned in Table 3.2. Here, the feed temperature is 108 ˚C, i.e.-far above normal temperature. So, additional amount of steam is used up to pre-heat the feed from its normal temperature, i.e. 30˚C to 108˚C. The empirical correlations for specific heat, latent heat, boiling point elevation and film coefficient used here are the same as those used in the three-effect system. A matlab code is developed to solve the system and the converged results are presented in Table 5.4. The results for the same are also shown schematically in Fig.5.3.

Table 5.4. Values of variables in the five-effect evaporator system

| Effect no. | Liquor flow rate L(kg/s) | Temperature of effect T(˚C) | Steam consumption Vo(kg/s) | Steam economy |
|---|---|---|---|---|
| 1 | 37.1875 | 117.0435 | 1.8853 | 3.92 |
| 2 | 36.4428 | 115.1293 | | |
| 3 | 35.3516 | 109.6693 | | |
| 4 | 33.3294 | 93.4221 | | |
| 5 | 29.7991 | 62.0000 | | |

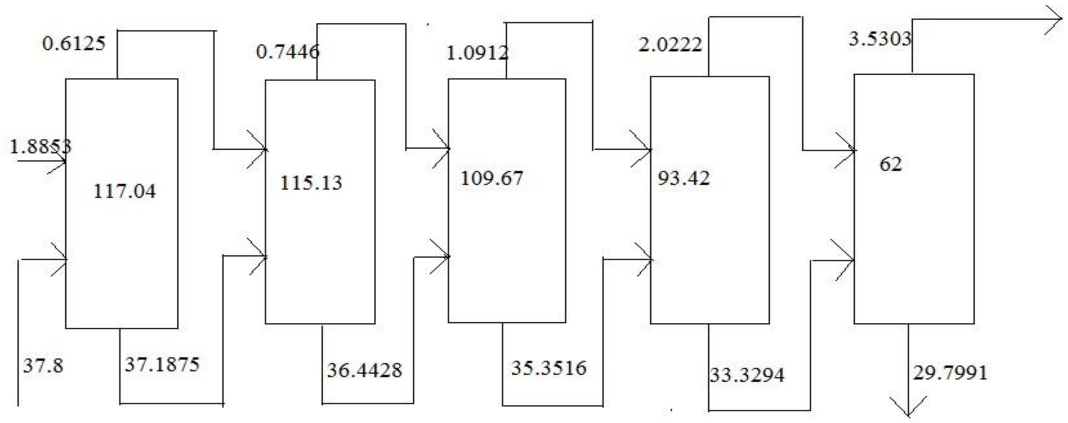


Fig.5.3. Schematic of five-effect forward feed system showing the different variables

Additional steam consumed to raise the feed temperature from 30˚C to 108˚C is found as 5.14 kg/s thus, total steam consumption for this system is 7.025 kg/s. Total cost of steam consumed per hour, taking the cost of steam to be $ 0.3 per $m^3$ is $6552.

## 5.4. Five-effect forward feed evaporator with vapor bleeding

The five-effect forward feed system is modified using vapor bleeding to pre-heat the feed liquor form normal temperature(30˚C) to the feed inlet temperature, i.e. 108˚C in three stages, from 30˚C to 50˚C, 50˚C to 70˚C and 70˚C to 88˚C. The additional sensible heat requirement to raise the temperature from 88˚C to 108˚C is provided by the steam. The additional costs incurred are the costs of the three heat exchangers, and that of the additional steam required. The results of this model and schematic diagram are shown in Table 5.5 and Fig.5.4, respectively.

Table 5.5 Values of variables in the five-effect forward feed evaporator system with bleeding

| Effect no. | Liquor flow rate L(kg/s) | Temperature T(˚C) | Bleed stream Vb(kg.s) | Steam consumption Vo(kg/s) | Steam economy |
|---|---|---|---|---|---|
| 1 | 35.6191 | 113.7696 | | 1.8820 | 4.07 |
| 2 | 33.0146 | 106.8789 | 1.1536 | | |
| 3 | 30.9778 | 95.9885 | 1.2521 | | |
| 4 | 29.5999 | 83.8982 | 1.2208 | | |
| 5 | 27.9590 | 62.0000 | | | |

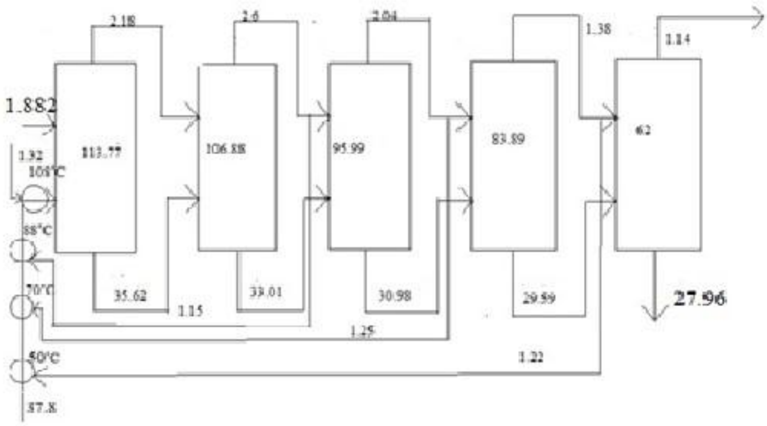


Fig.5.4. Schematic of the five-effect forward feed evaporator with bleeding

Additional amount of steam required to carry out the preheating of the feed required from 88˚C to 108˚C is 1.32 kg/s.Therefore, the total steam requirement is found as 2.715 kg/s.

### 5.4.1 Costs computation

Cost of steam per hour(at the rate of $0.3 per m$^3$) is found as $6540. Total capital cost of the three exchangers is obtained as $180108 considering areas of the three heat-exchangers as98.31 m$^2$, 83.8 m$^2$ and 68 m$^2$, respectively.

The steam consumption of the five effect system falls from 1.8853 kg/s to 1.8820 kg/s when bleeding is incorporated. There is an improvement in steam economy, from 3.92 to 4.02, from the system without bleeding to the system with bleeding. The annual savings in the cost of steam come out to be $86400.

Assuming the salvage value of the equipments to be $10000 and service life to be 10 years, annual depreciation = $17010

Total depreciable amount = $170108

This gives the payback period to be 1 year, 7 months and 23 days.

## 5.5. Five effect evaporator operated in backward feed flow without bleeding

The five-effect evaporator with the same operating parameters is operated in backward feed-flow sequence. Additional steam is employed to pre-heat the feed. The values of the variables calculated as a result of the matlab code are presented in Table 5.6 and shown schematically in Fig.5.5.

Table 5.6.. Values of variables in the five-effect backward feed evaporator system

| Effect no. | Liquor flow rate L(kg/s) | Temperature of effect T(˚C) | Steam consumption Vo(kg/s) | Steam economy |
|---|---|---|---|---|
| 1 | 28.0716 | 111.8301 | 1.5783 | 4.12 |
| 2 | 30.9464 | 102.6847 | | |
| 3 | 32.9625 | 87.4288 | | |
| 4 | 34.0202 | 70.8826 | | |
| 5 | 34.5686 | 62.0000 | | |

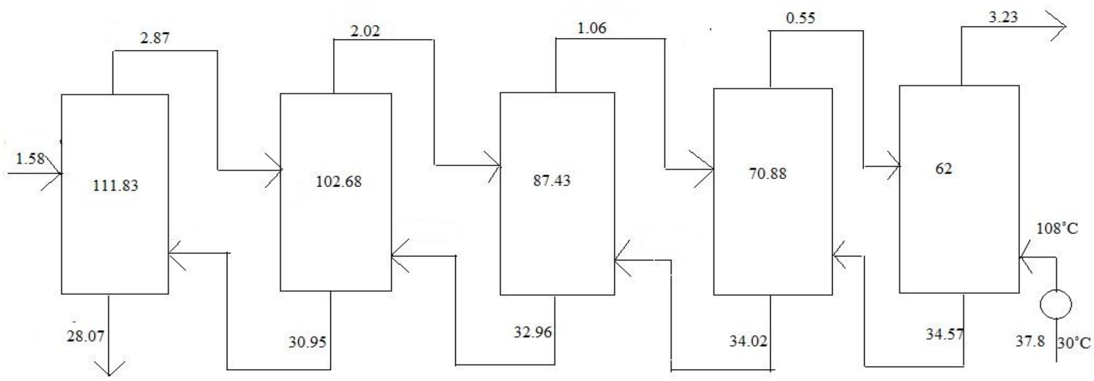


Fig.5.5.Schematic of the five-effect backward feed evaporator showing the different variables

Steam required to pre-heat the feed from 30 ˚C to 108˚C is 5.14 kg/s. Therefore the total cost of steam consumed per hour becomes $1873. The cost of additional heat exchanger of area 296 $m^2$ is $30000.

### 5.6. Five-effect backward feed evaporator with vapor bleeding

Vapor bled out of the stream leaving the 5th effect is used to pre-heat the feed. The maximum temperature to which the feed can be raised should be 5˚C less than that of the 5th effect, in order to maintain a temperature approach of 5˚C. Similarly, vapor bled out of the streams leaving 1st, 2nd, 3rd and 4th effects are used to pre-heat the liquor entering the same effect, allowing the liquor to rise to a temperature 5˚C less than the temperature of the effect which it is going to enter.

Table 5.7 lists in a tabular manner the values of the various variables obtained as a result of the matlab code. Fig.5.6 shows these variables in a schematic diagram of the evaporator system. The steam economy increases from 4.12 to 5.19 with vapor bleeding.

Table 5.7. Values of different variables in the five-effect backward feed flow system with bleeding

| Effect no. | Liquor flow rate L(kg/s) | Temperature of effect T(˚C) | Bleed stream Vb(kg.s) | Steam consumption Vo(kg/s) | Steam economy |
|---|---|---|---|---|---|
| 1 | 26.4812 | 109.1736 | 0.2977 | 1.5833 | 5.19 |
| 2 | 30.3150 | 97.8452 | 0.5649 | | |
| 3 | 32.9499 | 82.0112 | 0.4381 | | |
| 4 | 34.2353 | 68.6073 | 0.0664 | | |
| 5 | 34.7078 | 62.0000 | 1.4598 | | |

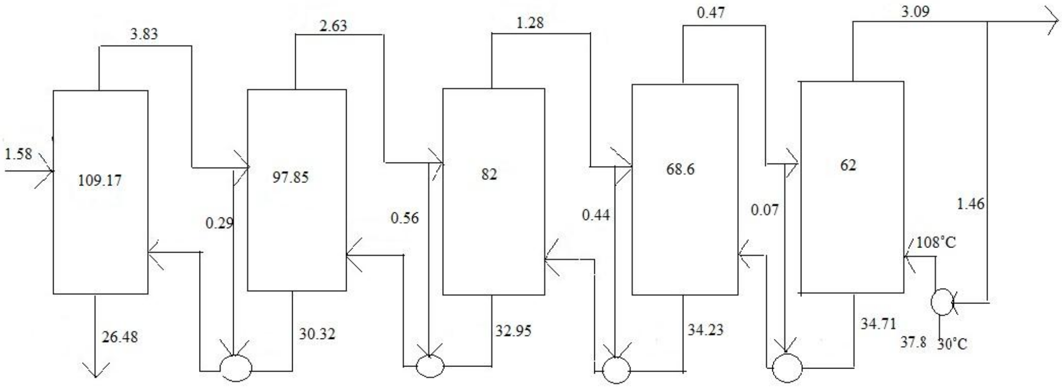


Fig.5.6. Schematic of the five-effect backward feed flow system with bleeding

Cost of steam at the rate of \$0.3 per $m^3$ is \$1879. Areas of the heat exchangers that need to be installed come out to be 201.66 $m^2$, 30.14 $m^2$, 124.8 $m^2$, 348.76 $m^2$ and 85.48 $m^2$ respectively, from right to left. This gives the capital cost of the exchangers to be \$1,50,291. The annual savings in the cost of steam with bleeding are \$43,200. Assuming the salvage value of the heat transfer equipment to be \$10000 and its service life to be 10 years, the payback period comes out to be 2 years 5 months and 12 days .

# CHAPTER SIX : CONCLUSION

In the present study, the simulation of a three-effect and a five-effect forward as well as backward feed evaporator is done with and without bleeding. The aim is to find the most thermo-economically viable solution for the system. Model is developed and solved using the Newton-Raphson method by developing a matlab code.

Taking the results into account, the following inference is drawn from the present study:

1. The steam economy of an evaporator when operated in backward feed is higher than when it is operated in forward feed flow.
2. Vapor bleeding increases the steam economy of all the sytems but at the added cost of the heat exchangers that need to be installed to carry out the bleeding operation
3. Vapor bleeding when applied to a five-effect backward feed problem shows better results than when applied to a forward feed problem for the same system.
4. The payback period of the heat exchangers is the highest in the five-effect backward feed problem, since here the maximum number of exchangers is required, as well as the head load on the exchangers is maximum.

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## APPENDIX

In the appendix, the matlab code developed for the solution of model developed under Section 4.7 is given:

```
T0=120;

lat0=2225.804;

Tf=108;

F=37.8;

xf=0.13;

cpf=4.19-2.35*xf;

V0=5.7;

T=rand(5,1);

x=rand(5,1);

L=rand(5,1);

V=rand(5,1);

V1=rand(5,1);

A=rand(5,1);

cp=rand(5,1);

bpe=rand(5,1);

lat=rand(5,1);

gamma=rand(5,1);

phi=rand(5,1);

A(1)=1800;

A(2)=1400;

A(3)=600;
```

```
A(4)=300;
A(5)=300;
T(1)=108.4;
T(2)=96.8;
T(3)=85.2;
T(4)=73.6;
T(5)=62;
L(5)=32.188;
L(4)=26.598;
L(3)=21.008;
L(2)=15.418;
L(1)=9.828;
V1(1)=0.096;
V1(2)=0.19;
V1(3)=0.25;
V1(4)=0.31;
V1(5)=1.46;
ho=9000;
hd=566;
hi=rand(5,1);
U=rand(5,1);
fori=1:5
V(i)=5.6;
x(i)=37.8*0.13/L(i);
```

```
cp(i)=4.19-2.35*x(i);

bpe(i)=1.78*x(i)+6.22*(x(i)^2);

lat(i)=2823.2-4.9783*T(i);

gamma(i)=L(i)/4;

end

phi(1)=V0*lat0/A(1);

phi(2)=[V(1)*lat(1)]/A(2);

phi(3)=[V(2)*lat(2)]/A(3);

phi(4)=[V(3)*lat(3)]/A(4);

phi(5)=[V(4)*lat(4)]/A(5);


fori=1:5

   hi(i)=218+24*phi(i)-37*100*x(i)+1090*gamma(i)+32*[T(i)+bpe(i)];

U(i)=[(1/hi(i))+(1/ho)+1/hd]^-1;

end

f=rand(15,1);

j=rand(15,15);

z=rand(15,1);

z(1:15,1)=1;

count=0;


fori=1:50

   f(1)=(V0*lat0+L(2)*cp(2)*(T(2)+bpe(2))-(L(2)-L(1))*(lat(1)+cp(1)*T(1))-
L(1)*cp(1)*(T(1)+bpe(1)))*1000;
```

```
f(2)=U(1)*A(1)*(T0-T(1))-V0*lat0*1000;
   f(3)=((L(2)-L(1)-V1(1))*lat(1)+L(3)*cp(3)*(T(3)+bpe(3))-(L(3)-L(2))*(lat(2)+cp(2)*T(2))-
L(2)*cp(2)*(T(2)+bpe(2)))*1000;
   f(4)=U(2)*A(2)*(T(1)-T(2))-(L(2)-L(1)-V1(1))*lat(1)*1000;
   f(5)=((L(3)-L(2)-V1(2))*lat(2)+L(4)*cp(4)*(T(4)+bpe(4))-(L(4)-L(3))*(lat(3)+cp(3)*T(3))-
L(3)*cp(3)*(T(3)+bpe(3)))*1000;
   f(6)=U(3)*A(3)*(T(2)-T(3))-(L(3)-L(2)-V1(2))*lat(2)*1000;
   f(7)=((L(4)-L(3)-V1(3))*lat(3)+L(5)*cp(5)*(T(5)+bpe(5))-(L(5)-L(4))*(lat(4)+cp(4)*T(4))-
L(4)*cp(4)*(T(4)+bpe(4)))*1000;
   f(8)=U(4)*A(4)*(T(3)-T(4))-(L(4)-L(3)-V1(3))*lat(3)*1000;
   f(9)=((L(5)-L(4)-V1(4))*lat(4)+F*cpf*Tf-(F-L(5))*(cp(5)*T(5)+lat(5))-
L(5)*cp(5)*(T(5)+bpe(5)))*1000;
  f(10)=U(5)*A(5)*(T(4)-T(5))-(L(5)-L(4)-V1(4))*lat(4)*1000;
f(11)=(V1(5)*lat(5)-3670.85)*1000;
  f(12)=(V1(4)*lat(4)-L(5)*cp(5)*(T(4)-5-(T(5)+bpe(5))))*1000;
  f(13)=(V1(3)*lat(3)-L(4)*cp(4)*(T(3)-5-(T(4)+bpe(4))))*1000;
  f(14)=(V1(2)*lat(2)-L(3)*cp(3)*(T(2)-5-(T(3)+bpe(3))))*1000;
  f(15)=(V1(1)*lat(1)-L(2)*cp(2)*(T(1)-5-(T(2)+bpe(2))))*1000;


  j(1,1)=lat0*1000;      j(1,2)=(-(L(2)-L(1))*cp(1)-L(1)*cp(1))*1000;      j(1,3)=L(2)*cp(2)*1000;
j(1,4)=0; j(1,5)=0;
  j(1,6)=((lat(1)+cp(1)*T(1))-cp(1)*(T(1)+bpe(1)))*1000;               j(1,7)=(cp(2)*(T(2)+bpe(2))-
(lat(1)+cp(1)*T(1)))*1000; j(1,8)=0; j(1,9)=0; j(1,10)=0;
```

j(1,11)=0;j(1,12)=0;j(1,13)=0;j(1,14)=0;j(1,15)=0;

j(2,1)=-lat0*1000; j(2,2)=-U(1)*A(1); j(2,3)=0; j(2,4)=0; j(2,5)=0; j(2,6)=0; j(2,7)=0; j(2,8)=0; j(2,9)=0; j(2,10)=0;j(2,11)=0;j(2,12)=0;j(2,13)=0;

j(2,14)=0;j(2,15)=0;

j(3,1)=0; j(3,2)=0; j(3,3)=(-(L(3)-L(2))*cp(2)-L(2)*cp(2))*1000; j(3,4)=L(3)*cp(3)*1000; j(3,5)=0; j(3,6)=-lat(1)*1000;

j(3,7)=(lat(1)+lat(2)+cp(2)*T(2)-cp(2)*(T(2)+bpe(2)))*1000; j(3,8)=(cp(3)*(T(3)+bpe(3))-(lat(2)+cp(2)*T(2)))*1000; j(3,9)=0; j(3,10)=0;

j(3,11)=-lat(1)*1000;j(3,12:15)=0;

j(4,1)=0; j(4,2)=U(2)*A(2); j(4,3)=-U(2)*A(2); j(4,4)=0; j(4,5)=0; j(4,6)=lat(1)*1000; j(4,7)=-lat(1)*1000; j(4,8)=0; j(4,9)=0; j(4,10)=0;

j(4,11)=lat(1)*1000;j(4,12:15)=0;

j(5,1)=0; j(5,2)=0;j(5,3)=0; j(5,4)=(-(L(4)-L(3))*cp(3)-L(3)*cp(3))*1000; j(5,5)=L(4)*cp(4)*1000; j(5,6)=0;

j(5,7)=-lat(2)*1000; j(5,8)=(lat(2)+lat(3)+cp(3)*T(3)-cp(3)*(T(3)+bpe(3)))*1000; j(5,9)=(cp(4)*(T(4)+bpe(4))-(lat(3)+cp(3)*T(3)))*1000; j(5,10)=0;

j(5,11)=0;j(5,12)=-lat(2)*1000; j(5,13:15)=0;

j(6,1)=0; j(6,2)=0; j(6,3)=U(3)*A(3); j(6,4)=-U(3)*A(3); j(6,5)=0; j(6,6)=0; j(6,7)=lat(2)*1000; j(6,8)=-lat(2)*1000; j(6,9)=0; j(6,10)=0;

j(6,11)=0; j(6,12)=lat(2)*1000;j(6,13:15)=0;

j(7,1)=0; j(7,2)=0; j(7,3)=0; j(7,4)=0; j(7,5)=(-(L(5)-L(4))*cp(4)-L(4)*cp(4))*1000; j(7,6)= 0; j(7,7)=0;

j(7,8)=-lat(3)*1000;j(7,9)=(lat(3)+lat(4)+cp(4)*T(4)-cp(4)*(T(4)+bpe(4)))*1000;j(7,10)=(cp(5)*(T(5)+bpe(5))-(lat(4)+cp(4)*T(4)))*1000;j(7,11)=0;

j(7,12)=0; j(7,13)=-lat(3)*1000; j(7,14)=0; j(7,15)=0;

j(8,1)=0; j(8,2)=0; j(8,3)=0; j(8,4)=U(4)*A(4); j(8,5)=-U(4)*A(4); j(8,6)=0; j(8,7)=0; j(8,8)=lat(3)*1000; j(8,9)=-lat(3)*1000; j(8,10)=0;j(8,11)=0;

j(8,12)=0;j(8,13)=lat(3)*1000;j(8,14)=0;j(8,15)=0;

j(9,1)=0; j(9,2)=0; j(9,3)=0; j(9,4)=0; j(9,5)=0; j(9,6)=0; j(9,7)=0; j(9,8)=0;

j(9,9)=-lat(4)*1000; j(9,10)=(lat(4)+cp(5)*T(5)+lat(5)-cp(5)*(T(5)+bpe(5)))*1000;j(9,11:13)=0; j(9,14)=-lat(4)*1000;j(9,15)=0;

j(10,1)=0; j(10,2)=0; j(10,3)=0; j(10,4)=0; j(10,5)=U(5)*A(5); j(10,6)=0; j(10,7)=0; j(10,8)=0; j(10,9)=lat(4)*1000; j(10,10)=-lat(4)*1000;

j(10,11:13)=0;j(10,14)=lat(4)*1000;j(10,15)=0;

j(11,1:14)=0;j(11,15)=lat(5)*1000;

```
j(12,1:4)=0;                j(12,5)=-L(5)*cp(5)*1000;j(12,6:9)=0;                j(12,10)=-cp(5)*(T(4)-5-(T(5)+bpe(5)))*1000;j(12,11:13)=0; j(12,14)=lat(4)*1000;j(12,15)=0;

j(13,1:3)=0;        j(13,4)=-L(4)*cp(4)*1000;j(13,5)=L(4)*cp(4)*1000;j(13,6:8)=0;        j(13,9)=-cp(4)*(T(3)-5-(T(4)+bpe(4)))*1000;j(13,10)=0;j(13,11:12)=0;
j(13,13)=lat(3)*1000;j(13,14:15)=0;

j(14,1:2)=0;    j(14,3)=-L(3)*cp(3)*1000;    j(14,4)=L(3)*cp(3)*1000;    j(14,5:7)=0;    j(14,8)=-cp(3)*(T(2)-5-(T(3)+bpe(3)))*1000; j(14,9:11)=0;j(14,12)=lat(2)*1000;
j(14,13:15)=0;

j(15,1)=0;      j(15,2)=-L(2)*cp(2)*1000;      j(15,3)=L(2)*cp(2)*1000;j(15,4:6)=0;      j(15,7)=-cp(2)*(T(1)-5-(T(2)+bpe(2)))*1000;j(15,8:10)=0;
j(15,11)=lat(1)*1000;j(15,12:15)=0;

z=-inv(j)*f;

V0=0.1*V0+0.5*z(1);
T(1)=T(1)+z(2);
T(2)=T(2)+z(3);
T(3)=T(3)+z(4);
T(4)=T(4)+z(5);
```

```
L(1)=L(1)+z(6);

L(2)=L(2)+z(7);

L(3)=L(3)+z(8);

L(4)=L(4)+z(9);

L(5)=L(5)+z(10);

V1(1)=V1(1)+z(11);

V1(2)=V1(2)+z(12);

V1(3)=V1(3)+z(13);

V1(4)=V1(4)+z(14);

V1(5)=V1(5)+z(15);


V(1)=L(2)-L(1);

V(2)=L(3)-L(2);

V(3)=L(4)-L(3);

V(4)=L(5)-L(4);

V(5)=F-L(5);


fori=1:5

x(i)=37.8*0.13/L(i);

cp(i)=4.19-2.35*x(i);

bpe(i)=1.78*x(i)+6.22*(x(i)^2);

lat(i)=2823.2-4.9783*T(i);

gamma(i)=L(i)/4;

end
```

```
phi(1)=V0*lat0/A(1);

phi(2)=[V(1)*lat(1)]/A(2);

phi(3)=[V(2)*lat(2)]/A(3);

phi(4)=[V(3)*lat(3)]/A(4);

phi(5)=[V(4)*lat(4)]/A(5);

fori=1:5

   hi(i)=218+24*phi(i)-37*100*x(i)+1090*gamma(i)+32*[T(i)+bpe(i)];

U(i)=[(1/hi(i))+(1/ho)+1/hd]^-1;

end

end
```

**RESULTS**

For 1st iteration:

The jacobian matrix obtained is as follows:

From columns 1 to 7

$1*10^6$ *

| | | | | | | |
|---|---|---|---|---|---|---|
| 2.2258 | -0.0465 | 0.0531 | 0 | 0 | 2.2762 | -2.2732 |
| -2.2258 | -0.8621 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | -0.0723 | 0.0765 | 0 | -2.2836 | 4.6207 |
| 0 | 0.6898 | -0.6898 | 0 | 0 | 2.2836 | -2.2836 |
| 0 | 0 | 0 | -0.0968 | 0.0999 | 0 | -2.3413 |
| 0 | 0 | 0.3004 | -0.3004 | 0 | 0 | 2.3413 |
| 0 | 0 | 0 | 0 | -0.1209 | 0 | 0 |
| 0 | 0 | 0 | 0.1518 | -0.1518 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0.1527 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | -0.1233 | 0 | 0 |
| 0 | 0 | 0 | -0.0999 | 0.0999 | 0 | 0 |
| 0 | 0 | -0.0765 | 0.0765 | 0 | 0 | 0 |
| 0 | -0.0531 | 0.0531 | 0 | 0 | 0 | -0.0186 |

From columns 8 to 15

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| -2.3615 | 0 | 0 | -2.2836 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 2.2836 | 0 | 0 | 0 | 0 |
| 4.7376 | -2.4307 | 0 | 0 | -2.3413 | 0 | 0 | 0 |
| -2.3413 | 0 | 0 | 0 | 2.3413 | 0 | 0 | 0 |
| -2.3990 | 4.8538 | -2.4941 | 0 | 0 | -2.3990 | 0 | 0 |
| 2.3990 | -2.3990 | 0 | 0 | 0 | 2.3990 | 0 | 0 |
| 0 | -2.4568 | 4.9697 | 0 | 0 | 0 | -2.4568 | 0 |
| 0 | 2.4568 | -2.4568 | 0 | 0 | 0 | 2.4568 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.5145 |
| 0 | 0 | -0.0237 | 0 | 0 | 0 | 2.4568 | 0 |
| 0 | -0.0228 | 0 | 0 | 0 | 2.3990 | 0 | 0 |
| -0.0213 | 0 | 0 | 0 | 2.3413 | 0 | 0 | 0 |
| 0 | 0 | 0 | 2.2836 | 0 | 0 | 0 | 0 |

$\Delta X_k$ = -2.3575

2.9704

4.2089

-0.6546

-4.1744

16.8817

14.6375

11.6148

7.451

2.4473

0.1198

0.2653

0.2195

-0.1856

-0.0002

Modified values after 1st iteration:

$V_0$ = -0.6087

$T_1$ = 111.3704

$T_2$ = 101.0089

T3 = 84.5454

$T_4$ = 69.4256

$L_1$ = 26.7097

$L_2$ = 30.0555

$L_3$ = 32.6228

$L_4$ = 34.0493

$L_5$ = 34.6353

The final converged solution comes out to be :

| Effect no. | Liquor flow rate L(kg/s) | Temperature of effect T(˚C) | Bleed stream Vb(kg.s) | Steam consumption Vo(kg/s) | Steam economy |
|---|---|---|---|---|---|
| 1 | 26.4812 | 109.1736 | 0.2977 | 1.5833 | 5.19 |
| 2 | 30.3150 | 97.8452 | 0.5649 | | |
| 3 | 32.9499 | 82.0112 | 0.4381 | | |
| 4 | 34.2353 | 68.6073 | 0.0664 | | |
| 5 | 34.7078 | 62.0000 | 1.4598 | | |