Design and Simulation of a Multiple Effect

Evaporator System

A thesis submitted in partial fulfilment of the Requirements for the degree of
Bachelor of Technology

in

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by

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CERTIFICATE

This is to certify that the project report entitled "**Design and Simulation of a Multiple Effect Evaporator System**", submitted by R. Raghuraman, Roll No.107CH005, for the requirements of degree of Bachelor of Technology in the 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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ABSTRACT

The objective of this report is to develop a model and an algorithm to design a multiple effect e evaporator system. Also, it is required to make to evaluate the amount of steam saved by the use of vapour compression. The use of vapour compression allows us to use the energy in the vapour leaving the last effect. Since evaporators are energy intensive system, use of vapour compression can considerably reduce steam consumption, but at the cost of electrical energy needed to run the compressor.

To achieve above targets a model based on nonlinaer equations is developed to design the multiple effect evaporator system of seven effects to concentrate black liquor. For this system, first the live steam requirement will be evaluated for the evaporator without any vapour compression. Then vapour compression will be used and the live steam requirement will be calculated. Also the cost for compression of the steam should been taken into account. This gives us a thermo- economic solution wherein both energy and money is being saved.

To select the best solution total 17 combinations of placing the compressor in the multiple effect system are identified. The best combination in terms of thermo- economic criterion is vapour from the sixth effect being compressed and sent into the second effect. The cost for running the equipment without any vapour compression is found out to be 4009 $/hr. however, for best combination cost is reduced to 3886 $/hr and the savings made are 23 $.hr.

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NOMENCLATURE

The following nomenclature is used for the development of modelling equations

Symbol Used	Parameter
L	Liquor flow rate (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_i	Vapour body temperature in an i-th effect (K)
T_L	Liquor temperature in an effect (K)
n	Total number of effects

P   Pressure of steam in vapour bodies (N/m^2)

CHAPTER ONE: INTRODUCTION

Evaporation falls into the concentration stage of downstream processing and is widely used to concentrate foods, chemicals, and salvage solvents. The goal of evaporation is to vaporize most of the water from a solution containing a desired product, or in the case of drinking water from seawater, an undesired product. After initial pre-treatment and separation, a solution often contains over 85% water. This is not suitable for industry usage because of the cost associated with processing such a large quantity of solution, such as the need for larger equipment. 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 in series for the concentration of any solution, it is called a multiple effect evaporator system. Unlike single-stage evaporators, these evaporators can be made of up to seven evaporator stages or effects. Adding one evaporator to the single effect decreases the energy consumption to 50% of the original amount. Adding another effect reduces it to 33% and so on. The number of effects in a multiple-effect evaporator is usually restricted to seven because after that, the equipment cost starts catching up to the money saved from the energy requirement drop. [1]

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. Evaporators find one of their most important applications in the food and drink industry. The goal of

evaporation is to concentrate a target liquid, and this needs to be achieved for many different targets today. One of the most important applications of evaporation is that on the food and drink industry. Many foods that are made to last for a considerable amount of time or food that needs a certain consistency, like coffee, need to go through an evaporation step during processing. It is also used as a drying process and can be applied in this way to laboratories where preservation of long-term activity or stabilization is needed (for enzymes for example). Evaporation is also used in order to recover expensive solvents such as hexane which would otherwise be wasted. Another example of evaporation is in the recovery of sodium hydroxide in Kraft pulping. Cutting down waste handling cost is another major application of evaporation for large companies. Legally, all producers of waste must dispose of the waste in a method that abides by environmental guidelines; these methods are costly. If up to 98% of wastes can be vaporized, industry can greatly reduce the amount of money that would otherwise be allocated towards waste handling. Evaporation is also used in pharmaceutical industry as to get a concentrated product and to improve the stability of the products.

1.2 Problems associated with multiple effect evaporators

The evaporators being a highly energy intensive system offer a great scope for reduction of costs by reducing the live steam requirements. 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, vapour compression, feed- and steam- splitting and using an optimum feed flow sequence, vapour bleeding, vapour compression.

One of the earliest works on optimizing a multiple effect evaporator by modifying the feed flow sequence was done by Harper and Tsao in 1972 by developing a model for optimizing a MEE system by considering both 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 MEE 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 on changing the operating strategy, a whole new set of equations were required for solving the new operating strategy. This problem was addressed by Stewart and Beveridge (1977) and Ayangbile, Okeke and Beveridge (1984). They developed a generalized cascade algorithm which would be solved again and again for the different operating strategies of a multiple effect evaporator system.

The reported literature considers a number of energy reduction methods such as flashing, steam and feed splitting, vapours bleeding and using an optimum feed flow sequence. In connection to these in the present work vapour compression is applied to an existing industrial multiple effect evaporator and overall cost computations will be made. Thus to achieve this target following objectives are to be met:

- To develop governing equations for multiple effect evaporator system with the induction of vapour compression.
- To develop computer program for solution of equations.
- To compute the operating cost as well as capital cost of the modified system
- To define a number of combinations in multiple effect evaporator and compressor to choose best combination based on total annual cost.

CHAPTER TWO: LITERATURE REVIEW

In Chemical Engineering '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]
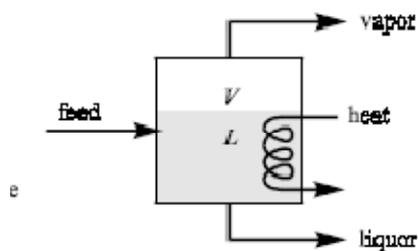
Fig. 2.1: Schematic Diagram of a Single Effect Evaporator. Source: [M]

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).

The different types of evaporators are

2.1.1 Horizontal tube evaporators

This was the first kind of evaporator to receive general recognition and was a design utilizing horizontal tubes. This type is seldom used except for a few special applications.

It has the simplest of designs with a shell and horizontal tube arrangement with heating medium in the tubes and evaporation on the shell side.

2.1.2 Horizontal spray film evaporators

The liquid in the horizontal, falling-film evaporator when distributed by recirculation through a spray system, gives the horizontal spray film evaporators. Gravity helps the sprayed liquid fall from one tube to another.

Advantages include:

(1) Non condensable are easily vented

(2) Distribution is more easily accomplished

(3) Precise levelling is not needed

(4) Vapour separation is easily accomplished

(5) Reliable operation can be carried out under scaling conditions

2.1.3 Short tube vertical evaporators

It was the first type to become really popular commercially. The first was built by Robert and the vertical tube evaporator is often called Standard Evaporator. It is also called calandria. Circulation of liquid past the heating surface is induced by boiling (natural circulation). Since the circulation rate through the evaporator is many times the feed rate the downcomers are required to permit liquid flow from the top tube sheet to the bottom tube sheet. Downcomers should be so sized that it reduces the liquid holdup above the tube sheet as this setup improves fluid dynamics, reduces foaming and increases heat transfer rate.

2.1.4 Basket type evaporators

The only difference between a standard evaporator and this one is that in the basket type the downcomer is. The annual downcomer is more economical as it allows the evaporator to be removed for cleaving and repair. Also, a deflector is installed to reduce "burping" which is caused due to entrainment.A difficulty sometimes is associated with the steam inlet line and the condensate outlet line and differential thermal expansion associated with them.

2.1.5 Long tube vertical evaporators
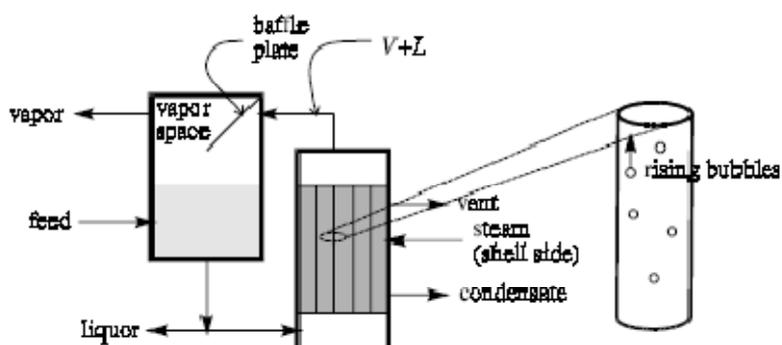
Fig. 2.2 Long tube vertical evaporators, Source [M]

It is versatile and often the cheapest per unit capacity. Long tube evaporators normally are designed with tubes 1 to 2 inches in diameter and from 12 to 30 feet in length. Long tube units may be operated as once-through or may be recirculating systems. Recirculated systems can be operated batchwise or continuously. Circulation of fluid across the heat transfer surface depends upon boiling. The temperature of the liquid in the tubes is difficult to predict because the distribution of temperature is not uniform. These units are more sensitive to changes while operating at lower temperature ranges.

2.1.6 Rising or climbing film evaporators

A: Product

B: Vapor

C: Concentrate

D: Heating Steam

E: Condensate
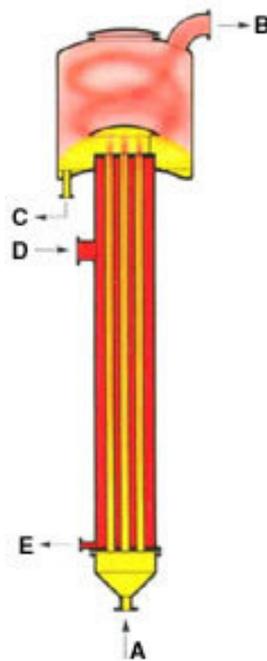
Fig 2.3: Rising or climbing film evaporators, Source [M]

These operate on a "thermo-siphon" principle. Feed enters from the bottom and the heating gives raise to steam. The steam moves upwards and boiling causes the liquid and vapours to flow upward. Simultaneously vapour is produced and the product is pushed as a thin film on the walls of the tubes and forces the liquid to raise vertically upwards. This movement against gravity causes a lot of turbulence and is highly beneficial. This is useful during while dealing with viscous or highly fouling products.

2.1.7 Falling film evaporators

A: Product

B: Vapour

C: Concentrate

D: Heating Steam

E: Condensate

1: Head

2: Calandria

3: Calandria, Lower part

4: Mixing Channel

5: Vapor Separator
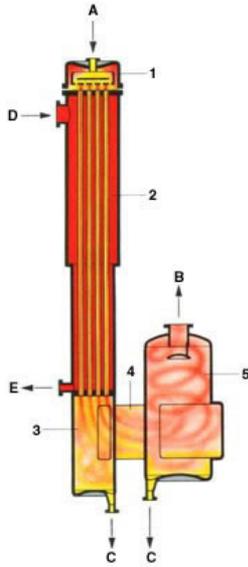
Fig. 2.4 Falling Film Evaporators, Source [M]

In falling film evaporators the liquid product usually enters the evaporator at the head of the evaporator. In the head evenly distributes the product into the heating tubes. A thin film of liquid enters the heating tube are it moves downward at boiling temperature and is partially evaporated. The product and the vapour both flow downwards in a parallel flow. The heat exchanger and the separator separate the concentrated product form its vapour in the lower part of the evaporator.

2.1.8 Rising falling film evaporators

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

2.1.9 Forced circulation evaporators
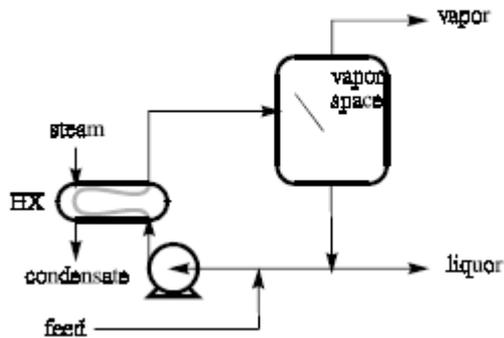
Fig. 2.5 Forced Circulation Evaporators, Source [M]

Sometimes we need to avoid the boiling of the product on the heating surface because of the fouling characteristics of the liquid. We use this evaporator especially in these cases. And to achieve this, high capacity pumps are used to maintain high velocity of the liquids in the tubes.

2.1.10 Plate evaporators
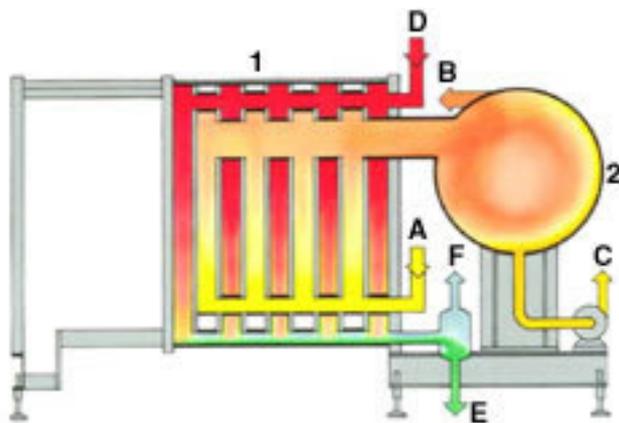
Fig 2.6 Plate Evaporators, Source [M]

Instead of tube and shell heat exchangers, framed plates can be used as an heating surface. These plate assemblies are similar to plate heat exchangers, but are equipped with large passages for the vapour flow. 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. In these units a product plate and a steam plate are connected alternately. The product passage is designed for even distribution of liquid on the plate surfaces and low pressure drop in the vapour phase.

2.1.11 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

1. Agitated vessels

2. Scraped surface evaporators

3. Mechanically agitated thin film evaporators

2.2 Modelling of multiple effect evaporators

Multiple effect evaporator systems can be modeled in 2 ways

1. In a model based on equations, the euations are developed for each effect and for every operating condition separately and are solved for the unknown variables.

The following equations are written for each evaporator in a mathematical model of a five effect evaporator system (Radovic et al, 1979) [3]

i. The enthalpy balance equations

ii. The heat transfer rates

iii. The phase equilibrium relationships

iv. The mass balance equations

Lambert, Joye and Koko in 1987 presented a model which was based on the non linear enthalpy relationships and boiling point rise. Curve fitting techniques and interpolation were used to reach these relationships.

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. A generalised cascade algorithm for steady state simulation of multiple effect evaporator systems is discussed. The algorithm, capable of handling any feed arrangement, includes heat recovery features such as liquor and condensate flash units and feed preheating. This is made possible by the use of composite flow fractions which fully describe the internal flow connections. The user-provided models for these units and all effects may be of varying.

Thus on changing the operating conditions like addition of flash tanks or introduction of vapour bleeding or changing the feed flow sequence does not require a change in the algorithm and the same program which is independent of the equations can be used for all operating conditions (Bhargava et al, 2010).[4] Another generalized model has been proposed by Stewart and Beveridge. The algorithm is based on the simultaneous solution of linearised forms of the effect models derived from knowledge of the significant factors determining their performance. The coefficients of these linear equations are process. Two linearisations are described, the first being adequate for lumped parameter effect models and the second for detailed effect models with strong interaction between the two-phase fluid flow and heat transfer phenomena (Stewart and Beveridge, 1977). Another generalized model was developed by Ayangbile, Okeke and Beveridge in 1984.

2.3 Energy Conservation in Evaporators

2.3.1 Flash Evaporation

Flash (or partial) evaporation is the partial vapour that occurs when a saturated liquid stream undergoes a reduction in pressure by passing through a throttling valve or other throttling device.

If the saturated liquid is a multi-component liquid (for example, a mixture of propane, isobutane and normal butane), the flashed vapour is richer in the more volatile components than is the remaining liquid.

If the feed is at a temperature above the boiling point in the vapour space, a portion of the feed is at the capacity is greater than that corresponding boiling point. This process is called flash evaporation.

In flashing some of the liquid directly vapourizes and thus it utilises the heat that the liquid has above what energy is required for evaporation. Thus energy is conserved.[5]

2.3.2 Vapour Compression

Multiple effects recover some of the latent heat of the overhead vapour by using it in place of steam to boil the liquor in downstream effects. Is there any way we can use the vapour in place of steam in a single – effect evaporator? The problem with using the vapour in place of steam is that the temperature of there vapours is the same as the temperature of the liquor. The liquor and the vapour leaving the same effect are already in thermal equilibrium with each other. In other words, there is no driving force for heat transfer.
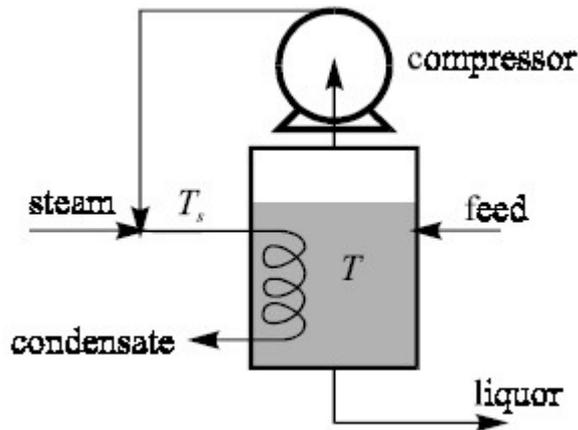
Fig. 2.7 Schematic Diagram of Single Effect evaporator with Vapour Compression

Without compression

$$\Delta T = T_s - T = 0$$

One way it increase the temperature of the vapour is to compress it. Figure shows how adiabatic compression of water vapour (treated as an ideal gas) increases its temperature . Note that the temperature rises faster with increase in pressure than the boiling point increases. Thus adiabatic compression of a saturated vapour nearly always produces a superheated vapour. When heat is removed from this compressed vapour, it will eventually condense at its boiling point for that pressure.

Increasing the pressure of the vapour also increases its boiling point, so that as the vapour condenses, it stays at a high temperature T_s so we always have some driving force :

With compression $\Delta T = T_s - T > 0$

Unfortunately, raising the temperature and pressure of the vapour actually lowers its latent heat per pound

$$\lambda_s < \lambda(because\ T_s > T)$$

Vapour-compression evaporation is the evaporation method by which a blower, compressor or jet ejector is used to compress, and thus, increase the pressure of the vapour produced. Since the pressure increase of the vapour also generates an increase in the condensation temperature, the same vapour can serve as the heating medium for its "mother" liquid or solution being concentrated, from which the vapour was generated to begin with. If no compression was provided, the vapour would be at the same temperature as the boiling liquid/solution, and no heat transfer could take place.

It is also sometimes called *Vapour compression distillation (VCD).* If compression is performed by a mechanically-driven compressor or blower, this evaporation process is usually referred to as MVR (Mechanical Vapour Recompression). In case of compression performed by high pressure motive steam ejectors, the process is usually called Thermocompression or Steam Compression.

2.3.2.1 MVR Process

In this case the energy input to the system lies in the pumping energy of the compressor. The theoretical energy consumption will be equal to $E = Q * (H2 - H1)$, where

- E is the total theoretical pumping energy
- Q is the mass of vapours passing through the compressor
- H_1, H_2 are the total heat content of unit mass of vapours, respectively upstream and downstream the compressor.

In SI units, these are respectively measured in kJ, kg and kJ/kg. This theoretical value shall be increased by the efficiency, usually in the order of 30 to 60 %. In a large unit, the compression energy is between 35 and 45 kW per metric ton of compressed vapors.

2.3.2.2 Equipment for MVR Evaporators

The compressor is necessarily the core of the unit. Compressors used for this application are usually of the centrifugal type, or positive displacement units such as the Roots blowers, similar to the (much smaller) Roots type supercharger. Very large units (evaporation capacity 100 metric tons per hour or more) use sometimes Axial-flow compressors. The compression work will deliver the steam superheated if compared to the theoretical pressure/temperature equilibrium. For this reason, the vast majority of MVR units feature a desuperheater between the compressor and the main heat exchanger.

2.3.3 Vapour Bleeding

Sometimes a small amount of vapour is removed from the vapours formed after the first effect and is used to heat the feed for the second effect. Now the second effect is bled to preheat the third effect's feed and so on.

Only a small portion of the vapour produced is bled. This method is followed in many sugar mills.

Thus some of the energy in the vapour is not directly used to vapourise more water by increasing the pressure of the vapours by vapour compression or by decreasing the absolute pressure of the consecutive effects. [6][7]

2.4 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.

2.4.1 Properties of black liquor

Some of the properties of black liquor are as follows (Ray et al, 1992) [8]

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.

2.4.2 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

Sr no.	Organic constituents of black liquor
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

Sr. 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 sulphur	Small
8	Sodium sulphite	Small

CHAPTER THREE: 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. 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

Sr. No.	Parameters	Values
1	Total number of effects	7
2	No. 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

It can be seen that the live steam temperatures are different. This difference has been considered in simulation because the problem statement is an actual scenario and the modelling has been done based on that. The difference in temperature could be because of the unequal distribution of steam from the header to these effects resulting in different pressures in the two effects.

Table 3.2.Geometrical parameters of the evaporator

Sr. 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)
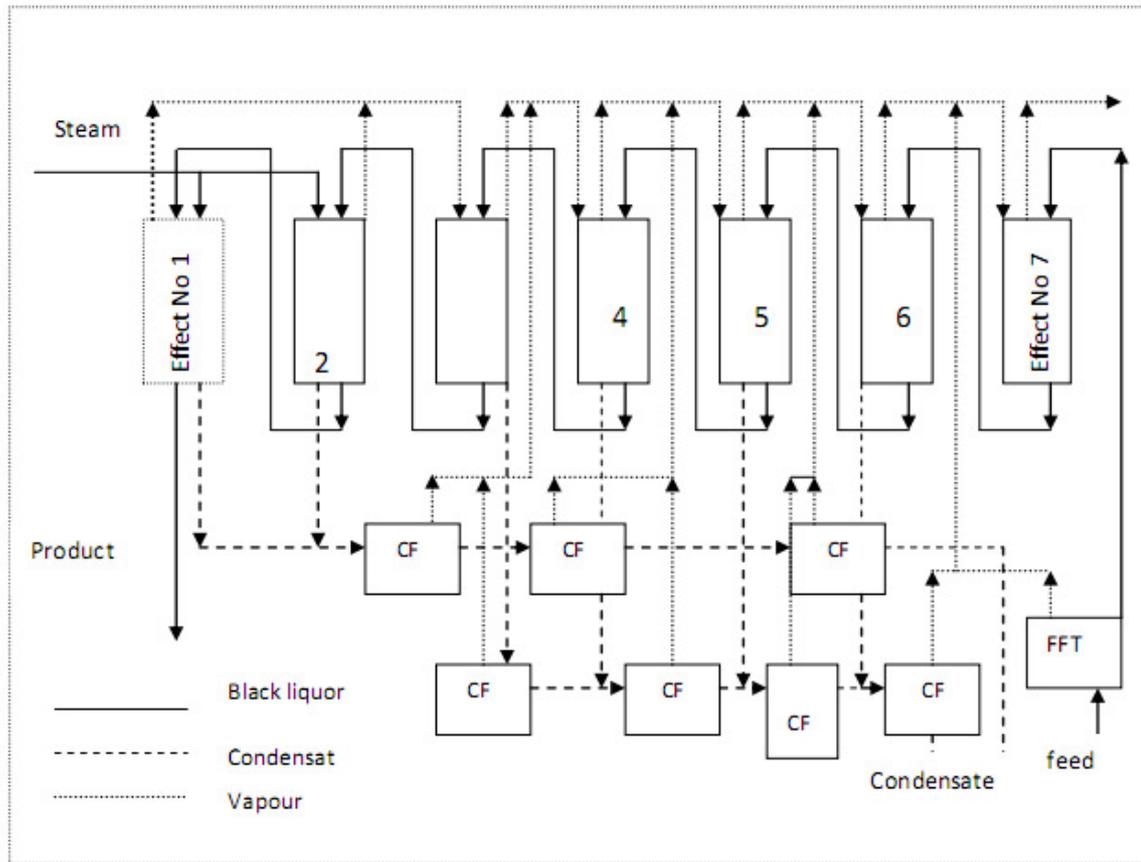
Fig 3.1 Schematic diagram of the system

Further, the cost of the compressor can be calculated from the graph below (Peters and Timmerhaus, 1991)
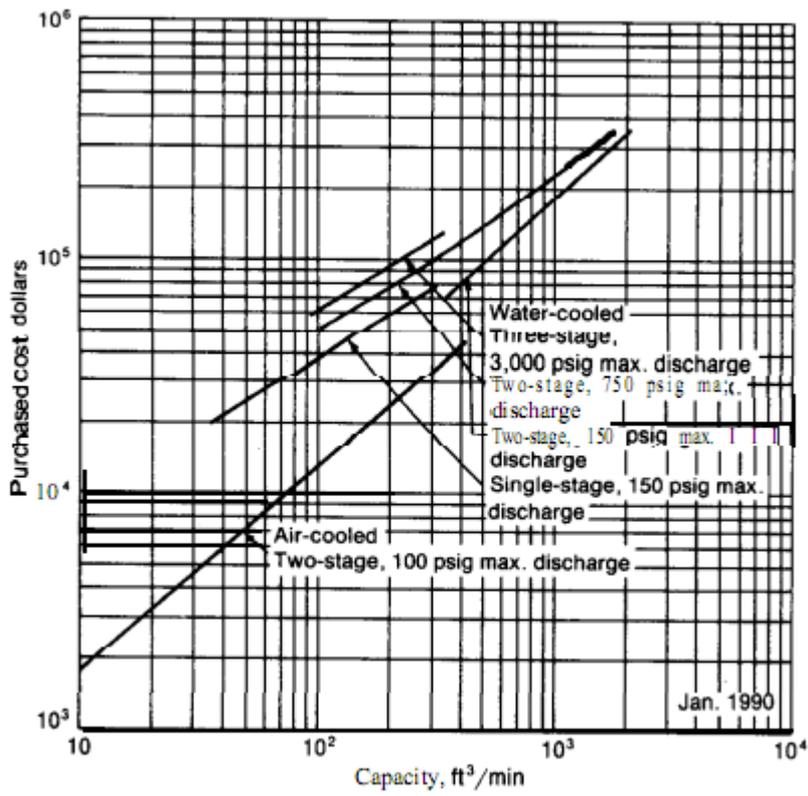
Fig 3.2 Cost of reciprocating compressors

CHAPTER FOUR: DEVELOPMENT OF A MODEL & SOLUTION TECHNIQUE

4.1 Model for MEE system

To develop a basic model for the system of septuple effect evaporator negligible boiling point elevations is considered. Also the variation in physical properties of liquor is neglected. These assumptions will be further relaxed. The governing equation of first effect is derived as follows:
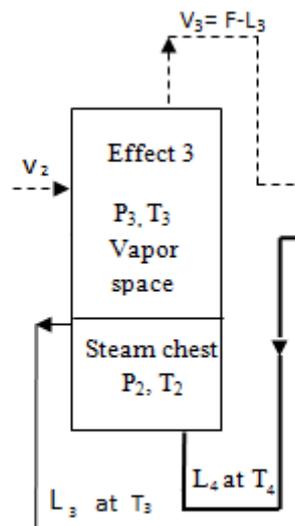
Fig 4.1 Single effect with all input and output stream with temperatures

An enthalpy balance on the process fluid stream is as follows:

$$Fh_f + Q_1 - (F - L_1) H_1 - L_1 h_1 = 0 \tag{1}$$

In the following expression the vapour is eliminated using appropriate total material balance. Also the enthalpies are approximated by taking them equal to those of the pure solvent. Thus enthalpies depend on temperature alone. For the first effect

$$V_1 = F - L_1 \tag{2}$$

Therefore equation (1) becomes

$$F(h_f - h_1) + Q_1 - (F - L_1)\lambda_1 = 0 \tag{3}$$

Where $\lambda_1 = H_j - h_j$, the latent heat of vaporization of the solvent form the thick liquor at temperature T_j and pressure P_j (j=1, 2, 3, the effect number)

Alternately, the result give by equation (3) may be obtained by taking the enthalpy reference for the first effect to be enthalpy of the thick liquor leaving the effect at the temperature T_1. The enthalpy balance on the heating medium is given by

$$Q_1 = V_0(H_0 - h_o) = V_0\lambda_0$$

And the rate of heat transfer by

$$Q_1 = U_1 A(T_0 - T_1)$$

Substituting for Q_1 final equation of first effect are found as

Enthalpy balance; $f_1 = L_2(h_s - h_1) + V_0\lambda_0 - (L_2 - L_1)\lambda_1$ $\tag{4}$

Heat transfer rate; $f_2 = U_1 A_1 (T_0 - T_1) - V_0\lambda_0$ $\tag{5}$

These equations will be followed for the second, third and so on till the seventh effect.

For second effect: $\quad f_3 = L_3(h_2 - h_3) + (L_3 - L_2)\lambda_2 - (L_2 - L_1)\lambda_1$ $\tag{6}$

$$f_4 = U_2 A_2(T_1 - T_2) - (L_2 - L_1)\lambda_1 \tag{7}$$

for third effect: $\quad f_5 = L_4(h_3 - h_4) - (L_4 - L_3)\lambda_3 + (L_3 - L_2)\lambda_2$ $\tag{8}$

$$f_6 = U_3 A_3(T_2 - T_3) - (L_3 - L_2)\lambda_2 \tag{9}$$

for fourth effect: $\quad f_7 = L_5(h_4 - h_5) + (L_4 - L_3)\lambda_3 - (L_5 - L_4)\lambda_4$ $\tag{10}$

$$f_8 = U_4 A_4 \ (T_3 - T_4) - (L_4 - L_3) \ \lambda_3 \qquad (11)$$

for fifth effect:
$$f_9 = L_6 (h_5 - h_6) + (L_5 - L_4)\lambda_4 - (L_6 - L_5) \ \lambda_5 \qquad (12)$$

$$f_{10} = U_5 A_5 \ (T_4 - T_5) - (L_5 - L_4) \ \lambda_4 \qquad (13)$$

for sixth effect:
$$f_{11} = L_7 (h_6 - h_7) + (L_6 - L_5)\lambda_5 - (L_6 - L_7) \ \lambda_6 \qquad (14)$$

$$f_{12} = U_6 A_6 \ (T_5 - T_6) - (L_6 - L_5) \ \lambda_5 \qquad (15)$$

for seventh effect:
$$f_{13} = F(h_f - h_7) + (L_7 - L_6)\lambda_6 - (F - L_7) \ \lambda_7 \qquad (16)$$

$$f_{14} = U_7 A_7 \ (T_6 - T_7) - (L_7 - L_6) \ \lambda_6 \qquad (17)$$

These nonlinear equations are solved using Newton-Raphson method which required scaling of each equation. For this purpose each functional equation is divided by the product $F\lambda_0$ and the new

The fourteen independent equations can be solved for the fourteen unknowns. In addition to these fourteen independent equations, seven additional equations that contain seven additional independent variables,

$$FX = L_j x_j = 0$$

These fourteen equations may be stated in compact form by means of the following matrix equation

$$J_k \Delta X_k = -f_k$$

Where J_k is called the Jacobian matrix and

$$\Delta X_k = X_{k+1} - X_k = [\Delta V_0 \ \Delta T_1 \ \Delta T_2 \Delta T_3 \Delta T_4 \Delta T_5 \Delta T_6 \ \Delta I_1 \Delta I_2 \Delta I_3 \Delta I_4 \Delta I_5 \Delta I_6 \ \Delta A]^T$$

The subscripts k and k+1 that elements of the matrices carrying these subscripts are those given by the kth and k+1st trials, respectively. In the interest of simplicity, the subscript k is omitted from the elements of X_k, J_k and f_k. On the basis of an assumes set of values for the elements of column vector

(or column matrix) X_k, which may be stated as the transpose of the corresponding row vector (or row matrix) J_k and f_k are computed. Adisplay of the elements of the J_k and f_k $follows$:

If the function $f_1, f_2, \ldots, f_{14}$ and their partial derivatives which appear in J_k are continuous and the determinant of J_k is not equal to zero, then the Newton Raphson method will converge, provided a set of assumed values of the variables which are close enough to the solution set can be found .

The nonlinear equations are solved using Newton-Raphson method which required scaling of each equation. For this purpose each functional equation is divided by the product $F\lambda_0$ and the new expression so obtained was denoted by g_j where $g_j = f_j / F\lambda_0$ (where j=1,2,3..14) and $L_j = l_j F$ and $V_j = v_j F$, $T_j = u_j T_0$. Differentiating $g_1, g_2, \ldots g_{14}$ with respect to v_0, u_1, l_1, u_2, l_2, u_3, l_3, u_4, l_4, u_5, l_5, u_6, l_6,a and keeping the expressions obtained in matrix forms. [9]

The steam requirement V_0 is calculated. Now, the cost of the steam is calculated.

Matrix for Eq. 4 to Eq. 11

1	$(-C_pT_o/\lambda_0)$	λ_1/λ_0	0	0	0	0	0	0	0	0	0	0	0
-1	$-(U_1aT_o)/(50\lambda_0)$	0	0	0	0	0	0	0	0	0	0	0	$(U_1T_0(1-U_1))/(50\lambda_0)$
0	$l_1C_pt_0/\lambda_0$	$C_pT_0(u_1-u_2)-(\lambda_1+\lambda_2)/\lambda_0$	$l_1C_pT_0/\lambda_0$	λ_2/λ_0	0	0	0	0	0	0	0	0	0
0	$(U_2aT_o)/(50\lambda_0)$	λ_1/λ_0	$-(U_2aT_o)/(50\lambda_0)$	0	0	0	0	0	0	0	0	0	$(U_2T_0(u_1-u_2))/(50\lambda_0)$
0	0	λ_2/λ_0	$l_2C_pT_0/\lambda_0$	$C_pT_0(u_2-u_3)-(\lambda_2+\lambda_3)/\lambda_0$	$-l_2C_pT_0/\lambda_0$	λ_3/λ_0	0	0	0	0	0	0	0
0	0	$-\lambda_2/\lambda_0$	$(U_3aT_o)/(50\lambda_0)$	λ_2/λ_0	$-(U_3aT_o)/(50\lambda_0)$	0	0	0	0	0	0	0	$(U_3T_0(u_2-u_3))/(50\lambda_0)$
0	0	0	0	λ_3/λ_0	$l_3C_pT_0/\lambda_0$	$C_pT_0(u_3-u_4)-(\lambda_3+\lambda_4)/\lambda_0$	$-l_3C_pT_0/\lambda_0$	λ_4/λ_0	0	0	0	0	0
0	0	0	0	$-\lambda_3/\lambda_0$	$(U_4aT_o)/(50\lambda_0)$	λ_3/λ_0	$-(U_4aT_o)/(50\lambda_0)$	0	0	0	0	0	$(U_4T_0(u_3-u_4))/(50\lambda_0)$
0	0	0	0	0	0	λ_4/λ_0	$l_4C_pT_0/\lambda_0$	$C_pT_0(u_4-u_5)-(\lambda_4+\lambda_5)/\lambda_0$	$-l_4C_pT_0/\lambda_0$	λ_5/λ_0	0	0	0

Matrix for Eq. 12 to Eq. 17

0	0	0	0	0	0	$-\lambda_4/\lambda_0$	$(U_5 a T_o)/(50\lambda_0)$	λ_4/λ_0	$-(U_5 a T_o)/(50\lambda_0)$	0	0	0	$(U_5 T_0(u_4-u_5))/(50\lambda_0)$
0	0	0		0	0	0	0	λ_5/λ_0	$l_5 C_p T_0/\lambda_0$	$C_p T_0(u_5-u_6)-(\lambda_5+\lambda_6)/\lambda_0$	$-l_5 C_p T_0/\lambda_0$	λ_6/λ_0	0
0	0	0	0	0	0	0	0	$-\lambda_5/\lambda_0$	$(U_6 a T_o)/(50\lambda_0)$	λ_5/λ_0	$-(U_6 a T_o)/(50\lambda_0)$	0	$(U_6 T_0(u_5-u_6))/(50\lambda_0)$
0	0	0	0	0	0	0	0	0	0	λ_6/λ_0	$-l_6 C_p T_0/\lambda_0$	$C_p T_0(u_6-u_7)-(\lambda_6+\lambda_7)/\lambda_0$	0
0	0	0	0	0	0	0	0	0	0	$-\lambda_6/\lambda_0$	$(U_7 a T_o)/(50\lambda_0)$	λ_6/λ_0	$(U_7 T_0(u_6-u_7))/(50\lambda_0)$

4.2 Empirical relation for overall heat transfer coefficient

The correlation given in equation 4.18 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.

$$\frac{U}{2000} = a \left(\frac{\Delta T}{40}\right)^{b} \left(\frac{x_{avg}}{0.6}\right)^{c} \left(\frac{F_{avg}}{25}\right)^{d} \tag{18}$$

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 Empirical constants to find out overall heat transfer coefficient

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

..

4.3 Modelling of MEE with vapour compression

In the simple case where BPE and ΔH_{dil} are negligible (i.e for inorganic colloids).H_f and H differ from the enthalpy of the saturated liquid only in sensible heat , To the extent that sensible heat is negligible, we can substitute the enthalpy of saturated liquid for H_f and H

$$q = (m_f - m)H_v - m_f H_L + mH_L$$

$$= H_v - (m_f - m)H_L$$

$$= (m_f - m)(H_v - H_L)$$

$$= (m_f - m)\lambda$$

Heat to boil vapour: This heat duty is partially offset by the latent heat recovered by condensing the compressed vapour. The remainder comes from makeup stream:

$$q = = (m_f - m)\lambda_s + m_s \lambda_s$$

where we are compressing the vapour to the same pressure as the make up steam .Eliminating q, we can solve for the steam requirements :

$$m_s = (m_f - m)(\frac{\lambda}{\lambda_s} - 1)$$

Notice that any compression allows us to recover all the latent heat of the vapour, thus significantly reducing steam consumption without compression. However greater compression actually increases steam consumption. Rearranging this expression, we can calculate the economy:

$$\frac{m_f - m}{m_s} = \frac{\lambda_s}{\lambda - \lambda_s} \gg 1$$

Performance ratio, PR, is defined as the ratio of total amount of distillate produced to the total amount of steam spent. [10][11]

$$PR = L/V_s$$

If the final vapour released from the seventh effect is now pumped back to the first effect, the heat in this vapour is not wasted and can be further used for heating the liquor. In this case the equations will be as follows:

Enthalpy balance; $f_1 = L_1(h_s - h_1) + V_0 \lambda_0 - (F - L_7) \lambda_s$ (19)

Heat transfer rate; $f_2 = U_1 A(T_0 - T_1) - V_0 \lambda_0 + (F - L_7) \lambda_s$ (20)

For second effect: $f_3 = L_3(h_2 - h_3) + (L_3 - L_2)\lambda_2 - (L_2 - L_1)\lambda_1$ (21)

$f_4 = U_2 A_2(T_1 - T_2) - (L_2 - L_1)\lambda_1$ (22)

for third effect: $f_5 = L_4(h_3 - h_4) - (L_4 - L_3)\lambda_3 + (L_3 - L_2)\lambda_2$ (23)

$f_6 = U_3 A_3(T_2 - T_3) - (L_3 - L_2)\lambda_2$ (24)

for fourth effect: $f_7 = L_5(h_4 - h_5) + (L_4 - L_3) \lambda_3 - (L_5 - L_4)\lambda_4$ (25)

$f_8 = U_4 A_4 (T_3 - T_4) - (L_4 - L_3) \lambda_3$ (26)

for fifth effect: $f_9 = L_6(h_5 - h_6) + (L_5 - L_4)\lambda_4 - (L_6 - L_5) \lambda_5$ (27)

$f_{10} = U_5 A_5 (T_4 - T_5) - (L_5 - L_4) \lambda_4$ (28)

for sixth effect: $f_{11} = L_7(h_6 - h_7) + (L_6 - L_5)\lambda_5 - (L_6 - L_7) \lambda_6$ (29)

$$f_{12} = U_6 A_6 \ (T_5 - T_6) - (L_6 - L_5) \ \lambda_5 \tag{30}$$

for seventh effect: $\quad f_{13} = F(h_f - h_7) + (L_7 - L_6)\lambda_6 - (F - L_7) \ \lambda_7 \tag{31}$

$$f_{14} = U_7 A_7 \ (T_6 - T_7) - (L_7 - L_6) \ \lambda_6 \tag{32}$$

Again the Jacobian matrix is formed and solved for the unknown variables, $\Delta u_1, \Delta l_1, \Delta u_2, \Delta l_2 \ \Delta u_3, \Delta l_3, \Delta u_4, \Delta u_5, \Delta l_5, \Delta u_6, \Delta l_6 \ and, v_o \ and \ \Delta a$. The fresh steam requirement V_0 is calculated. The steam cost is calculated. Also, the energy requirement for pumping is calculated using the formula provided by Al-Sahali et al, 1997. [12]

$$W = \frac{\gamma}{(\eta(\gamma - 1))} P_v V_v \left((P_s / P_v)^{\left(\frac{\gamma - 1}{\gamma}\right)} - 1 \right)$$

$$\tag{33}$$

A total of 17 combinations of vapour compression routes have been considered. These include 5 from effect 7, 5 from effect 6, 4 from effect 5 and 3 from effect 4. They are listed as follows:

Sr. No.	Configurations
1	7 to 1
2	7 to 2
3	7 to 2 (50%) and 3(50%)
4	7 to 3
5	7 to 4
6	6 to 1
7	6 to 2

8	6 to 3
9	6 to 4
10	6 to 5
11	5 to 1
12	5 to 2
13	5 to 3
14	5 to 4
15	4 to 1
16	4 to 2
17	4 to 3

Form the work done for compression, the cost for compressing the steam can be calculated. The profit is made by conserving fresh steam requirements. Thus we can find of the venture is profitable by comparing the money spent in compressing the vapour to the money saved in the form of fresh steam required.

Furthermore, the compressor cost can be calculated by Fig. 3.2.

4.4 Algorithm

The algorithm of the MATLAB code is as follows:

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

- Geometrical parameters of the evaporators

2. The vapour pressure of each effect is computed from the pressure values of the first and the seventh effect by assuming equal pressure drop across each effect. These pressure values are then used to compute the physical properties of condensate and steam in each effect.

3. A reasonable value of the temperature difference in each effect, solvent evaporated in each effect, and steam requirement is assumed.

4. Scaling procedure is followed to reduce the terms appearing in the matrix and equations. $l_j = \frac{L_j}{F}, v_j = \frac{V_j}{F}, T_j = u_j T_0$

5. Now the values of the individual terms in the Jacobian matrix are calculated and the Jacobian matrix is completed.

$$J_k * \Delta X_k = f_k$$

6. Now the matrix equation is complete. Both J_k and f_k are known but to compute the values of the unknown variables in ΔX_k we need to find out the inverse of J_k. Thus using MATLAB, the inverse of J_k is computed and by simple matrix multiplication the unknown variables are found out.

7. This is the result from the first iteration. The values of variables are used instead of the values chosen in the third step and steps 3-6 are repeated till the values of two consecutive iterations differ by a value <=0.000001

CHAPTER FIVE: RESULT AND DISCUSSION

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

5.1 Cost Computation without Vapour Compression

Considering the operating parameters shown in Table 3.1 and 3.2, the model shown through Eq. 4 to 17 is solved using MATLAB. This model is without vapour compressor. In this model the values of heat transfer coefficients are taken from equation 4.18. As the solution of the model is based on iterations the results of all iterations are shown in Table 5.1.

Table 5.1: Iterative results from the MATLAB code

Iteration	v_0	Δl_1	Δl_2	Δl_3	Δl_4	Δl_5	Δl_6	Δu_1	Δu_2	Δu_3	Δu_4	Δu_5	Δu_6
1	0.1339	0.173	0.3359	0.4788	0.537	0.728	0.738	0.05	0.137	0.06	0.069	0.0954	0.0102
2	0.1338	0.171	0.3354	0.4788	0.539	0.721	0.746	0.05	0.134	0.056	0.067	0.0953	0.01018
3	0.1338	0.169	0.335	0.4788	0.54	0.72	0.741	0.05	0.130	0.05	0.065	0.0954	0.01019
4	0.1338	0.169	0.335	0.4788	0.54	0.72	0.741	0.05	0.130	0.05	0.065	0.0954	0.01019

From these results, the following values of variables are predcited as shown in Table 5.2.

These values are also presented in MEE system shown in Figure 5.1.

Table 5.2: Variables in the different effects

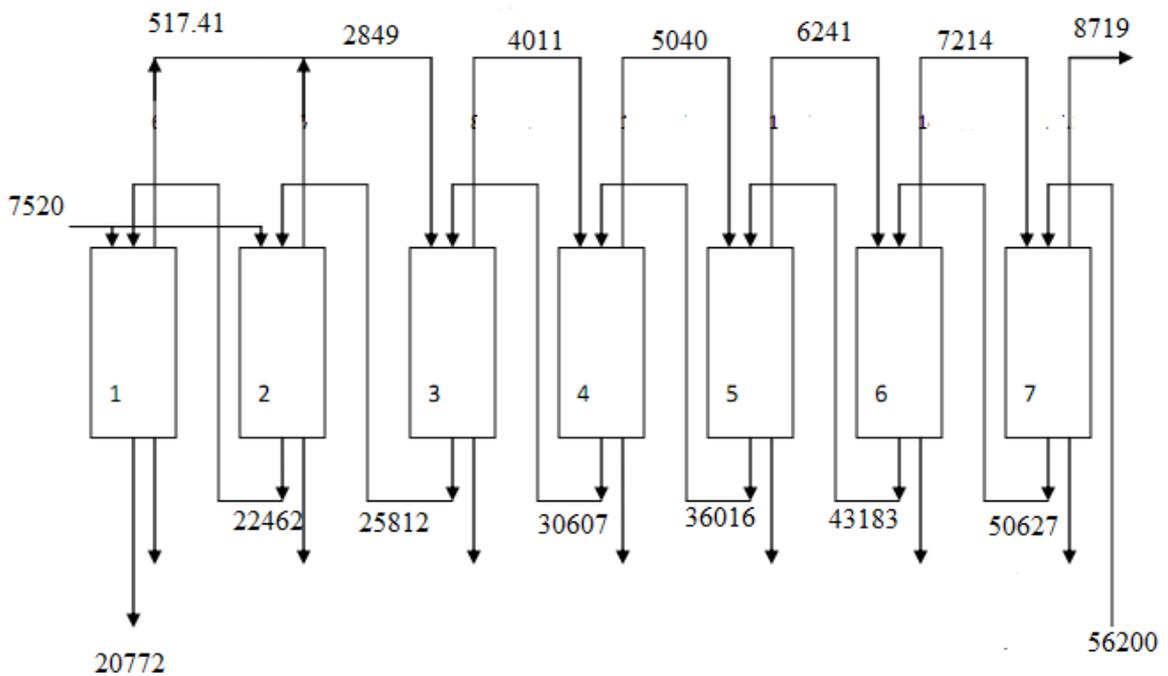| Effect	Liquid Flow, kg/hr		Temperature, °C		Pressure, bar	
	Variable	Value	Variable	Value	Variable	Value
1	L_1	20772	T_1	146	P_1	2.8195
2	L_2	22462	T_2	143	P_2	2.4620
3	L_3	25812	T_3	128	P_3	1.9983
4	L_4	30607	T_4	121	P_4	1.5190
5	L_5	36016	T_5	111	P_5	1.2839
6	L_6	43183	T_6	97	P_6	1.0878
7	L_7	50627	T_7	83	P_7	0.7009

Fig 5.1 Schematic Diagram with values.

Also, the steam requirement is 7520 kg/hr. So, using the cost of steam at $ 0.3/m^3 of steam according to Al-Sahali et al. (1997) the cost for this operation is $ 4095.

5.2 Solution of model with Vapour Compression

Considering the operating parameters shown in Table 3.1 and 3.2, the model shown through Eq. 4.19 to 4.32 is solved. This model is with vapour compressor. Here the values of heat transfer coefficients are taken same as considered for model without compressors. The results of all iterations are shown in Table 5.3.

Table 5.3: Iterative results from the MATLAB code

Iteration	v_0	Δl_1	Δl_2	Δl_3	Δl_4	Δl_5	Δl_6	Δu_1	Δu_2	Δu_3	Δu_4	Δu_5	Δu_6
1	0.0621	0.149	0.3245	0.4017	0.518	0.691	0.738	0.03	0.128	0.092	0.078	0.110	0.01
2	0.0622	0.148	0.3241	0.4011	0.519	0.691	0.746	0.04	0.128	0.094	0.080	0.110	0.0107
3	0.0622	0.149	0.3241	0.4011	0.519	0.691	0.741	0.04	0.128	0.094	0.080	0.110	0.0107

From these results, the following values of variables are predcited as shown in Table 5.4. These values are also presented in MEE system shown in Figure 5.1.

Table 5.4: Variables in the different effects

Effect	Liquid Flow, kg/hr		Temperature, °C	
	Variable	Value	Variable	Value

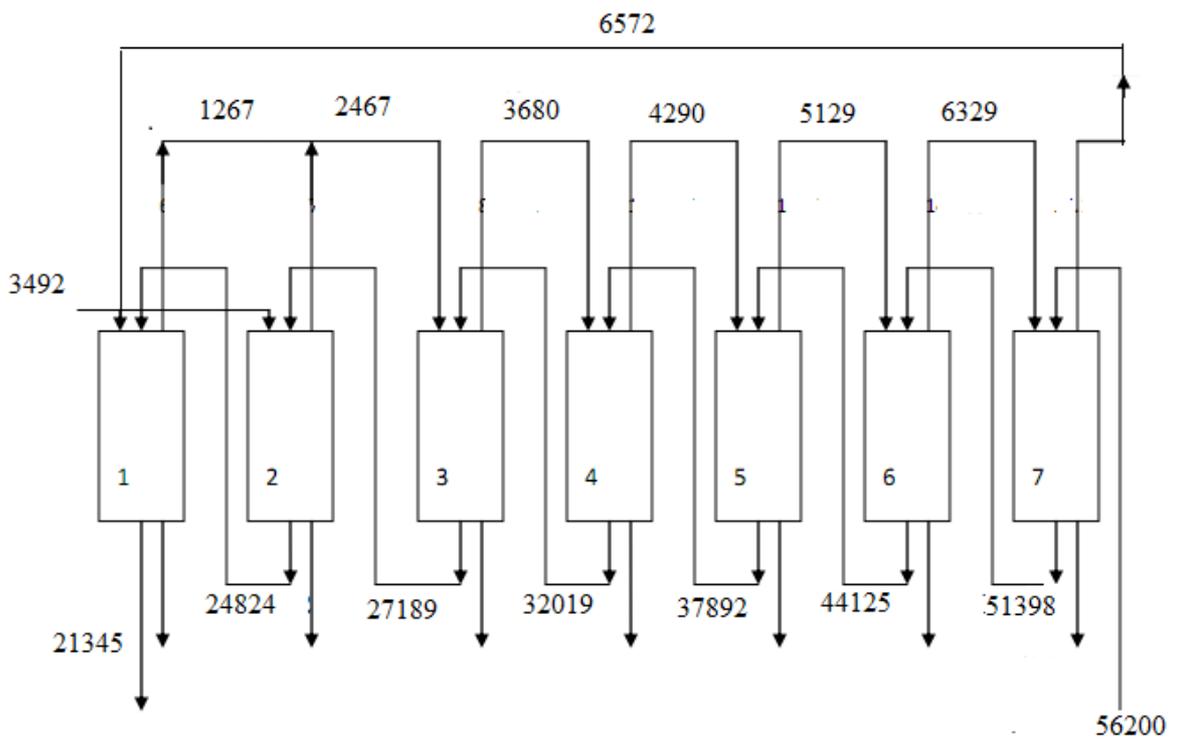| 1	L_1	21345	T_1	139
2	L_2	24824	T_2	143
3	L_3	27189	T_3	126
4	L_4	32019	T_4	123
5	L_5	37892	T_5	116
6	L_6	44125	T_6	94
7	L_7	51398	T_7	88

Fig 5.2 Schematic Diagram with values with vapour compression

Further, 16 more configurations have been considered. They have been listed in section 4.3 and have been discussed in detail in the next section.

5.2.1 Cost Computation with Vapour Compression

When the vapour from the 7th effect is compressed and sent to the 1st effect and the Jacobian matrix is solved, we get the steam requirements to be 3492.18 kg/hr and the steam costs to be 1977.45 $/hr.

But also some cost is required to compress the steam from its pressure of 0.7009 bar to 2.8195 bar, this cost can be computed using equation for energy consumption of a compressor given by Al-Sahali et al. (1997):

$$W = \frac{\gamma}{(\eta(\gamma-1))} P_v V_v \left((P_s / P_v)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1 \right)$$

Using this equation we get the work done to be 8154 KWh and again using the cost of electricity given by Al-Sahali et al. (1997), we get the costs to be $ 2446. This results in a total cost of 4423 $/hr which is greater than the cost for the operation without vapour compression. So, even though the steam required is vastly reduced, the high cost of compression makes this configuration unviable.

Now we compress the vapour from the 7th effect and send it to other effects and compute the total costs.

For each configuration the equations are altered and Jacobian Matrix is formed again. Now the matrix is iterated and the variables are calculated. After the calculation of the variables the total steam requirement is calculated. Then, from the pressure values in each effect, the total cost of compression is computed and the resultant total cost is compared.

The resulting total costs are tabulated as follows:

Table 5.5: Costs for Different configurations for vapour compression from 7th effect

Configuration	Cost of Steam	Cost of Compression	Total Cost
7 to 1	1977	2446	4423
7 to 2	2006	2219	4225
7 to 2 (50%) and 3 (50%)	2024	2108	4132
7 to 3	2068	2079	4147
7 to 4	2127	2034	4161

From the table 5.5 it can be seen that while in the first two cases the steam cost is drastically reduced, the cost from compression is high and thus there are no savings made by vapour compression and the method is not viable

Also, the 4th and 5th case even though the cost is very low in compressing but also, the saving made on compression are not enough to counter the higher steam requirements. Thus it is seen that the 3rd case is a profitable venture. But still no savings are made, from fig. 5.3

In the 3rd case we split the vapour from the 7th effect and feed them equally to both the 2nd and the 3rd effect.

Fig. 5.3: Plot of total costs vs different configurations for vapour compression from 7th effect

Similar calculations and simulations for the sixth effect lead to the following table and plot.

Table 5.6: Costs for Different configurations for vapour compression from 6th effect

Configuration	Cost of Steam	Cost of Compression	Total Cost
6 to 1	2040	2092	4132
6 to 2	2081	1905	3986
6 to 3	2134	1882	4016
6 to 4	2303	1798	4101

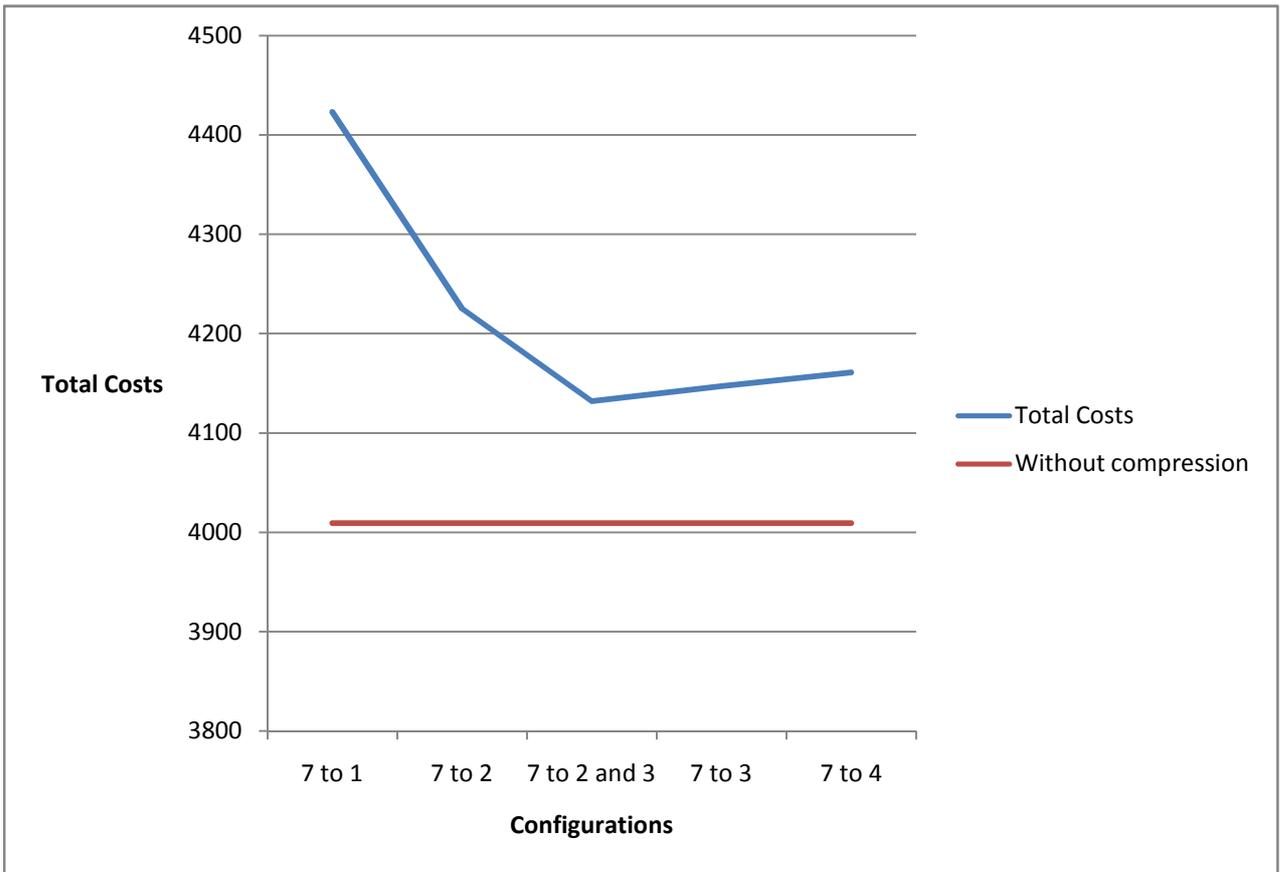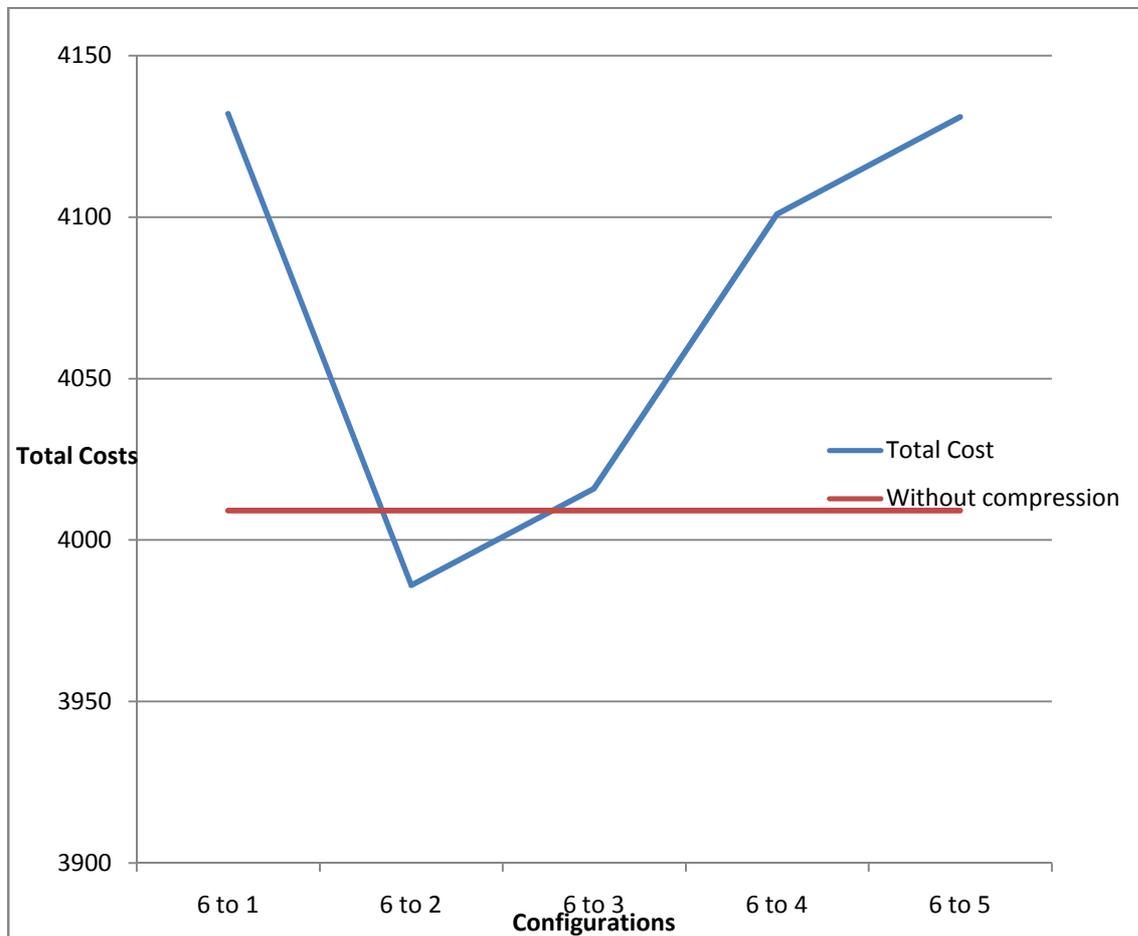| 6 to 5 | 2428 | 1703 | 4131 |

Fig. 5.4: Plot of total costs vs different configurations for vapour compression from 6th effect

Similar calculations and simulations for the fifth effect lead to the following table and plot.

Table 5.7: Costs for Different configurations for vapour compression from 5th effect

Configuration	Cost of Steam	Cost of Compression	Total Cost
5 to 1	2051	2038	4089

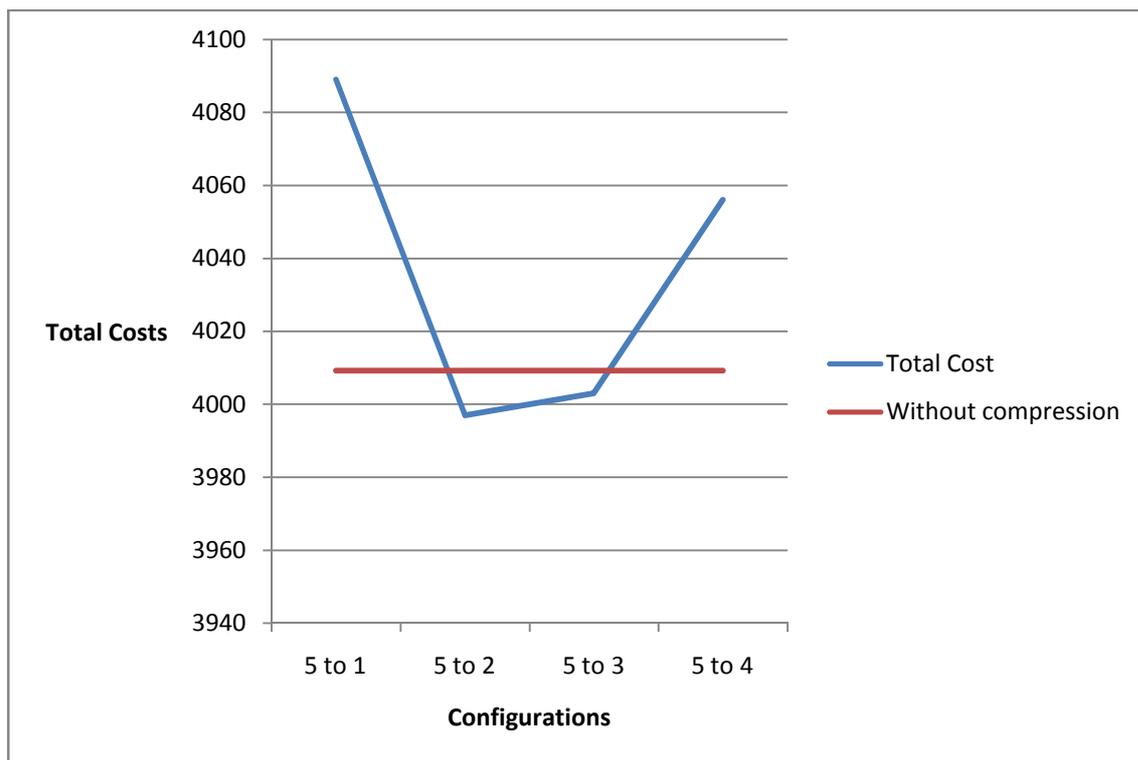|			
5 to 2	2068	1929	3997
5 to 3	2162	1841	4003
5 to 4	2278	1778	4056

Fig. 5.5: Plot of total costs vs different configurations for vapour compression from 5th effect

Similar calculations and simulations for the fourth effect lead to the following table and plot.

Table 5.8 Costs for Different configurations for vapour compression from 4th effect

Configuration	Cost of Steam	Cost of Compression	Total Cost
4 to 1	2175	1937	4112

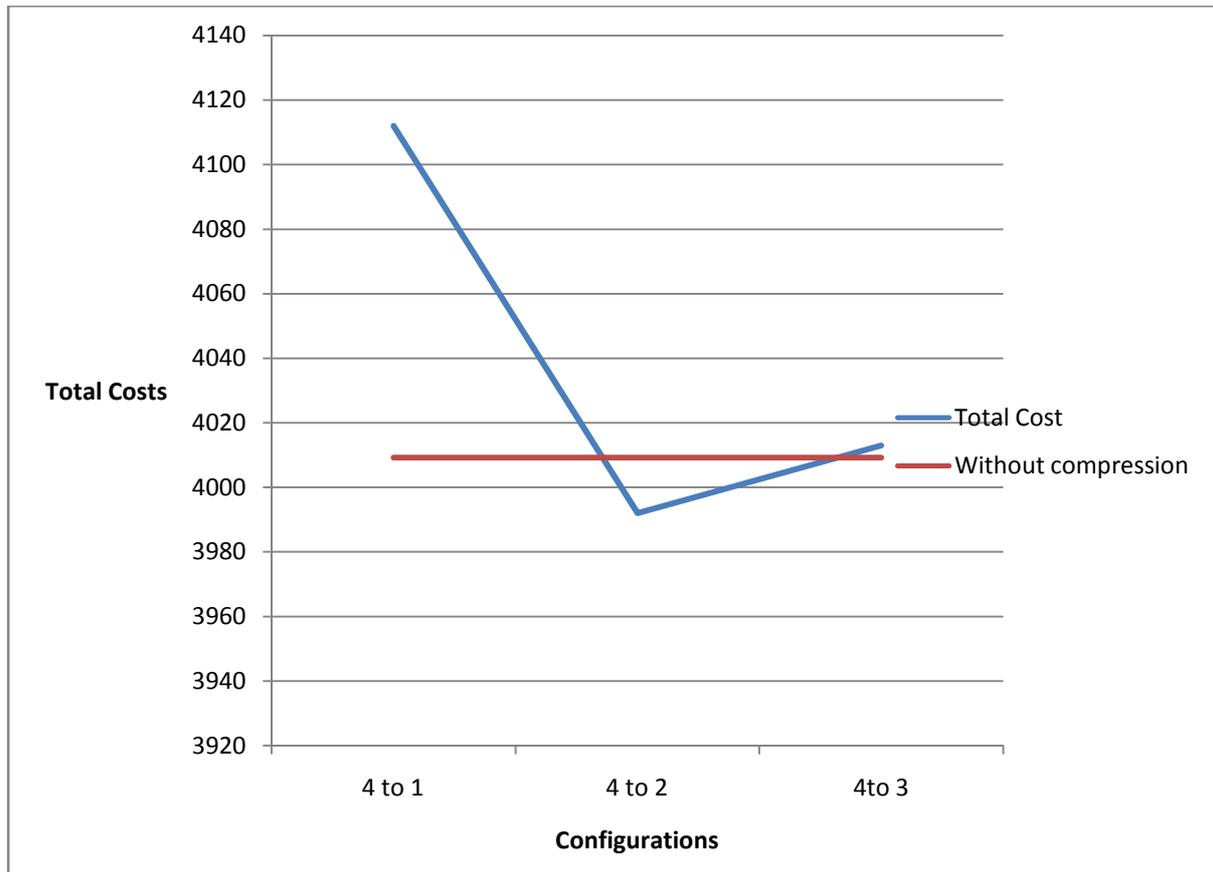| 4 to 2	2194	1798	3992
4to 3	2250	1763	4013

Fig. 5.6: Plot of total costs vs different configurations for vapour compression from 4th effect

The maximum profit is made when the vapour from the 6th effect is compressed and sent back to the 2nd effect. In this operation we save about 23$/hr. The final MEE system for this case is shown in Fig. 5.7.
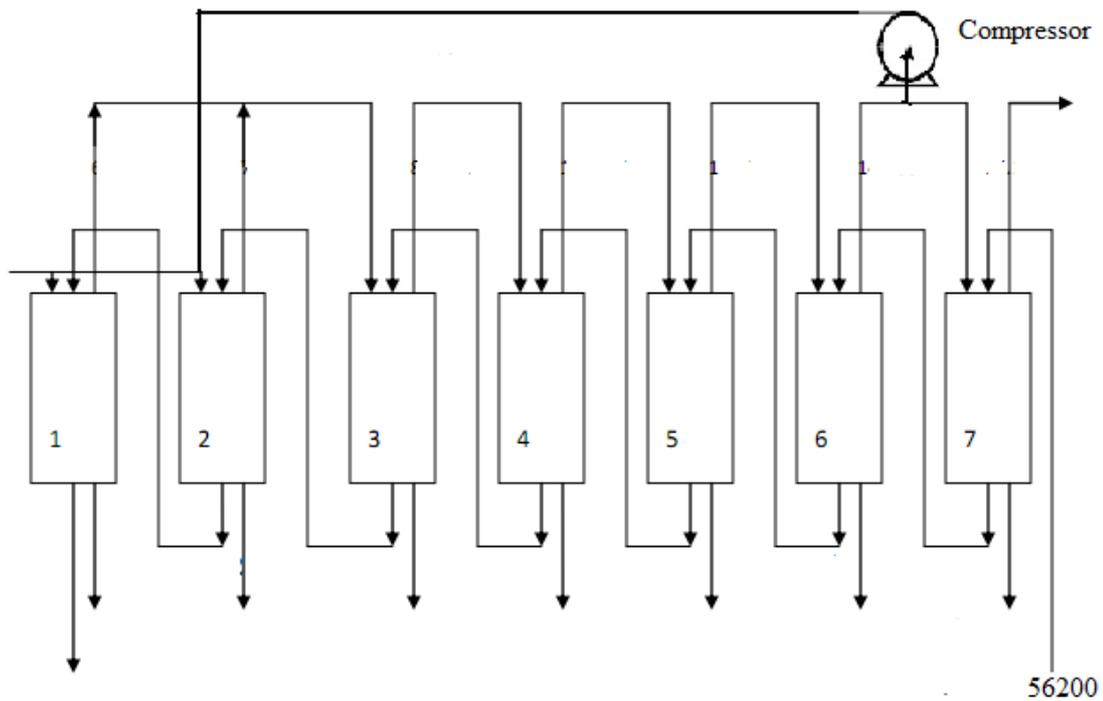
Fig. 5.7 Final flow sheet of the selected configuration

5.3 Payback Period

To calculate payback period, first we need to first use a suitable compressor. This can be done based on figure 4.1. It is found that for the required operation we may use 2 stage 150 psig maximum reciprocating pump which costs $200,000.

Salvage Value = $20,000

Installation costs = 50% of purchased equipment cost = $100,000

Life of compressor = 10 years

Depreciation = 280,000/8 = $28,000

Profit/hr = \$23

Profit/year = 23x300x20 = 138,000

Payback period $= \frac{Total\ Depreciable\ costs}{Profit+Depreciation}$

Therefore, payback period = 280,000/(138,000+28,000) = 1.68 years = 1 year, 8 months and 5 days.

Therefore the initial cost invested in purchasing, freight and installation of the equipment can be recovered in almost 1 year and 8 months and after that the unit will be making profit.

CHAPTER SIX: CONCLUSION

In the present work, simulation of a flat falling film seven effect evaporator is done in order to apply vapour compression to the system and to find of the most thermo-economically viable route of compressed vapour. A generalized solution technique is developed so that the same algorithm maybe used for different vapour compression routes with only slight modification in the inputs. Hence there is no need of different codes for different routes of vapour compression.

Taking the results into account, the conclusions that can be drawn from the work are as follows:

1. Pumping back compressed vapour we can reduce the live steam requirement, but also the cost of compressing the vapour is very high and so all the vapour compression routes are not economically viable even though thermally they save a lot of energy. Thus the most thermo-economically viable route has been chosen.

2. In the present work, first the live steam requirement is evaluated for the evaporator without any vapour compression. Then vapour compression is used and the live steam requirement has been calculated.

3. The cost for running the equipment without any vapour compression is found out to be 4009 $/hr. With the vapour from the sixth effect being compressed and sent into the second effect the cost of running is reduced to 3886 $/hr. The savings made are 23 $.hr.

4. The initial investment of compressor, the cost of installation and the salvage value of the compressor were taken into account to calculate the payback period for the arrangement and it was found to be 1 year and 8 months. As this arrangement reduces both live steam requirement and the cost of the process and thus is viable.

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APPENDIX

In this applendix the computaer code with results generated for solving the model of multiple effecte vaporator system with and without compressor is shown.

Code:

```
#include<iostream.h>
#include<conio.h>
#include<math.h>
#include<stdio.h>
#include<stdlib.h>
void arg(float *a,float *b,int *n,int x,int y)
{int k,l,i,j;
for(i=0,k=0;i<*n;i++,k++){
for(j=0,l=0;j<*n;j++,l++){
if(i==x)
i++;
if(j==y)
j++;
*(b+14*k+l)=*(a+14*i+j);}
}*n=*n-1;}
int det(float *p,int *n){
float d[14][14],sum=0;
int i,j,m;
m=*n;
if(*n==2)
return(*p**(p+15)-*(p+1)**(p+14));
for(i=0,j=0;j<m;j++){
*n=m;
arg(p,&d[0][0],n,i,j);
```

```
sum=sum+*(p+10*i+j)*pow(-1,(i+j))*det(&d[0][0],n);

}return(sum);

}int main()

{double
A,F,V0,T0,V1,L1,T1,lambda0,hF,h1,TF,U1,V2,L2,T2,lambda1,h2,U2,V3,L3,T3,lambda2,h3,U3,
lambda3,xF,xL3,delT,delT1,delT2,delT3,h4,U4,V4,L4,T4,lambda4,h5, U5,V5,L5,T5,lambda5,
h6,U7,V7,L7,T7, lambda7, h8,U8,V8,L8,T8, lambda8,h9,U9,V9,L9,T9,
lambda9,h10,U10,V10,L10,T10,lambda10,h11,U11,V11,L11,T11,lambda11,h12,U12,V12,L12,T12,
lambda12,h13,U13,V13,L13,T13,lambda13,h14,U14,V14,L14,T14,lambda14;

cout<<"enter the values of
A,T0,T3,TF,F,xF,xL3,V0"<<endl;cin>>A>>T0>>T3>>TF>>F>>xF>>xL3>>V0;

        delT=(T0-T3)/3; delT1=delT2=delT3=delT; T1=T0-delT1; T2=T1-delT2;T3=T2-delT3;

        T4=T3-delT4; T5=T4-delT5;  T6=T5-delT6;T7=T6-delT7;T8=T7-delT8;T9=T8-
delT9;T10=T9-delT10; T11=T10-delT11; T12=T11-delT12;  T13=T12-delT13; T14=T13-delT14;


            double l1,l2,l3,u1,u2,u3,a1,v0;float v[14];

        int i,n,ctr=0;

        cout<<"enter order";

        cin>>n;

   for(i=0;i<n;i++)

{v[i]=0;}

v0=V0/F;u1=T1/T0;u4=T4/T0;u5=T5/T0;u6=T6/T0;u7=T7/T0;u8=T8/T0;u2=T2/T0;u3=T3/T0;

        l1=L1/F;l2=L2/F;l3=L3/F;l4=L4/F;l5=L5/F;l6=L6/F;l7=L7/F;

        do{

        ctr=ctr+1;

        v0=v0+v[0];

        u1=u1+v[1];

        l1=l1+v[2];

        u2=u2+v[3];

        l2=l2+v[4];

        u3=u3+v[5];

        l3=l3+v[6];

        u4=u4+v[7];

        l4=l4+v[8];
```

```cpp
u5=u5+v[9];

l5=l5+v[10];

u6=u6+v[11];

l6=l6+v[12];

a1=a1+v[13];

double Cp,f1,f2,f3,f4,f5,f6,f7,f8,f9,f10,f11,f12,f13,f14;

cout<<"enter the value of Cp,U1,U2,U3,lambda0"<<endl;

cin>>Cp>>U1>>U2>>U3>>lambda0;

lambda1=lambda2=lambda3=lambda0;

cout<<"lambda1="<<lambda1;

float bb[14][14];

bb[0][1]=-(Cp*T0)/lambda0;

bb[1][1]=-(U1*a1*T0)/(50*lambda0);

bb[2][1]=(l1*Cp*T0)/lambda0;

bb[3][1]=(U2*a1*T0)/(50*lambda0);

bb[1][5]=(U1*(1-u1)*T0)/(50*lambda0);

bb[2][3]=-(l1*Cp*T0)/lambda0;

bb[3][3]=-(U2*a1*T0)/(50*lambda0);

bb[4][3]=(l2*Cp*T0)/lambda0;

bb[5][3]=(U3*a1*T0)/(50*lambda0);

bb[4][4]=((Cp*(u2-u3)*T0)-(lambda2+lambda3))/lambda0;

bb[5][5]=(U3*(u2-u3)*T0)/(50*lambda0);

bb[2][2]=((Cp*(u1-u2)*T0)-(lambda1+lambda2))/lambda0;

bb[3][5]=(U2*(u1-u2)*T0)/(50*lambda0);

bb[3][3]=-(U2*a1*T0)/(50*lambda0);

bb[6][6]=(l3*Cp*T0)/lambda0;

bb[5][7]=-(U3*a1*T0)/(50*lambda0);

bb[6][4]=-(l2*Cp*T0)/lambda0;

bb[6][5]=-(U3*(u2-u3)*T0)/(50*lambda0);

bb[7][6]=((Cp*(u3-u4)*T0)-(lambda3+lambda4))/lambda0;

bb[8][6]=-(l4*Cp*T0)/lambda0;
```

bb[8][8]=(l4*Cp*T0)/lambda0;

bb[7][8]=(U4*a1*T0)/(50*lambda0);

bb[8][9]=((Cp*(u4-u5)*T0)-(lambda4+lambda5))/lambda0;

bb[5][5]=(U3*(u2-u3)*T0)/(50*lambda0);

bb[2][2]=((Cp*(u1-u2)*T0)-(lambda1+lambda2))/lambda0;

bb[1][13]=(U1*(1-u1)*T0)/(50*lambda0);

bb[7][7]=-(U4*a1*T0)/(50*lambda0);

bb[10][12]=-(l4*Cp*T0)/lambda0

bb[11][11]=(U6*a1*T0)/(50*lambda0);

bb[12][12]=((Cp*(u6-u7)*T0)-(lambda2+lambda3))/lambda0;

bb[3][13]=(U2*(u1-u2)*T0)/(50*lambda0);

bb[12][14]=(l6*Cp*T0)/lambda0;

bb[12][12]=-(l6*Cp*T0)/lambda0;

bb[9][10]=-(U5*a1*T0)/(50*lambda0);

bb[4][4]=((Cp*(u2-u3)*T0)-(lambda2+lambda3))/lambda0;

bb[13][5]=(U3*(u2-u3)*T0)/(50*lambda0);

bb[13][7]=(U4*(u3-u4)*T0)/(50*lambda0);

bb[13][9]=(U5*(u4-u5)*T0)/(50*lambda0);

bb[13][11]=(U6*(u5-u6)*T0)/(50*lambda0);

bb[13][13]=(U7*(u6-u7)*T0)/(50*lambda0);

bb[2][2]=((Cp*(u1-u2)*T0)-(lambda1+lambda2))/lambda0;

bb[3][5]=(U2*(u1-u2)*T0)/(50*lambda0);

bb[0][2]=lambda1/lambda0;

bb[2][4]=lambda2/lambda0;

bb[3][2]=lambda1/lambda0;

bb[4][2]=lambda2/lambda0;

bb[5][4]=lambda2/lambda0;

bb[5][5]=-lambda2/lambda0;

bb[6][5]=lambda3/lambda0;

bb[7][5]=-lambda3/lambda0;

bb[8][7]=lambda4/lambda0;

```cpp
        bb[9][7]=-lambda4/lambda0;

        bb[6][9]=lambda4/lambda0;

        bb[9][9]=lambda4/lambda0;

        bb[10][9]=lambda5/lambda0;

        bb[11][9]=-lambda5/lambda0;

        bb[8][10]=lambda5/lambda0;

        bb[11][10]=lambda5/lambda0;

        bb[12][10]=lambda6/lambda0;

        bb[13][10]=-lambda6/lambda0;

        bb[10][12]=lambda6/lambda0;

        bb[13][12]=-lambda6/lambda0;


        cout<<"bb[0][1]="<<bb[0][1]<<endl<<"bb[1][1]="<<bb[1][1]<<endl<<"bb[2][1]="<<bb[2][
1]<<endl<<"bb[3][1]


="<<bb[3][1]<<endl<<"bb[1][5]="<<bb[1][5]<<endl<<"bb[2][3]="<<bb[2][3]<<endl<<"bb[3][3]="<
<bb[3][3]<<endl<<"bb[4]


[3]="<<bb[4][3]<<endl<<"bb[5][3]="<<bb[5][3]<<endl<<"bb[4][4]="<<bb[4][4]<<endl<<"bb[5][5]
="<<bb[5][5]<<endl<<"bb
[2][2]="<<bb[2][2]<<endl<<"bb[3][5]="<<bb[3][5];

goto x;void arg(float *,float *, int *,int ,int );int det(float *,int *);int i,j,m,n;

float a[14][14],b[14][14],c[14][14],d;

printf("Enter the order of the matrix");scanf("%d",&n);printf("Enter the matrix");

for(i=0;i<n;i++)

{for(j=0;j<n;j++)

scanf("%f",&a[i][j]);}if(n==2){c[0][0]=a[1][1];

c[1][1]=a[0][0];

c[0][1]=-a[0][1];

c[1][0]=-a[1][0];

d=a[0][0]*a[1][1]-a[0][1]*a[1][0];

printf("Determinant is:%f\n",d);

if(d==0){
```

```
getch();

exit(d-'0');}

for(i=0;i<n;i++)

{printf("\n");

for(j=0;j<n;j++)

printf(" %f",c[i][j]/d);

}}else

{m=n;for(i=0;i<m;i++){for(j=0;j<m;j++){n=m;

arg(&a[0][0],&b[0][0],&n,i,j);

c[j][i]=pow(-1,(i+j))*det(&b[0][0],&n);}}

n=m;

d=det(&a[0][0],&n);

printf("Determinant is :%f\n",d);

if(d==0)

{

printf("INVERSE DOES NOT EXIST\n");

cout<<"No more iterations possible"<<endl;

printf("Number of iterations is:%d\n",ctr);

cout<<"The final values after iteration are:"<<endl;

cout<<"v0="<<v0<<endl<<"u1="<<u1<<endl<<"l1="<<l1<<endl<<"u2="<<u2<<endl<<"l2="<<l2<<endl<<"a1="<<a1<<endl;

getch();

exit(d-'0');

}

for(i=0;i<m;i++)

{

printf("\n");

for(j=0;j<m;j++)

printf(" %f",c[i][j]/d);

}

}
```

```c
hF=Cp*TF;

h1=Cp*T1;

h2=Cp*T2;

h3=Cp*T3;

h4=Cp*T4;h5=Cp*T5;h6=Cp*T6;h7=Cp*T7;

 double g1,g2,g3,g4,g5,g6;

        g1=f1/(F*lambda0);

        g2=f2/(F*lambda0);

        g3=f3/(F*lambda0);

        g4=f4/(F*lambda0);

        g5=f5/(F*lambda0);

        g6=f6/(F*lambda0);

        g7=f7/(F*lambda0);

        g8=f8/(F*lambda0);

        g9=f9/(F*lambda0);

        g10=f10/(F*lambda0);

        g12=f12/(F*lambda0);

        g11=f11/(F*lambda0);

        g13=f13/(F*lambda0);

        g14=f14/(F*lambda0);

 float u[10];

printf("Enter the order of the matrix");

scanf("%d",&n);

printf("Enter the matrix");

for(i=0;i<n;i++)

{scanf("%f",&u[i]);}

int k;

for(i=0;i<n;i++)

{ v[i]=0; for(k=0;k<n;k++)

        { v[i]=v[i]+(c[i][k]/d)*u[k];  }  }

{for(i=0;i<n;i++){printf("\n");printf(" %f",v[i]);}
```

```
}
getch();
}
```

Results:

For the case of evaporator without vapour compression

Input:

```
n 7
T10 140
T20 147
xf 0.118
Tf 64.7
F 56200
T7 52
```

Output:

Iteration	v 0	l1	l2	l3	l4	l5	l6	u1	u2	u3	u4	u5	u6
1	0.1339	0.173	0.3359	0.4788	0.537	0.728	0.738	0.05	0.137	0.06	0.069	0.0954	0.0102
2	0.1338	0.171	0.3354	0.4788	0.539	0.721	0.746	0.05	0.134	0.056	0.067	0.0953	0.01018
3	0.1338	0.169	0.335	0.4788	0.54	0.72	0.741	0.05	0.130	0.05	0.065	0.0954	0.01019
4	0.1338	0.169	0.335	0.4788	0.54	0.72	0.741	0.05	0.130	0.05	0.065	0.0954	0.01019

Iteration				
1	L1	20772	T1	146
2	L2	22462	T2	143
3	L3	25812	T3	128
4	L4	30607	T4	121
5	L5	36016	T5	111
6	L6	43183	T6	97
7	L7	50627	T7	83

V0 = 7520