OPTIMIZATION OF MULTIPLE EFFECT EVAPORATOR SYSTEM BASED ON DIFFERENT CONFIGURATIONS OF VAPOR BLEEDING

A DISSERTATION

Submitted in partial fulfillment of the
requirements for the award of the degree
of
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by

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CANDIDATE'S DECLARATION

I hereby declare that the work being presented in the **M. Tech Dissertation** entitled **"OPTIMIZATION OF MULTIPLE EFFECT EVAPORATOR SYSTEM BASED ON DIFFERENT CONFIGURATIONS OF VAPOR BLEEDING",** in partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY WITH SPECIALIZATION IN INDUSTRIAL SAFETY AND HAZARDS MANAGEMENT,** submitted in the Department of Chemical Engineering of the Indian Institute of Technology Roorkee, Roorkee, is an authentic record of my own work carried out under the supervision of **Dr. Shabina Khanam**, **Assistant Professor, Department Of Chemical Engineering, Indian Institute of Technology Roorkee, Roorkee India.**

The matter embodied in this dissertation has not been submitted by me for the award of any other degree of this or any other institute

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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

This work reports on advancement of a model and an algorithm to design a multiple effect evaporator system. Then, it is needed to determine the extent of savings of steam using vapour bleeding. To obtain above targets different models based on non-linear equations are developed to design the multiple effect evaporator system to concentrate black liquor.

For 1st part model is developed for simplified model, which is considered as base case for further reference. Then the simplified model is modified to account variation in physical properties, BPR and steam splitting. Further, model developed in second part is modified to include vapor bleeding with different configurations such as steam splitting, configuration 1 and 2 for system with vapor bleeding, considering vapor bled from vapor generated in second effect, third, fourth, fifth and preheating of liquor using condensate in seven effect evaporator system and steam splitting model and vapor bleeding in ten effect system.

In the present work two MEE systems such as seven effect and ten effect evaporator systems are considered to concentrate black liquor solution.

In the present work, the best and published models are developed for seven and ten, respectively, effect evaporator system. These are compared based on steam economy. For seven effect evaporator system, Mod-9 model which considers preheating of liquor using condensate is found as best. This model enhances the steam economy of the system by 7.151% in comparison to published model. However, for ten effect evaporator system, Mod-11 which incorporates vapor bleeding is found as best, which increases the steam economy of the system by 4.34%. Further, comparison between the published model and the best model is done for seven effect evaporator system. For the best model steam economy is 5.999 and steam consumption is 2.097 kg/s. However, for published model steam economy and steam consumption is 5.570 and 2.138 kg/s, respectively. As the economy and steam consumption of the best model is 7.151% more than the steam economy and 1.917 % less steam consumption in compared of published model, it is found that the best model is better than the published.

ACKNOWLEDGEMENT

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(PRATAP SINGH)

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NOMENCLATURE

Symbol used	Parameter
F	Feed flow rate (kg/s)
L	Flow rate of liquor stream (kg/s)
T	Temperature (°C)
ΔT	Temperature drop (°C)
V	Flow rate of vapor stream (kg/s)
V_0	Steam flow rate (kg/s)
A	Heat transfer area of an effect (m^2)
U	Overall heat transfer coefficient (KW/m^2K)
Λ	Heat of vaporization/latent heat (KJ/kg)
BPR	Boiling point rise (°C)
C_P	Specific heat (KJ/kg °C)
V’	Bled vapor flow rate (kg/s)
X	Solid concentration
Q	Heat flux (KW/m^2)

Subscripts

V	Vapor
F	Feed
0	Steam
L	Liquor
1-7	Effect number
1-10	Effect number

CHAPTER 1

INTRODUCTION

Evaporation is the process of separation of the solvent from solvent and solute. It is normally handled to withdrawn wood and solution. The main purpose is to evaporate considerable amount of the water from a solution, which a single evaporator is used for the concentration of either solution, it is said to be a single effect evaporator system. However, if more than one evaporator is used in series for the concentration of solution, it is said to be a multiple effect evaporator (MEE) system. Dissimilar single stage evaporators, these can be fabricated till SEEEs.

1.1. Application of evaporators

Evaporators are essential many sectors such as Milk, Juice, Chemical, Paper, Caustic soda, Pulp and Drying process etc. It is also used as a drying process. It is employed to improve more solvents like Hexane that was waste and also to improve caustic NAOH for pulp mill.

1.2. Problems associated with multiple effect evaporators

The evaporator is an energy intensive process. It presents a great scope for reduction of costs by decreasing the live steam requirements. In this operation, efforts to propose new operating strategies have been made by several researchers to reduce SC in a MEE system to increase SE. Some of these systems strategies are steam splitting feed, product vapor bleeding and condensate and One of the earliest works on optimizing a multiple effect evaporator was done by estimating a system for optimizing a system by multiple effect evaporators assuming both backward and forward and feed flow sequences. This operation was forwarded. They included FFSs to optimize a multiple effect evaporators system for obtaining a non inferior feed flow sequence. A whole new set of equations were required for solving the new operating strategy. Here established a GCAS that was developed again and again for the many operating strategies of a MEE. These process includes a number of energy reduction systems such as flashing, steam and feed splitting, vapours bleeding and it is used an optimum feed flow sequence. Add a few recent articles here and try to draw gaps from it.

1.3 Objective

The objectives of the present work are;

1. To derive governing equations of MEE system to handle several constitutions like deviation in physical properties of liquor, condensate, vapour, BPR, steam splitting etc.
2. To define a number of combinations considering different configurations of vapor bleeding in MEE system.
3. To compare the steam economy predicted by models of different combinations to choose the best one based on different configurations and to propose modified design of MEE system.
4. To compare results of present work with published work.

CHAPTER 2

LITERATURE REVIEW

2.1 EVAPORATION

The process of separating solvent from solvent and solute and concentrating is said to Evaporation. The period withdrawing from compound is reduced by spilling the solution to a larger area, which are obtained in a higher residence time or by heating the solution to a higher temperature. It is reduced the temperature and residence time.

2.2 Variety of evaporators

Evaporator is normally described to several ways:

1. In (THS) tubular heating surfaces Evaporators, the evaporating liquid can be removed from the heating medium

2. In the evaporators, the heating medium is bounded to double walls, coils and jackets etc.

3. It is found for solar radiation in heating medium.

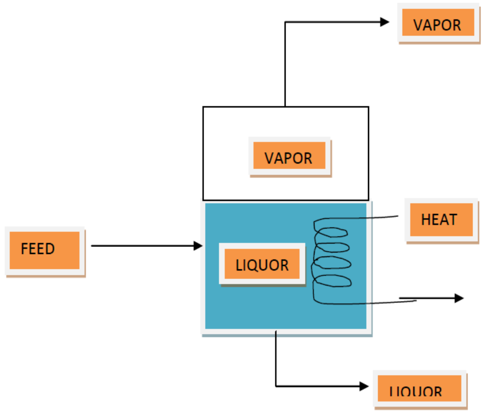

Fig. Schematic Diagram of a Single Effect Evaporator

Figure 2.1 Schematic diagram of a SEE

2.2.1 Falling film evaporators

FFEs added upward the raw materials. which mainly enters the compound into the tube. A narrow solution moves downward in the tube at boiling temperature and is partially evaporated. The vapour and materials fall to the bottom in a same direction. The heat exchanger and the separator separate the concentrated product form its vapour in the lower part of the evaporator.

Where

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.

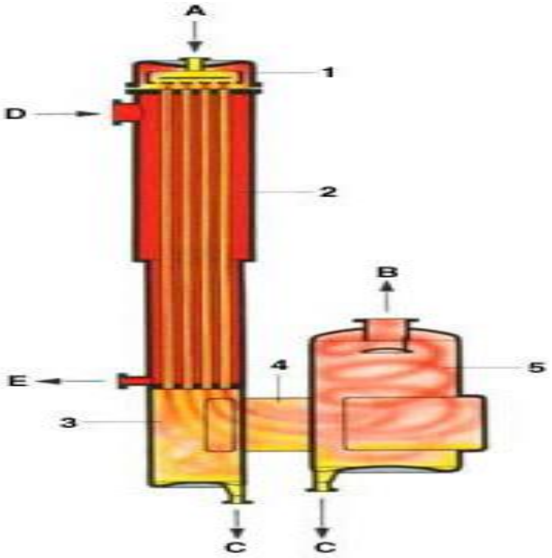

Fig 2.2 FF evaporators

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2.2.2 Rising falling film evaporators

If both RFE and FFF is accommodated in the same amount, it is said to be a rising falling film evaporator. As evaporators are low residence time and high heat transfer rates.

2.2.3 Horizontal tube evaporators

This is the first type of evaporator to obtain common realization and is designed normally horizontal tubes. This is hardly used except for some particular operation. It includes the elementary of methods with a horizontal and shell tube, Evaporation is produced at shell side and Heating Medium for tube.

2.2.4 Horizontal spray film evaporators

The liquid in the horizontal, falling-film evaporator when is dispersed by recirculation through a spray system, Then it provides the horizontal spray film evaporators. Gravity uses the sprayed liquid fall from one tube to another.

2.2.4.1 Advantages:

(1) Transporation are more smoothly polished
(2)Vapour removable are simply polished
(3) Steady application can be achieve under scaling conditions

2.2.5 Short tube vertical evaporators

It is the first form to come actually suitable economically. It is also said to be calandria. Down comers must be more calculated that it decreases the liquid holdup over the tube sheet as this setup increases fluid dynamics, decreases foaming and improves heat transfer rate.

2.2.6 Basket type evaporators

The main difference between a standard evaporator and it is that in the basket type the down comer. The annual down comer is more commonly as it uses the evaporator to be separated for cleaving and repair. Also, a deflector is used to increase “burping” which is produced due to entrainment.

2.2.7 Forced circulation evaporators

Consistently it is required to remove the boiling of the product on the heating surface, because of the fouling properties of the liquid. This are used evaporator normally in this situation. And to obtain it, more capacity pumps are used to control more velocity of the liquids in the tubes.

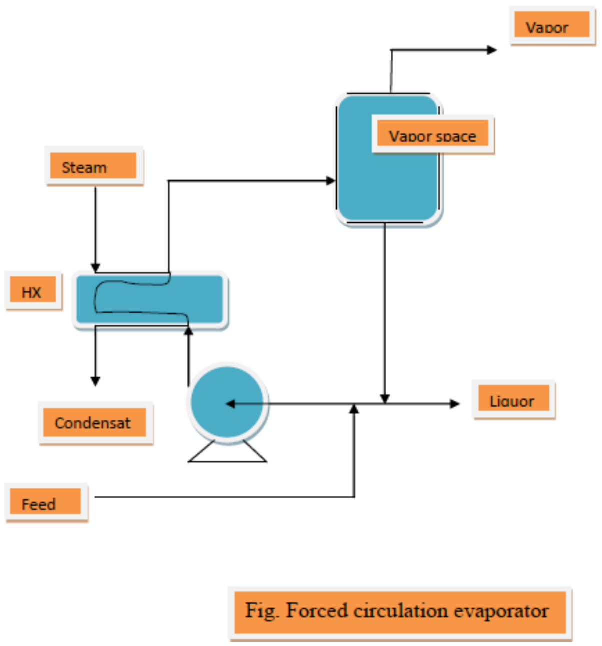

Fig.2.3 Schematic diagram of forced circulation evaporators

2.2.8 Plate evaporators

In tube and shell heat exchangers, framed plates are handled in the process of a heating surface. The plates accumulations are related to PHES, The evaporators are designed of flat plates or corrugated plates. In the case of helping plates is that scales will shed the plates high immediately, then they act so from curved surfaces. In a few flat evaporators, plate surfaces are helped such that alternately one side is helped as the steam side and liquor side so that when a side is handled as liquor side and scales are accumulated on the surface, it is handled as steam side to dissolve those scales.

2.2.9 Mechanically aided evaporators

The evaporators are generally used from two points
In the heat transfer surface, the first point is to regularly fragment the materials
The next point is to help in enhancing the heat transfer by producing turbulence.
These are of many forms like

1. Agitated vessels
2. Scraped surface evaporators
3. Mechanically agitated thin film evaporators

2.3 Black liquor

This liquor is the waste solution that is derived from the mill. It is obtained from Pulp wood and digested to paper and pulp and other things from the raw material (wood) is 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.

2.3.1 Properties of black liquor

Some of the properties of black liquor are as follows

1. Black liquor is normally 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 instance 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 thermal conductivity, specific gravity, viscosity, specific heat, density is enhanced presence of inorganic compounds in black liquor, but it has no effect which is removed the cellulose fibers on the surface tension.

2.3.2 Composition of black liquor in the current study

The composition of weak Kraft black liquor that is used in the current study is given below:
Organic constituents of black liquor are Sugar and, Iso-saccharinic acid, Resins and fatty acid soaps, Alkali lignin, etc. While inorganic constituents of black liquor are Sodium hydroxide, Sodium sulphide, Sodium carbonate, Sodium thiosulphate, Sodium polysulphides, Sodium sulphate, Elemental sulphur and Sodium

Weak kraft black liquor constituents

S. NO.	Inorganic compounds	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 sulphate	Small

2.4 Mathematical modeling of MEE system

Stewart and Beveridge [1] developed a generalized cascade algorithm for the simulation of MEES with backward feed.This algorithm is defined on the simultaneous solution of lineralized forms of the effects models derived from knowledge of the significant factors determining their performance. The coefficients of these linear equations are determined directly from the non-linear effect models without recourse to any perturbation or numerical differentiation process. Two linearizations are described lumped parameter effect models and the effect models with strong interaction between the two-phase fluid flow and heat transfer phenomena.

Nishitani and Kunugita [2] developed a vector minimum problem for MEESs. Firstly a new method to estimate the design problem for different flow-patterns with no stream mixing or splitting and an arbitrary number of effects is detailed. Secondly the set of non inferior flow-patterns is used by calculating one-by-one for all flow-patterns. This method acts well in synthesizing multiple effect evaporator configurations. System structures are produced combinatorial by connecting the input and output terminals of the units. Synthesis of a multiple effect system is a matter of interconnecting evaporator units with pipes and the flow-pattern of vapor and liquid in this system has a sufficient effect on the performance.

Barba and Felice [3] proposed approach for evaporation (no-nucleate boiling) heat transfer coefficient in a horizontal tube falling film. The correlation is derived from an analysis of the thermal boundary layer under the assumption of turbulent flow regime as in the Dukler and for vertical long tube falling film, but the thermal developing region is consider due to the short run of the vaporizing liquid on the tube. The tube has been considered “unwrapped” to form vertical surface, where the velocity profile is considered fully developed so that the u component can be ignored and the film thickness can be considered constant.

Okeke et al.[4] developed a generalized cascade algorithm for steady state simulation of multiple effect evaporator systems. In 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 degrees of sophistication.

Ettouney et al. [5] developed a performance analysis for the vapour compression parallel feed multiple effect evaporation water desalination process. The process consider mechanical (MVC) and thermal (TVC) vapour compression. The process models include the dependence of the stream physical properties on temperature and salinity, thermodynamic losses, temperature depression in the vapour stream due to pressure losses and non condensable gases, flashing through the effects, and the presence of flashing boxes. The analysis is done as function of the brine distribution configuration (parallel or parallel/cross flow).

Low et al.[6] developed and fabricated a test rig to study the heat transfer of falling film flow on a doubly fluted plate. And parametric data to test the thermal performance based on the measured data. The effects of the temperature difference and feed water flow rate are performance with a given flow rate. The effect of steam flow rate was also explained under fixed feed water flow rate. In the testing, dry patches appeared on the plate surface when the feed water flow rate is less than 350l/h.

Chen and Gao [7] proposed black liquor of the chemical recovery loop in the pulping and paper industry, is mostly viscous alkaline organic mixture. The double salt burkeite ($2Na_2SO_4.Na_2CO_3$) is said to be scaling at heat transfer surface. In a pulping mill, a multi-effect evaporator system is normally designed to concentrate black liquor from 14-18% up to 68%. However, soluble scale fouling does produce in a conventional black liquor evaporator. Scaling in conventional black liquor evaporators has existed problems for many years, impleding the increase of productivity in paper mills.

Bharagava et al. [8] developed a non linear mathematical model for the analysis of septuple effect flat falling film evaporator system used for concentrating black liquor in a nearby paper mill. it simulates the plant data with considerably smaller amount of error in comparison to published model. The correlations developed for Ʈ and U predict the plant data with average absolute errors of 2.4% and 10% respectively.

Cardoso et al. [9] developed require a high efficiency to make the pulp in pulp and paper industries. And the main purpose of this sector is to reduce the energy consumption in this process. And this shows it in the process that an application of computer simulations in a Brazilian pulp mill. To handled two strategies for minimizing the mill energy consumption. In the first strategy, the overall heat transfer coefficient has been predicted for each body of the multiple effect evaporators in the black liquor recovery unit, handling continuous on-line, containing time oscillations. In the second strategy, to advance the effect of increasing the liquor solids concentration on the recovery boiler efficiency, the liquor combustion has been simulated as a function of the solids content in the feeding .The is a modular program designed to act the mass and energy balance calculations is called WINGEMS methods. Developing scaling on the black liquor evaporators, which is a serious problem to be overcome for improving the Kraft mill production. And used superheat steam from heat of black liquor combustion, and chemicals are also recovered. They generated steam is developed by the mills as a hot fluid in heat transfer operations and as a producer of a electrical energy. The methodology are used in the simulation - acquisiting data from the Brazilian mill, elaborating the block diagram that explained the process handling the basic modular units existed in Win GEMS, and simulating the black liquor evaporation and combustion stages. This results show that, the burning of liquor with a higher solids concentration (above 80%) leads to enhance in the boiler efficiency and stability.

Oliveira et al. [10] To analyzed effects of black liquor properties on its recovery unit operation. Kraft (or sulfate) and soda are used the two major alkaline processes to make chemical pulps, being the former the most important for pulp industries, From which is generally used to produce non-wood pulps, such as bagasse, straw, grass and bamboo. Howeverin both processes, cellulose fibers are separated from lignin by chemical reactions. Their actions form in a pressurized digester, where wood chips or fibers are heated and cooked with the cooking liquor, composed basically of NaOH.

Johansson et al. [11] developed only on performance of black liquor, a fluid produced through the production of chemical pulp from wood or annual plants, in which main constituents are lignin and other organic product separated from wood, cooking chemicals and process water. Black liquor consist numerous surfactants, which are likely to increase bubble formation and stabilization in the fluid and on the film interface. The observed important effect of bubble formation is fluid loss due to bubble- bursting arosalization.

Vamling et al. [12] proposed relations for FFE heat transfer and fluids with relatively low Pr numbers. Black liquor is increased with increase viscosity, generally at large dry solid content or low temperature. Which mean extensive Pr number. But it is not allowed for higher black liquor evaporation conditions. Experimental transfer data from black liquor evaporation are offered. This show that the Nu numbers as excepted, enhances in the turbulent region. However at a specific Re number for each Pr level, the Nu number ceases to number with increasing Re number.

Vasseur et al. [13] the thermal concentration by evaporation is commonly used for liquid for three main targets: to decrease the volume and the weight of the product, to enhance the stability of liquid food and as intermediate processing in food industry. Define the boiling heat transfer coefficient (h) versus the main process parameters, handling a pilot scale falling film evaporator which is found several food industries. Sugar solutions at many concentrations are used for a model of Newtonian liquid food. The nature of heated surface is kept constant and the effect of the emitted vapor velocity is not taken into account in our study.

Khanam and Mohanty [14] advanced for analysis of multiple effects evaporator [MEE] systems with the induction of condensate flashing in a new scalable. In which has been used the concepts of stream analysis and temperature path for the formulation of model equations. In order to the MEE system, several operating strategies are used to decrease overall steam consumption (SC) and consequently, to enhance steam economy (SE) of the system. The possible strategy of them is to handle condensate flashing such as it decreases the steam economy (SC) about 4% to 7%. To advanced a simplified model some assumptions which have been taken into account such as equal to driving (ΔT) in every effect, ignore-heat loss and –heat mixing between different streams of feed.

Khanam et al. [15] developed different energy reduction schemes in this work and handled to decrease SE in MEE system. The energy reduction schemes are condensate-, feed- and product-flashing and vapor bleeding, which is handled to preheat the liquor for chest of an effect, it enter into a counter current heat exchanger. The results show that

1-The best energy reduction schemes is selected based on steam consumption as well as number of units involved in ERS. The different ERSs is saved steam up to 24.6%.

2-The liquor is heated with condensate, which is contributed mostly to decrease steam Consumption. Further, it is also produced low complex MEE network in comparison to another ERSs.

Rangaiah et al. [16] estimated NSGA-II and EMOO system at benchmark problems to use MOO of design of a FFE system, which are made evaporator, steam jet ejector, pre-heater and vapor condenser. The EMOO program gave well – distributed Pareto – optimal solutions for the MOO problems tested. On other hand, many engineers are usual with MS excel, which is used in both academia and industry for data analysis and engineering calculations. For example use Excel for studying the optimal design and operating situations of a multi-effect evaporator for tomato paste. Optimization methods are used in business, industry, government and engineering.

CHAPTER 3

PROBLEM STATEMENT

In present chapter, MEEs is employed to withdrawing thick liquor. The operating conditions are assumed in this chapter. The present chapter is developed with simulation and modeling for multiple effect evaporator system.

3.1 PROBLEM STATEMENT

In the present work two MEE systems are considered: seven effect and ten effect evaporator systems.

3.1.1 Seven effect evaporator system

In Kraft mill, SEE systems are used to concentrate in black liquor. These effects are falling film evaporators. This model is found raw wood by disaster process.

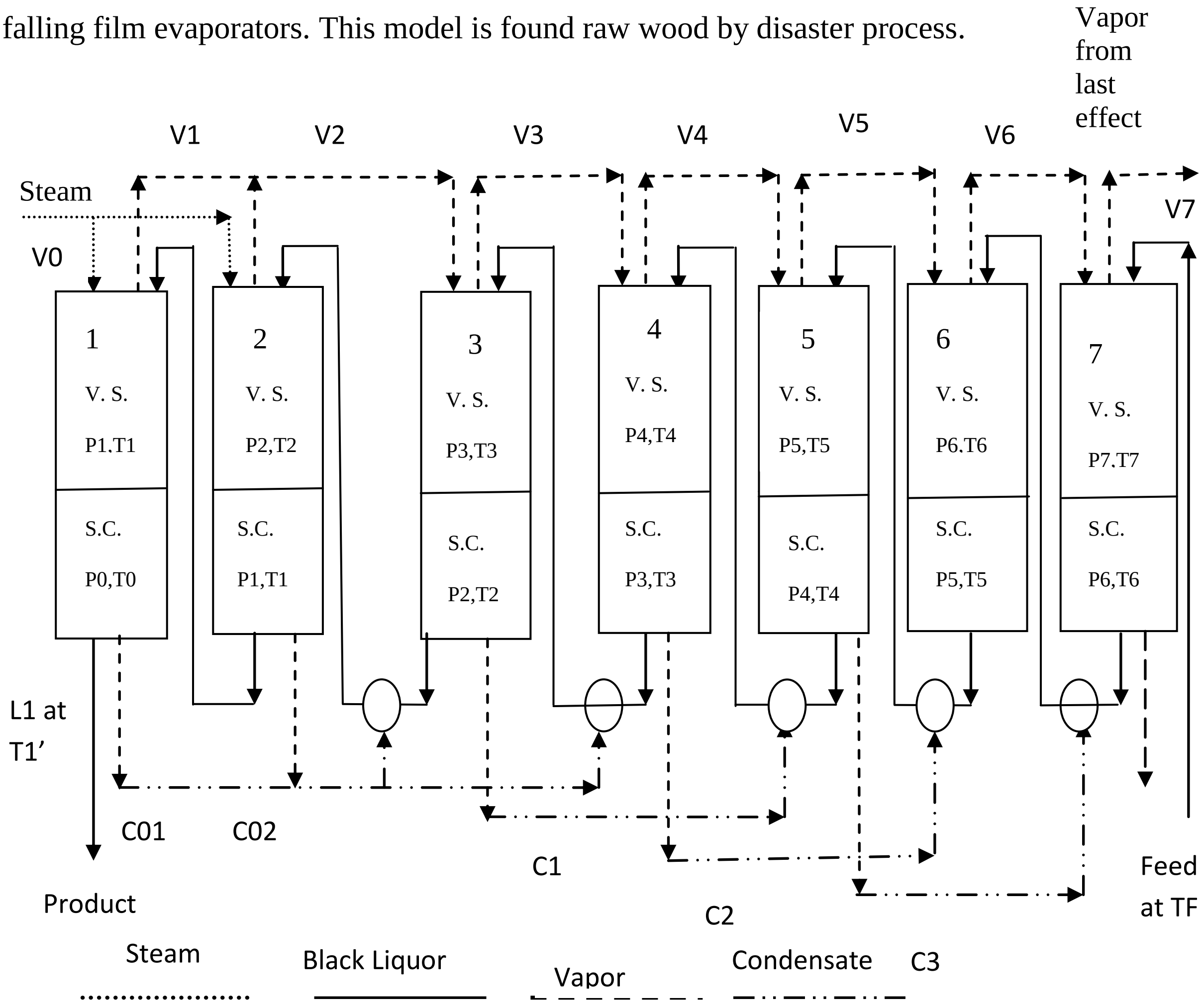

Fig. 3.1: Schematic diagram of SEE system

These are obtained raw compounds that are currently recovered by evaporation and incineration. Fig. 3.1 is a backward feed flow sequence which enters initially to 7th effect. Further, it moves to sixth effect and so on. The concentrated liquor exits from 1st effect as product. Live steam is added simultaneously to 1st and 2nd effect. The operating data of the system is shown in Table 3.1. It shows that steam enters to 1st and 2nd effect at different temperatures. This is process condition and considered as it is. Condensate flashing is used to produce vapor that is handled to increase the total SE in the process.

Table 3.1: Typical conditions of SEE system

S.NO.	Parameters	Values
1	Overall effects	7
2	Effect carried in steam	2
3	Feed rate of thick liquor	55,199.9 kg/hr
4	Feed flow sequence	Backward
5	Vapor temperature of last effect	52 °C
6	In effect 1, Live temperature	139.90 °C
7	In effect 2, Live temperature	146.80 °C
8	Inlet concentration of black liquor	0.1178
9	Inlet temperature of black liquor	64.7 °C
10	Area for 1st effect and 2nd effect	540 m^2
11	Area for 3rd effect and 6th effect	660 m^2
12	Area for 7th effect	690 m^2

3.1.2 Ten effect evaporator system

In mill, the ten effect evaporator is handled to withdrawn for black liquor. These effects are FFEs system. This model is found a by- product of the raw material digesting system. These are obtained raw wood compound by disaster process.

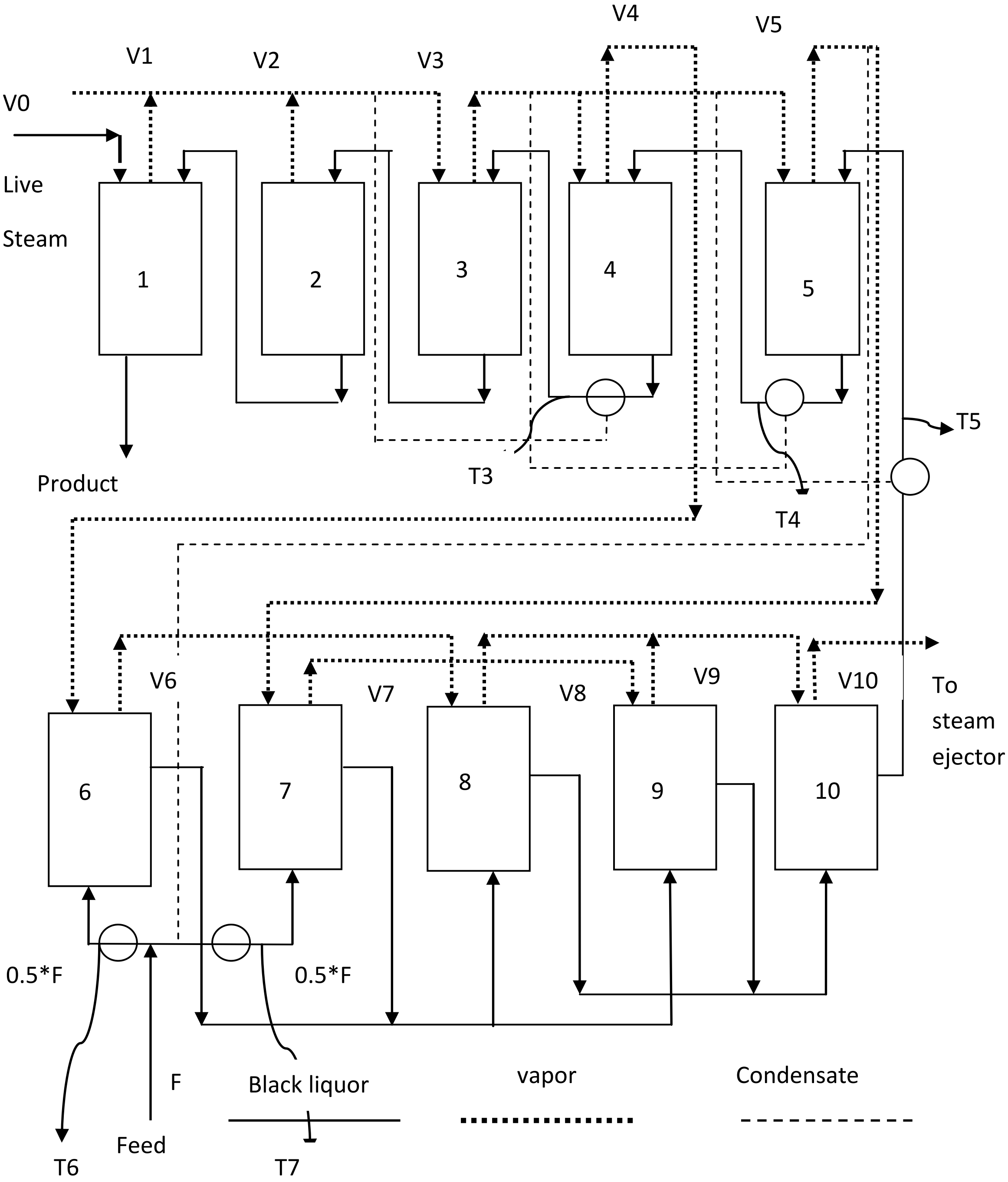

Figure 3.2: Schematic diagram of ten effect evaporator system

The schematic of the system is shown in Fig. 3.2. In this system feed flow sequence is backward which enters initially to 10th effect. Further, it moves to ninth effect and so on. The concentrated liquor exits from 1st effect as product. Live steam is added simultaneously to 1st and 2nd effect. The operating data of the system is shown in Table 3.2. It shows that steam enters to 1st and 2nd effect at different temperatures. This is process condition and considered as it is. Condensate flashing is used to produce vapor that is used to increase the overall steam economy of the process.

Table 3.2: Typical conditions of TEE system

S.NO.	Parameters	Values
1	Total effect	10
2	Total effect carried in steam	2
3	Feed rate for thick liquid	169800 kg/hr
4	Feed flow sequence	Backward
5	Vapor temperature of last effect	80 °C
6	In effect 1, steam temperature	139.99 °C
7	In effect 1, steam temperature	139.99 °C
8	Inlet feed concentration	0.160
9	Inlet temperature of black liquor	57.60 °C
10	Area of 1st effect and 3rd effect	600 m^2
11	Area of 4th effect and 5th effect	570 m^2
12	Area of 6th effect and 7th effect	550 m^2
13	Area of 8th effect and 10th effect	660 m^2

CHAPTER 4

DEVELOPMENT OF MODEL

This development of model focuses on mathematical model for MEE systems. In the present work two MEE systems such as seven effect and ten effect evaporator systems are considered to concentrate black liquor solution.

4.1 DEVELOPMENT OF CORRELATIONS

At the several temperatures, the several effects enter steam/vapor. The temperature varies with the condensate and properties. The models are needed to be developing the temperature dependent expressions of heat of enthalpy and vaporization. In these models, the range of temperature is found to be 52-148°C. The λ, h and H is fitted to get following equations. The R^2 values of Eq. 4.1, Eq. 4.2 and Eq. 4.3 respectively, as shown below.

$$\lambda = -0.003*T^2 - 2.068*T + 2493 \quad (4.1)$$

$$h = 4.222*T - 2.6593 \quad (4.2)$$

$$H = - 0.0028*T^2 + 2.1093*T + 2493.3 \quad (4.3)$$

4.2 CORRELATIONS WITH BPR AND PHYSICAL PROPERTIES FOR SOLUTION

In the present mathematical model variations in boiling point rise (BPR) and specific heat capacities of black liquor are accounted. These are computed through equations developed in the work of Bhargava et al. (2008):

$$Ꞇ = 20*(0.1 + x)^{2} \quad (4.4)$$

$$Cp = C_1{}^{*}(1- C_4{}^{*}X) = 4.187*(1-0.54*X) \quad (4.5)$$

4.3 MODEL FOR OVERALL HEAT TRANSFER COEFFICIENT

To compute overall heat transfer coefficients for each effect the empirical correlation, The correlation taken from the work of Bhargava et al. (2008) are indicated in Eq. 4.6. In Table1 is indicated value for coefficients. This correlation is also used in ten effect evaporator system to concentrate black liquor.

$$Uc/2000 = a*((\Delta T/40)^{b})*((X_{avg}/0.6)^{c})*((F_{avg}/25)^{d}) \tag{4.6}$$

Table 4.1: Value of coefficients for SEEs :

Effect No.	a	b	C	D
1 and 2	0.0604	-0.3717	-1.2273	0.0748
3 and 7	0.1396	-0.7949	0.0	0.1673

4.4 MODEL DEVELOPMENT OF MEE SYSTEM

In this model, two different evaporators are considered. These are seven and ten EESs employed to concentrate solvent for mills. The operating conditions are different for these two systems models for these are developed separately. For seven and ten effect evaporator system models are developed under Section 4.4.1 and 4.4.2, respectively.

4.4.1 Model for seven effect evaporator system

Under this section, model for seven effect system is developed. Fig 3.1 are estimated several parts. For 1st part, This model is developed for simplified model, which is considered as base case for further reference. Then the simplified model is modified to account variation in physical properties, BPR and steam splitting. Further, model developed in second part is modified to include vapor bleeding.

4.4.1.1 Model of simple seven effect evaporator system

Fig. 4.1 shows that simple seven effect system is being operated with backward sequence where feed enters to 7theffect and product exists from 1steffect.

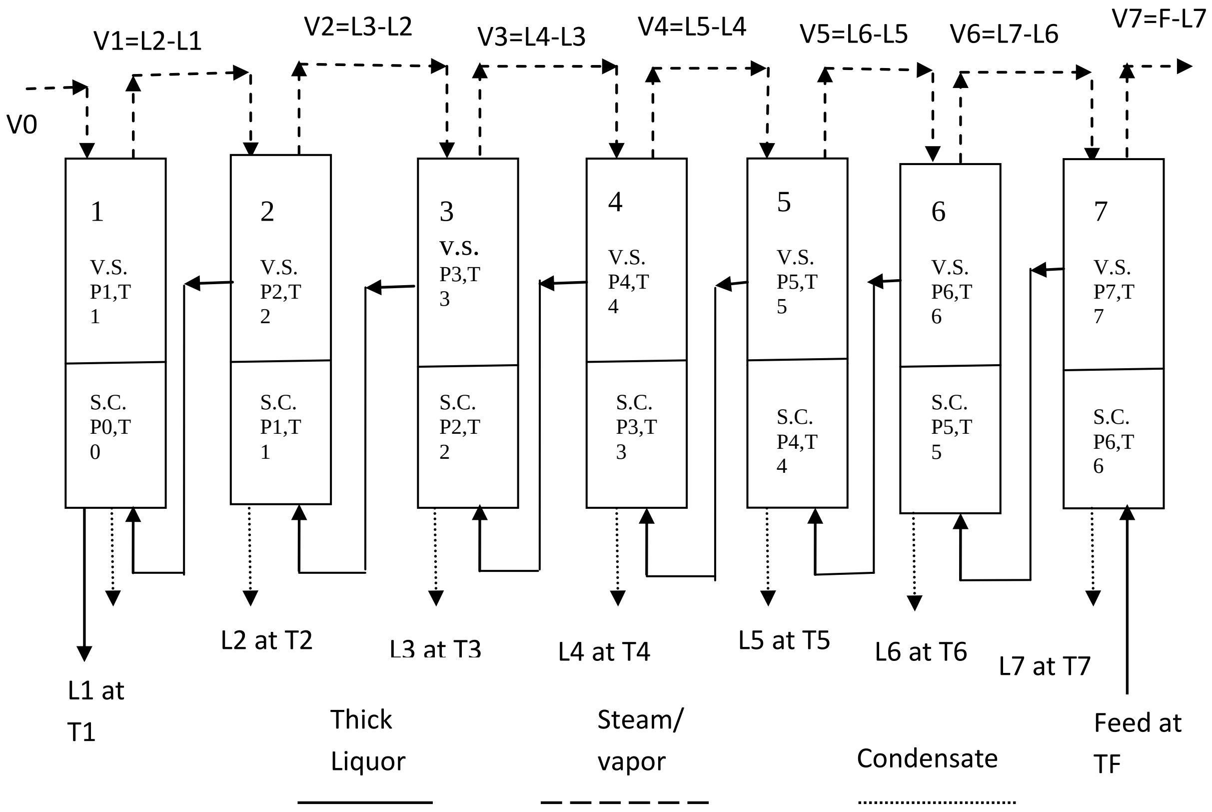

Fig 4.1: Schematic diagram for SEE system

amount of steam inlets in 1st effect and out in form of condensate. The produced vapor in 1steffect move 2nd effect. While the produced vapor of second effect go to 3rd effect and till seventh effect. The model developed for present simplified system is named as Mod-1. The governing equations for 1st to 7th effect are developed using material and energy balances around these effects. The energy balances in 1st effect is shown as :

Energy balance

[steam entering the steam chest of 1steffect for latent heat] + [Liquor entering the effect from 2ndeffect with sensible heat] = [vapor leaving the 1st effect with enthalpy of vapor] + [liquor leaving the 1steffect with sensible heat]

$$[L2*CP2*T2] + [V0*\lambda 0] = [V1*(h1 + \lambda 1)] + [L1*CP1*T1]$$

$$[L2*CP2*T2] + [V0*\lambda 0] = [V1*h1] + [V1* \lambda 1] + [L1*CP1*T1]$$

Therefore $V1 = L2 - L1$

$$[L2*CP2*T2] + [V0*\lambda 0] = [(L2 - L1)*h1] + [(L2 - L1)*\lambda 1] + [L1*CP1*T1]$$

Enthalpy $h1 = CP1*T1$

$$[L2*CP2*T2] + [V0*\lambda 0] = [(L2 - L1)*CP1*T1] + [(L2 - L1)*\lambda 1] + [L1*CP1*T1]$$

$$[L2*CP2*T2] + [V0*\lambda 0] = [L2*CP1*T1] - [L1*CP1*T1] + [(L2 - L1)*\lambda 1] + [L1*CP1*T1]$$

$$[L2*CP2*T2] + [V0*\lambda 0] = [L2*CP1*T1] + [(L2 - L1)*\lambda 1]$$

$$[L2*CP*(T2 - T1)] + [V0*\lambda 0] = [(L2 - L1)*\lambda 1] \quad \text{ASSUME } CP1 = CP2$$

$$[L2*CP*(T2 - T1)] + [V0*\lambda 0] - [(L2 - L1)*\lambda 1] = 0$$

$$F1 = [L2*CP*(T2 - T1)] + [V0*\lambda 0] - [(L2 - L1)*\lambda 1] \tag{4.7}$$

Heat transferred to the 1st effect = latent heat supplied by the steam

$$U1*A1*(T0 - T1) = V0*\lambda 0$$

$$F2 = U1*A1*(T0 - T1) - V0*\lambda 0 \tag{4.8}$$

2nd effect

$$F3 = [L3*CP*(T3 - T2)] + [(L2 - L1)*\lambda 1] - [(L3 - L2)*\lambda 2] \tag{4.9}$$

$$F4 = U2*A2*(T1 - T2) - (L2 - L1)*\lambda 1 \tag{4.10}$$

3rd effect

$$F5 = [L4*CP*(T4 - T3)] + [(L3 - L2)*\lambda 2] - [(L4 - L3)*\lambda 3] \quad (4.11)$$

$$F6 = U3*A3*(T2 - T3) - (L3 - L2)*\lambda 2 \quad (4.12)$$

4th effect

$$F7 = [L5*CP*(T5 - T4)] + [(L4 - L3)*\lambda 3] - [(L5 - L4)*\lambda 4] \quad (4.13)$$

$$F8 = U4*A4*(T3 - T4) - (L4 - L3)*\lambda 3 \quad (4.14)$$

5th effect

$$F9 = [L6*CP*(T6 - T5)] + [(L5 - L4)*\lambda 4] - [(L6 - L5)*\lambda 5] \quad (4.15)$$

$$F10 = U5*A5*(T4 - T5) - (L5 - L4)*\lambda 4 \quad (4.16)$$

6th effect

$$F11 = [L7*CP*(T7 - T6)] + [(L6 - L5)*\lambda 5] - [(L7 - L6)*\lambda 7] \quad (4.17)$$

$$F12 = U6*A6*(T5 - T6) - (L6 - L5)*\lambda 5 \quad (4.18)$$

7th effect

$$F13 = [F*CP*(Tf - T7)] + [(L7 - L6)*\lambda 6] - [(F - L7)*\lambda 7] \quad (4.19)$$

$$F14 = U7*A7*(T6 - T7) - (L7 - L6)*\lambda 6 \quad (4.20)$$

4.4.1.2 Model with steam splitting, variable physical properties and BPR

In actual scenario the properties of liquor continuously vary with temperature and concentration. Therefore, the present model of seven effects evaporator system, Mod-2, is modified to incorporate - variations in physical properties. These are specific heat capacity of liquor, Cp latent heat of vaporization, λ, enthalpy of vapor and BPR. In this model live steam, divided equally in first and second effects as shown in Fig. 4.2, is also accounted. The vapor exiting from 1stand 2ndeffects enter to third effect.

The model developed for present simplified system is named as Mod-2. Governing equations of 1st and **7th**effects are derived based on material and energy balances as carried out for Mod-1. The equations of 1stand 2nd effects are similar to Eq. 4.8 to 4.21 of Mod-1 with a slight change that instead of total steam enters in to 1steffect of Mod-1, steam is divided equally and then enters to 1stand 2nd effect simultaneously. Therefore, in Eq. 4.22 to 4.25 amount of steam, V0, with factor 0.5 is used. The equations for 1stand 2ndeffects are shown

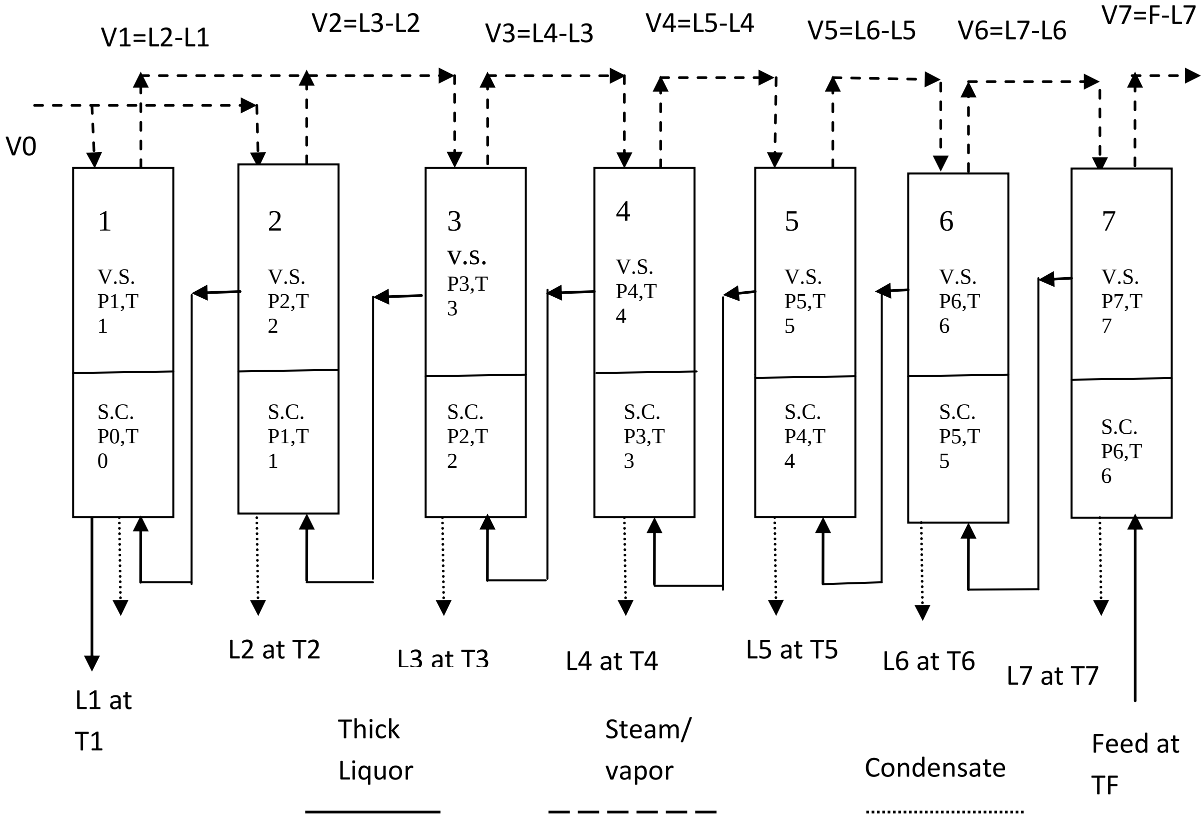

Figure 4.2: Seven effect evaporator system with steam splitting

Energy balance

1st effect

$$F1 = [L2*CP2*(T2 + t2)] - [0.5*V01*\lambda 01] - [L1*CP1*(T1 + t1)] - [(L2 - L1)*(\lambda 1 + (4.2*T1)] \tag{4.21}$$

$$F2 = [U1*A1*(T01 - T1 - t1)] - [0.5*V01*\lambda 1] \tag{4.22}$$

2nd effect

$$F3 = [L3*CP3*(T3 + t3)] - [0.5*V02*\lambda 02] - [L2*CP2*(T2 + t2)] - [(L3 - L2)*(\lambda 2 + (4.2*T2)] \tag{4.23}$$

$$F4 = [U2*A2*(T02 - T2 - t2)] - [0.5*V02*\lambda 2] \tag{4.24}$$

3rd effect

$$F5 = [L4*CP4*(T4 + t4)] - [L3*CP3*(T3 + t3)] + [(L2 - L1)*\lambda 1] + [(L3 - L2)*\lambda 2] - [(L4 - L3)*(\lambda 3 + (4.2*T3)] \tag{4.25}$$

$$F6 = U3*A3*((T1+T2)/2) - T3 - t3) - [(L2 - L1)*\lambda 1] - [(L3 - L2)*\lambda 2] \tag{4.26}$$

4th effect

$$F7 = [L5*CP5*(T5 + t5)] - [L4*CP4*(T4 + t4)] + [(L4 - L3)*\lambda 3] - [(L5 - L4)*(\lambda 4 + (4.2*T4)] \tag{4.27}$$

$$F8 = [U4*A4*(T3 - T4 - t4)] - [(L4 - L3)*\lambda 3] \tag{4.28}$$

5th effect

$$F9 = [L6*CP6*(T6 + t6)] – [L5*CP5*(T5 + t5)] + [(L5 – L4)*\lambda 4] - [(L6 – L5)*(\lambda 5 + (4.2*T5)] \qquad (4.29)$$

$$F10 = [U5*A5*(T4 – T5 – t5)] – [(L5 – L4)*\lambda 4] \qquad (4.30)$$

6th effect

$$F11 = [L7*CP7*(T7 + t7)] – [L6*CP6*(T6 + t6)] + [(L6 – L5)*\lambda 5] - [(L7 – L6)*(\lambda 6 + (4.2*T6)] \qquad (4.31)$$

$$F12 = [U6*A6*(T5 – T6 – t6)] – [(L6 – L5)*\lambda 5] \qquad (4.32)$$

7th effect

$$F13 = [F*CPf*Tf] – [L7*CP7*(T7 + t7)] + [(L7 – L6)*\lambda 6] - [(F – L7)*(\lambda 5 + (4.2*T7)] \qquad (4.33)$$

$$F14 = [U7*A7*(T6 – T7 – t7)] – [(L7 – L6)*\lambda 6] \qquad (4.34)$$

4.4.1.3 Model of seven effect evaporator system with vapor bleeding

As the seven effect evaporator system is being operated with backward sequence, feed enters to an effect at lower temperature. Further, feed acquires the temperature of effect using heat from vapor entering to that effect. Such heating of feed an also be carried out using vapor bleeding. Usually, vapor generated in one effect is completely utilized in next effect. However, in the present work a part of vapor generated in one effect, which is called bled vapor, is utilized to preheat the liquor exiting from subsequent effects. This effect is considered in the model and hence, Mod-2 is modified model and named as Mod-3. The model developed for present simplified system is named as Mod-3. The previous model maintained in section will similar to equations of 1st, 2ndand 7th. For remaining of effects, the equations are solved as given below.

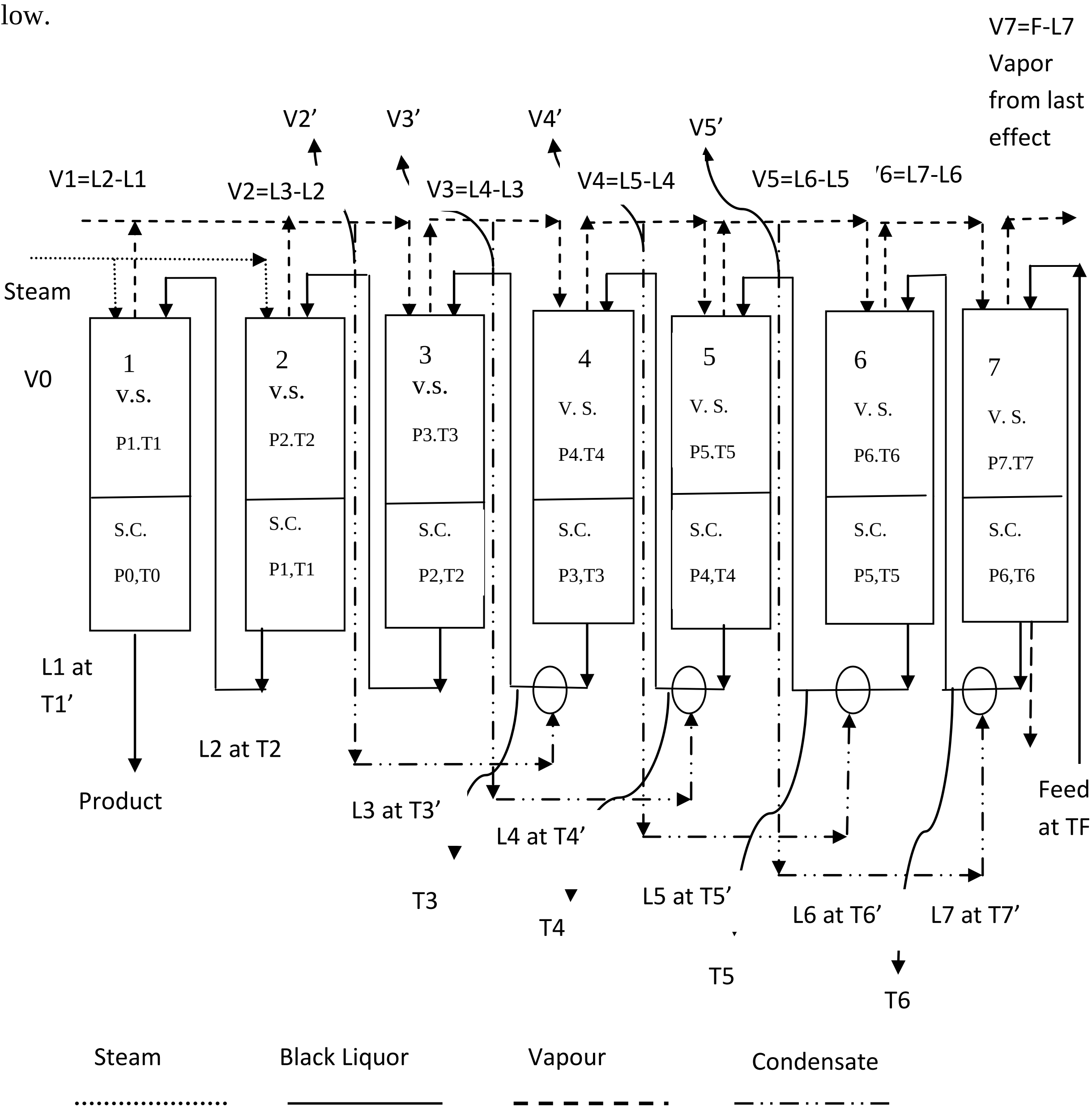

Figure 4.3: Schematic diagram of Seven effect evaporator system with vapor

The schematic diagram of pre heater-1 is shown in figure between 3rdand 4theffects

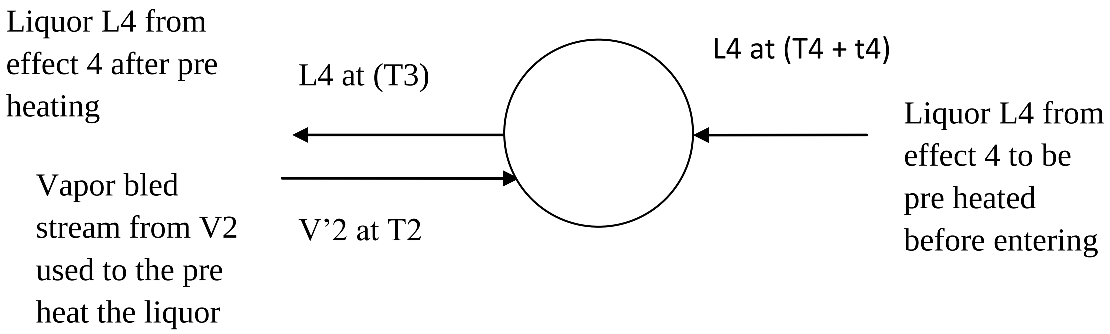

Figure 4.4: Schematic diagram of pre-heater

Material balance around pre-heater 1 is given as:

$$V2'*\lambda 2 = L4*CP4*(T3 - T4 - t4)$$

Equations of 3rd effect can be solved and used and shown in figure 4.5.

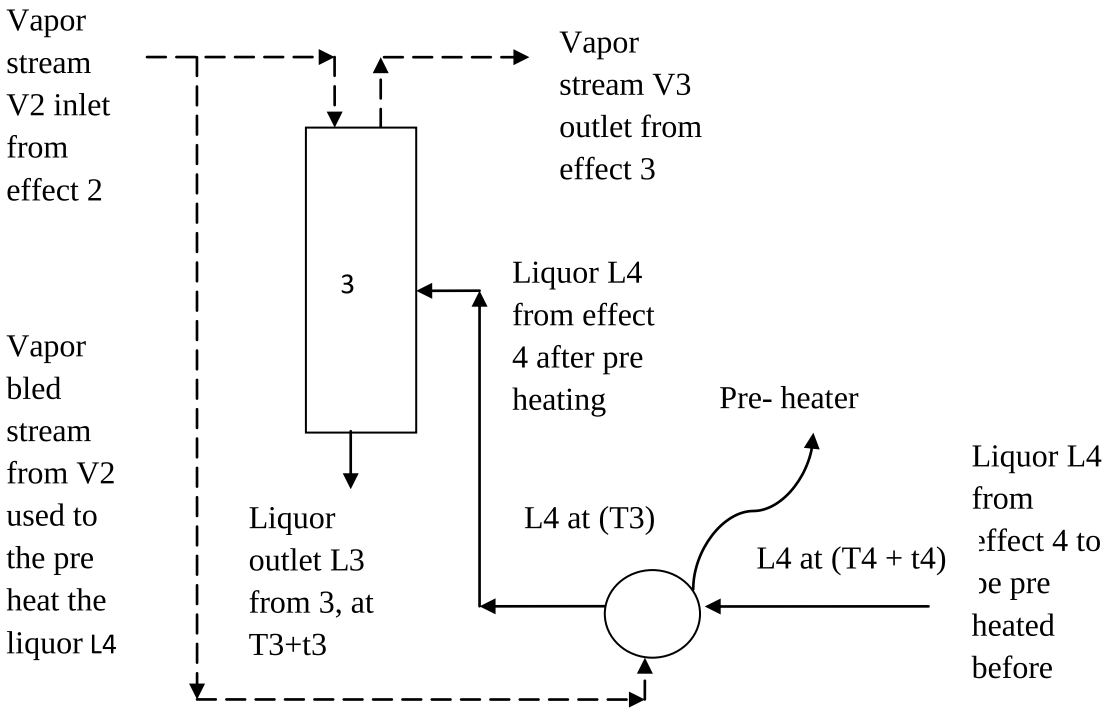

Figure 4.5: Schematic diagram of 3rdeffect with vapor bleeding

Energy balance :

Latent heat of vapor (V1) + Sensible heat of liquor (L4) + latent heat of vapor

(V2) – Latent heat of vapor (V’2) = latent heat of vapor stream (V3) + Sensible heat of liquor (L3)

3rd effect

$$F5= [L4*CP4*(T3)] - [L3*CP3*(T3 + t3)] + (L2 - L1)*\lambda 1 + (L3 - L2)*\lambda 2 - V'2*\lambda 2 - [(L4 - L3)*(\lambda 3 + (4.2*T3)] \tag{4.35}$$

$$F6=U3*A3*((T1 + T2)/2) - T3 - t3) - (L2 - L1)*\lambda 1 - (L3 - L2)*\lambda 2 - V'2*\lambda 2 \tag{4.36}$$

$$F7= V'2*\lambda 2 - L4*CP4*(T3 + t3 - T4 - t4) \tag{4.37}$$

4th effect

$$F8= [L5*CP5*(T4)] - [L4*CP4*(T4 + t4)] + (L4 - L3 - V'3)*\lambda 3 - [(L5 - L4)*(\lambda 4 + (4.2*T4)] \tag{4.38}$$

$$F9=U4* A4*(T3 + t3 - T4 - t4) - (L4 - L3 - V'3)*\lambda 3 \tag{4.39}$$

$$F10= V'3*\lambda 3 - L5*CP5*(T4 + t4 - T5 - t5) \tag{4.40}$$

5th effect

$$F11= [L6*CP6*(T5)] - [L5*CP5*(T5 + t5)] + (L5 - L4 - V'4)*\lambda 4 - [(L6 - L5)*(\lambda 5 + (4.2 *T5)] \tag{4.41}$$

$$F12=U5*A5*(T4 + t4 - T5 - t5) - (L5 - L4 - V'4)*\lambda 4 \tag{4.42}$$

$$F13= V'4*\lambda 4 - L6*CP6*(T5 + t5 - T6 - t6) \tag{4.43}$$

6th effect

$$F14= [L7*CP7*(T6)] - [L6*CP6*(T6 +t6)] + (L6 - L5 - V'5)*\lambda 5 - [(L7 - L6)*(\lambda 6 + (4.2 *T6)] \tag{4.44}$$

$$F15=U6*A6*(T5 + t5 - T6 - t6) - (L6 - L5 - V'5)*\lambda 5 \tag{4.45}$$

$$F16= V'5*\lambda 5 - L7*CP7*(T6 + t6 - T7 - t7) \tag{4.46}$$

Further, another configuration of vapor bleeding where four pre heaters are placed is considered. It is referred as Conf-2. In this configuration four pre-heaters are placed at same position as indicated in Fig. 4.3. However, in this case vapor streams are bled from V3, V4, V5 and V6 instead of V2, V3, V4 and V5. In this configuration liquor streams L4, L5, L6 and L7 are preheated up to the temperatures (T3+T4)/2, (T4+T5)/2, (T5+T6)/2 and (T6+T7)/2, respectively. These liquor streams are heated up to average temperatures only as sufficient driving force is required to transfer the heat from bled vapor to liquor. The model developed for Conf-2 is Mod-4.

Summarize the model

The Mod-2 modified model is named Mod-3 in which 18 equation, 18 unknown variables and 33known variables are involved. In this model four pre-heaters are placed between3rdand 4th, 4thand 5th, 5thand 6thand 6th and 7theffects at same position as indicated in Fig. 4.3.It is referred as Conf-2.

4.4.1.4 Model of seven effect evaporator systems when vapor is bled from second effect-

A pre-heater is placed between 3rdand 4theffect where vapor bled from 2ndeffect is used as heating medium. The schematic of the system is shown in Fig. 4.6. This configuration and respective model is named as Conf-3 and Mod-5

In this configuration liquor stream L4 is heated from T4 to T3. The model developed for present simplified system is named as Mod-5. The previous model maintained in section will similar to equations of 1st, 2nd and 7th. For remaining of effects, the equations are solved as given below.

Energy balance :-

latent heat of vapor (V1) + Sensible heat of liquor (L4) + latent heat of vapor(V2) – Latent heat of vapor (V’2) = latent heat of vapor stream (V3) + Sensible heat of liquor (L3)

3rd effect

$$F5= [L4*CP4*(T3)] - [L3*CP3*(T3 + t3)] + (L2 - L1)*\lambda1+ (L3 - L2)*\lambda2 - V'2*\lambda2 – [(L4 -L3)*(\lambda3 + (4.2*T3)] \quad (4.47)$$

$$F6=U3*A3*((T1+T2)/2) - T3 - t3) – (L2 - L1)*\lambda 1 – (L3 - L2)*\lambda 2 – V'2 *\lambda 2 \quad (4.48)$$

$$F7= V'2*\lambda 2 – L4*CP4*(T3 + t3 - T4 - t4) \quad (4.49)$$

4^{th} effect

$$F8= [L5*CP5*(T4)] - [L4*CP4*(T4 + t4)] + (L4 - L3)*\lambda 3 – [(L5 - L4)*(\lambda 4 + (4.2*T4)] \quad (4.50)$$

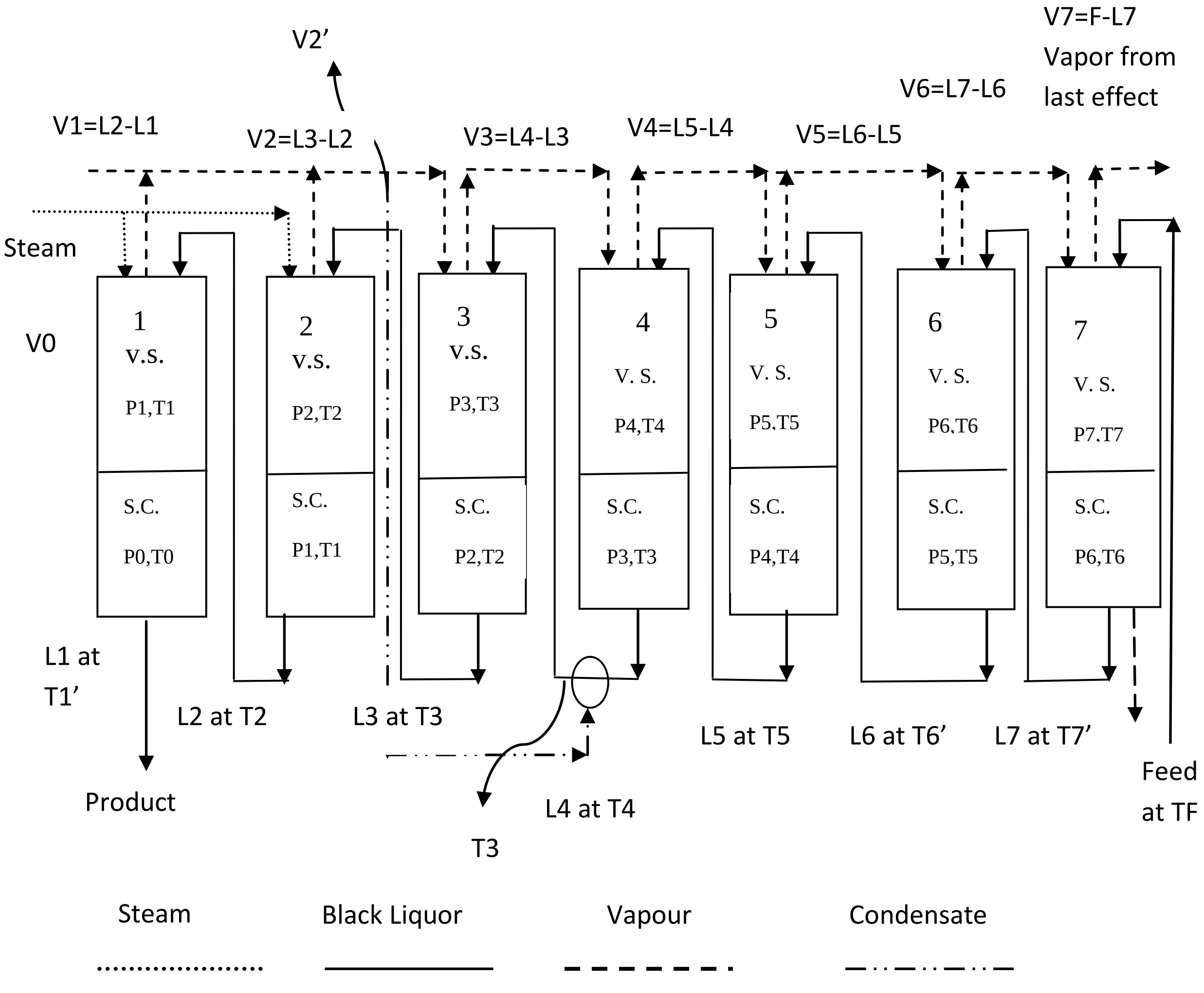

Figure 4.6: Schematic diagram of seven effect evaporator systems with considered vapor bled from second effect

$$F9=U4*A4*(T3 + t3 - T4 - t4) - (L4 - L3)*\lambda 3 \tag{4.51}$$

$$F10= V'2*\lambda 3 - L5*CP5*(T4 + t4 - T5 - t5) \tag{4.52}$$

5th effect

$$F11= [L6*CP6*(T5)] - [L5*CP5*(T5 + t5)] + (L5 - L4)*\lambda 4 - [(L6 - L5)*(\lambda 5 + (4.2*T5)] \tag{4.53}$$

$$F12=U5*A5*(T4 + t4 - T5 - t5) - (L5 - L4)*\lambda 4 \tag{4.54}$$

$$F13= V'2*\lambda 4 - L6*CP6*(T5 + t5 - T6 - t6) \tag{4.55}$$

6th effect

$$F14= [L7*CP7*(T6)] - [L6*CP6*(T6+t6)] + (L6 - L5)*\lambda 5 - [(L7 - L6)*(\lambda 6 + (4.2*T6)] \tag{4.56}$$

$$F15=U6*A6*(T5 + t5 - T6 - t6) - (L6 - L5)*\lambda 5 \tag{4.57}$$

$$F16= V'2*\lambda 5 - L7*CP7*(T6 + t6 - T7 - t7) \tag{4.58}$$

Further, another configuration of vapor bleeding where one pre heaters are placed is considered. It is referred as Conf-3. In this configuration one pre-heaters are placed at same position as indicated in Fig. 4.6. However, in this case vapor streams are bled from V2. In this configuration liquor streams L4 are preheated up to the temperatures (T3+T4)/2, respectively. These liquor streams are heated up to average temperatures only as sufficient driving force is required to transfer the heat from bled vapor to liquor. The model, developed for Conf-3 is Mod-5.

Summarize the model

In Mod-5, the 18 equation, 18 unknown variables and 33known variables are involved. It is referred as Conf-3. In this model one pre-heater are placed between3rdand 4theffect at same position as indicated in Fig. 4.6.

4.4.1.5 Model of seven effect evaporator systems when vapor is bled third effect

It is the seven effect evaporator system when single pre-heater is placed between 4th and 5th effect. The heating of liquor stream, L4, takes place from T5 to T4 using vapor bled from 3rd effect. The schematic of the present seven effect evaporator system is shown in Fig. 4.7. The present configuration and model is referred as Conf-4 and Mod-6.

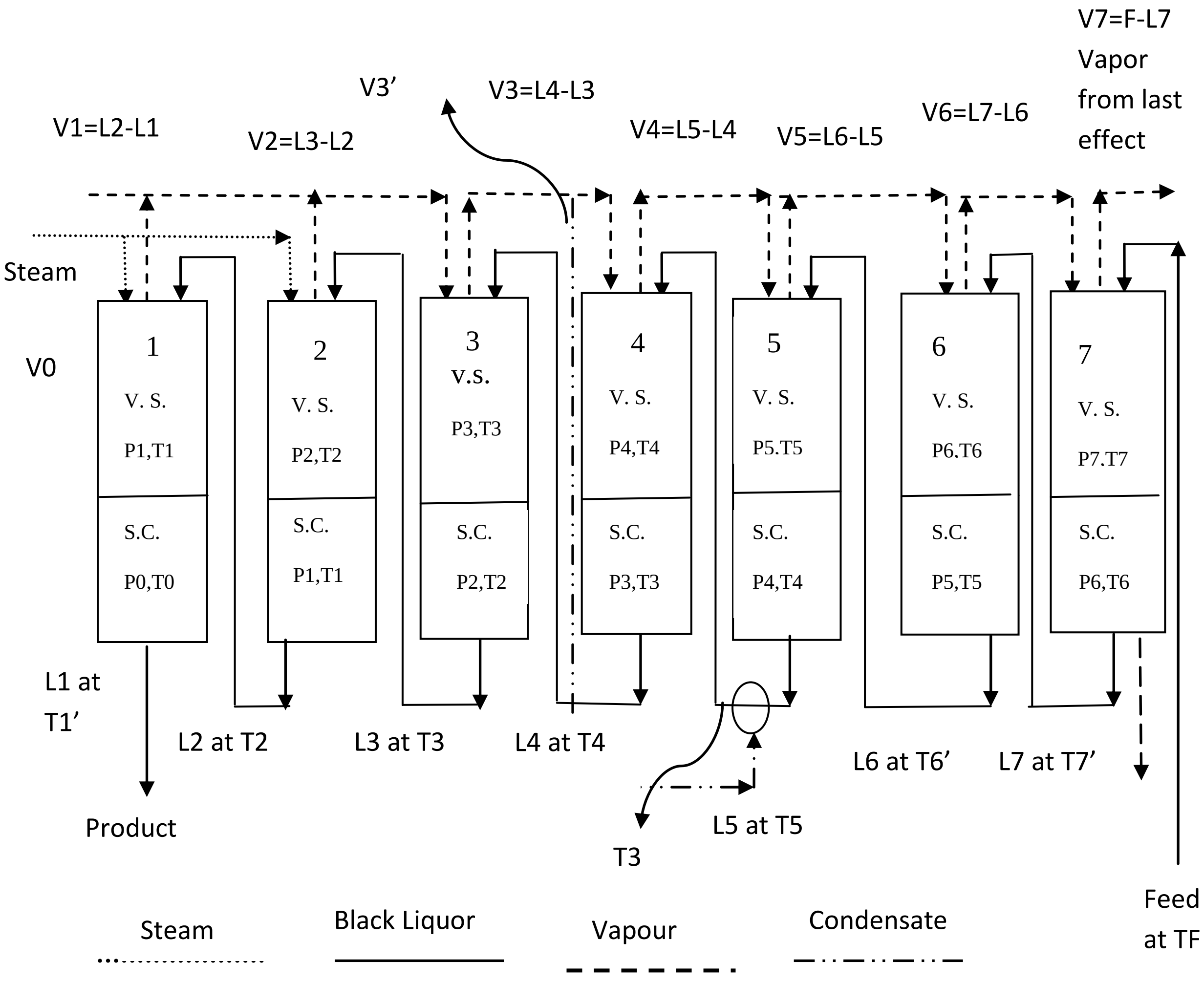

Figure 4.7: Schematic diagram of seven effect evaporator systems with considered vapor bled from third effect

The model developed for present simplified system is named as Mod-6. The previous model maintained in section will similar to equations of 1st, 2nd and 7th. For remaining of effects, the equations are solved as given below.

Energy balance around 4th effect is

Sensible heat of liquor (L5) + latent heat of vapor (V3)

– Latent heat of vapor (V'3) = Sensible heat of liquor (L4) + latent heat of vapor stream (V4)

3rd effect

$$F5= [L4*CP4*(T3)] - [L3*CP3*(T3 + t3)] + (L2 - L1)*\lambda1 + (L3 - L2)*\lambda2 – [(L4 - L3)*(\lambda3 + (4.2 *T3)] \tag{4.59}$$

$$F6=U3*A3*((T1+T2)/2) - T3 - t3) – (L2 - L1)*\lambda1 – (L3 - L2)*\lambda2 \tag{4.60}$$

4th effect

$$F7= [L5*CP5*(T4)] - [L4*CP4*(T4 + t4)] + (L4 - L3 – V'3)*\lambda3 – [(L5 - L4)*(\lambda4 + (4.2*T4)] \tag{4.61}$$

$$F8=U4* A4*(T3 + t3 – T4 – t4) – (L4 - L3 –V'3)*\lambda3 \tag{4.62}$$

$$F9= V'3*\lambda3 – L5*CP5*(T4 + t4 – T5 – t5) \tag{4.63}$$

5th effect

$$F10= [L6*CP6*(T5)] - [L5*CP5*(T5 + t5)] + (L5 - L4)*\lambda4 – [(L6 – L5)*(\lambda5 + (4.2 *T5)] \tag{4.64}$$

$$F11=U5*A5*((T4 + t4– T5 – t5) – (L5 – L4)*\lambda4 \tag{4.65}$$

$$F12= V'3*\lambda4 – L6*CP6*(T5 + t5 – T6 – t6) \tag{4.66}$$

6^{th} effect

$$F13= [L7*CP7*(T6)]-[L6*CP6*(T6+t5)] + (L6 - L5)*\lambda 5-[(L7 - L6)*(\lambda 6+ (4.2 *T6)] \tag{4.67}$$

$$F14=U6*A6*((T5 + t5 - T6 - t6) - (L6 - L5)*\lambda 5 \tag{4.68}$$

$$F15= V'3*\lambda 5 - L7*CP7*(T6 + t6 - T7 - t7) \tag{4.69}$$

Further, another configuration of vapor bleeding where one pre heaters are placed is considered. It is referred as Conf-4. In this configuration one pre-heaters are placed at same position as indicated in Fig. 4.7. However, in this case vapor streams are bled from V3. In this configuration liquor streams L5 are preheated up to the temperatures (T4+T5)/2, respectively. These liquor streams are heated up to average temperatures only as sufficient driving force is required to transfer the heat from bled vapor to liquor. The model, developed for Conf-4 is Mod-6.

Summarize the model

In Mod-6, the 17 equation, 17 unknown variables and 33 known variables are involved. It is referred as Conf-4. In this model one pre-heater are placed between4thand 5theffect at same position as indicated in Fig. 4.7.

4.4.1.6 Model of seven effect evaporator systems where vapor is bled from fourth effect

In this case single pre-heater is placed between 5thand 6theffect in which vapor bled from vapor generated in 4theffect is used. Consequently, liquor stream, L5, is heated from T6 to T5. The schematic of the present system is shown in Fig. 4.8. The present configuration and model is referred as Conf-5 and Mod-7. The model developed for present simplified system is named as Mod-7. The previous model maintained in section will similar to equations of 1st, 2nd and 7th. For remaining of effects, the equations are solved as given below.

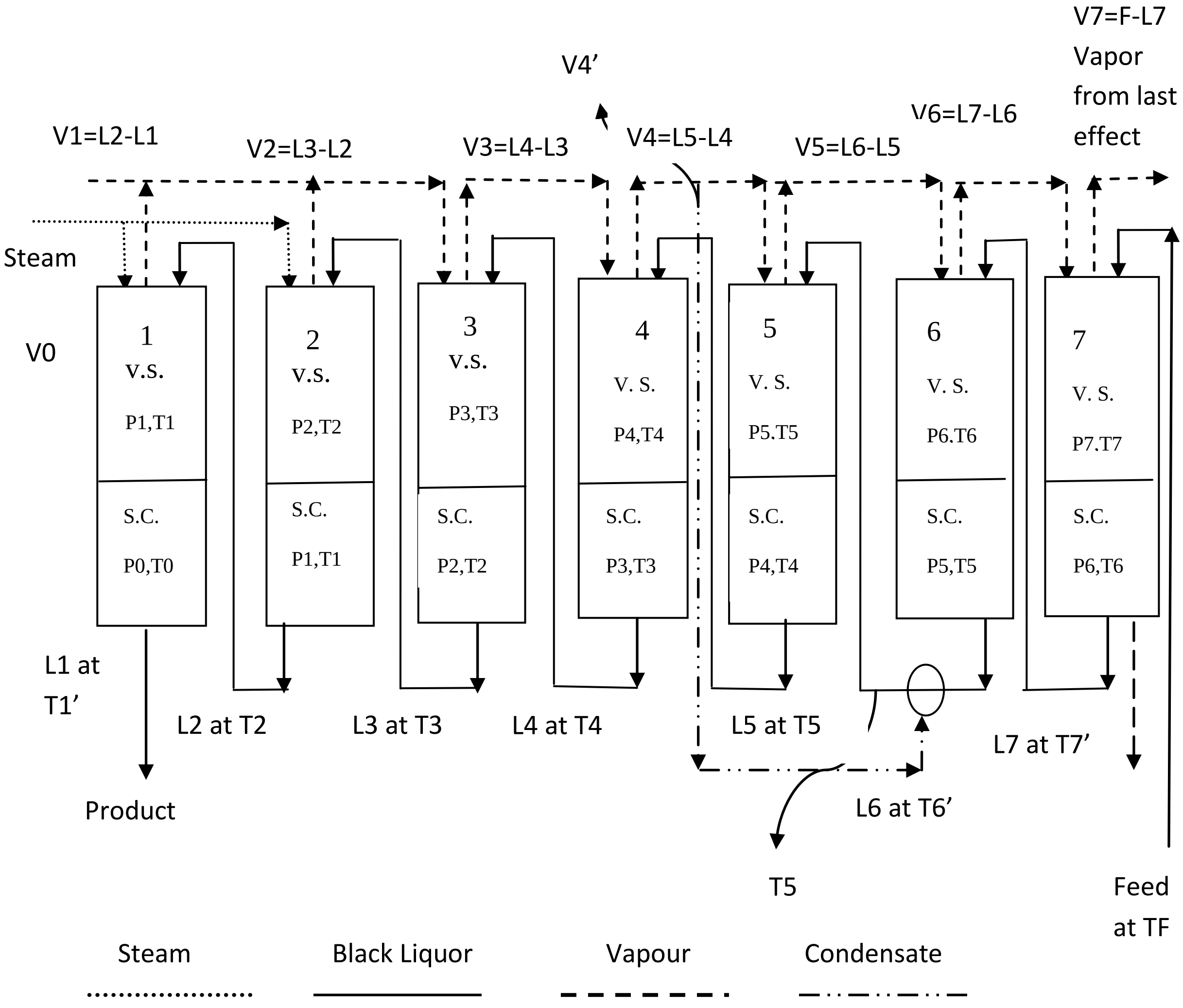

Figure 4.8: Schematic diagram of seven effect evaporator systems with considered vapor bled from fourth effect

Energy balance around 5th effect is

Sensible heat of liquor (L6) + latent heat of vapor (V4) – Latent heat of vapor (V'4) = Sensible heat of liquor (L5) + latent heat of vapor stream (V5)

3rd effect

$$F5= [L4*CP4*(T3)] - [L3*CP3*(T3 + t3)] + (L2-L1)*\lambda1+ (L3 - L2)*\lambda2 - [(L4 - L3)*(\lambda3 + (4.2 *T3)] \qquad (4.70)$$

$$F6=U3*A3*((T1+T2)/2) - T3 - t3) - (L2 - L1)*\lambda 1 - (L3 - L2)*\lambda 2 \tag{4.71}$$

4th effect

$$F7= [L5*CP5*(T4)] - [L4*CP4*(T4 + t4)] + (L4 - L3)*\lambda 3 - [(L5 - L4)*(\lambda 4 + (4.2 *T4)] \tag{4.72}$$

$$F8=U4*A4*(T3 + t3 - T4 - t4) - (L4 - L3)*\lambda 3 \tag{4.73}$$

5th effect

$$F9= [L6*CP6*(T5)] - [L5*CP5*(T5+t5)] + (L5 - L4 - V'4)*\lambda 4 - [(L6 - L5)*(\lambda 5 + (4.2 *T5)] \tag{4.74}$$

$$F10=U5* A5*(T4 + t4 - T5 - t5) - (L5 - L4 -V'4)*\lambda 4 \tag{4.75}$$

$$F11= V'4*\lambda 4 - L6*CP6*(T5 + t5 - T6 - t6) \tag{4.76}$$

6th effect

$$F12= [L7*CP7*(T6)] - [L6*CP6*(T6 + t6)] + (L6 - L5)*\lambda 5 - [(L7 - L6)*(\lambda 6 + (4.2*T6)] \tag{4.77}$$

$$F13=U6*A6*(T5+ t5 - T6 - t6) - (L6 - L5)*\lambda 5 \tag{4.78}$$

$$F14= V'4* \lambda 5 - L7*CP7*(T6 + t6 - T7 - t7) \tag{4.79}$$

Further, another configuration of vapor bleeding where one pre heaters are placed is considered. It is referred as Conf-5. In this configuration one pre-heaters are placed at same position as indicated in Fig. 4.8. However, in this case vapor streams are bled from V4. In this configuration liquor streams L6 are preheated up to the temperatures (T5+T6)/2, respectively. These liquor streams are heated up to average temperatures only as sufficient driving force is required to transfer the heat from bled vapor to liquor. The model, developed for Conf-5 is Mod-7.

Summarize the model

In Mod-7, the 16 equation, 16 unknown variables and 33 known variables are involved. It is referred as Conf-3. In this model one pre-heater are placed between5rdand 6theffect at same position as indicated in Fig. 4.8.

4.4.1.7 Model of seven effect evaporator systems where vapor is bled from fifth effect

A pre-heater is placed between 6thand 7theffect where vapor bled from 5theffect is used as heating medium. The schematic of the system is shown in Fig. 4.9. This configuration and respective model is named as Conf-6 and Mod-8. In this configuration liquor stream L6 is heated from T7 to T6. The model developed for present simplified system is named as Mod-8. The previous model maintained in section will similar to equations of 1st, 2nd and 7th. For remaining of effects, the equations are solved as given below.

Energy balance around 6th effect is

Sensible heat of liquor (L7) + latent heat of vapor (V5) – Latent heat of vapor (V’5) = Sensible heat of liquor (L6) + latent heat of vapor stream (V6)

3rd effect

$$F5= [L4*CP4*(T3)] - [L3*CP3*(T3 + t3)] + (L2 - L1)*\lambda 1 + (L3 - L2)*\lambda 2 – [(L4 - L3)*(\lambda 3 + (4.2 *T3)] \qquad (4.80)$$

$$F6=U3*A3*((T1 + T2)/2) - T3 - t3) – (L2 - L1)*\lambda 1 – (L3 - L2)*\lambda 2 \qquad (4.81)$$

4th effect

$$F7= [L5*CP5*(T4)] - [L4*CP4*(T4 + t4)] + (L4 - L3)*\lambda 3 – [(L5 - L4)*(\lambda 4 + (4.2*T4)] \qquad (4.82)$$

$$F8=U4*A4* (T3 + t3 – T4 – t4) – (L4 - L3)*\lambda 3 \qquad (4.83)$$

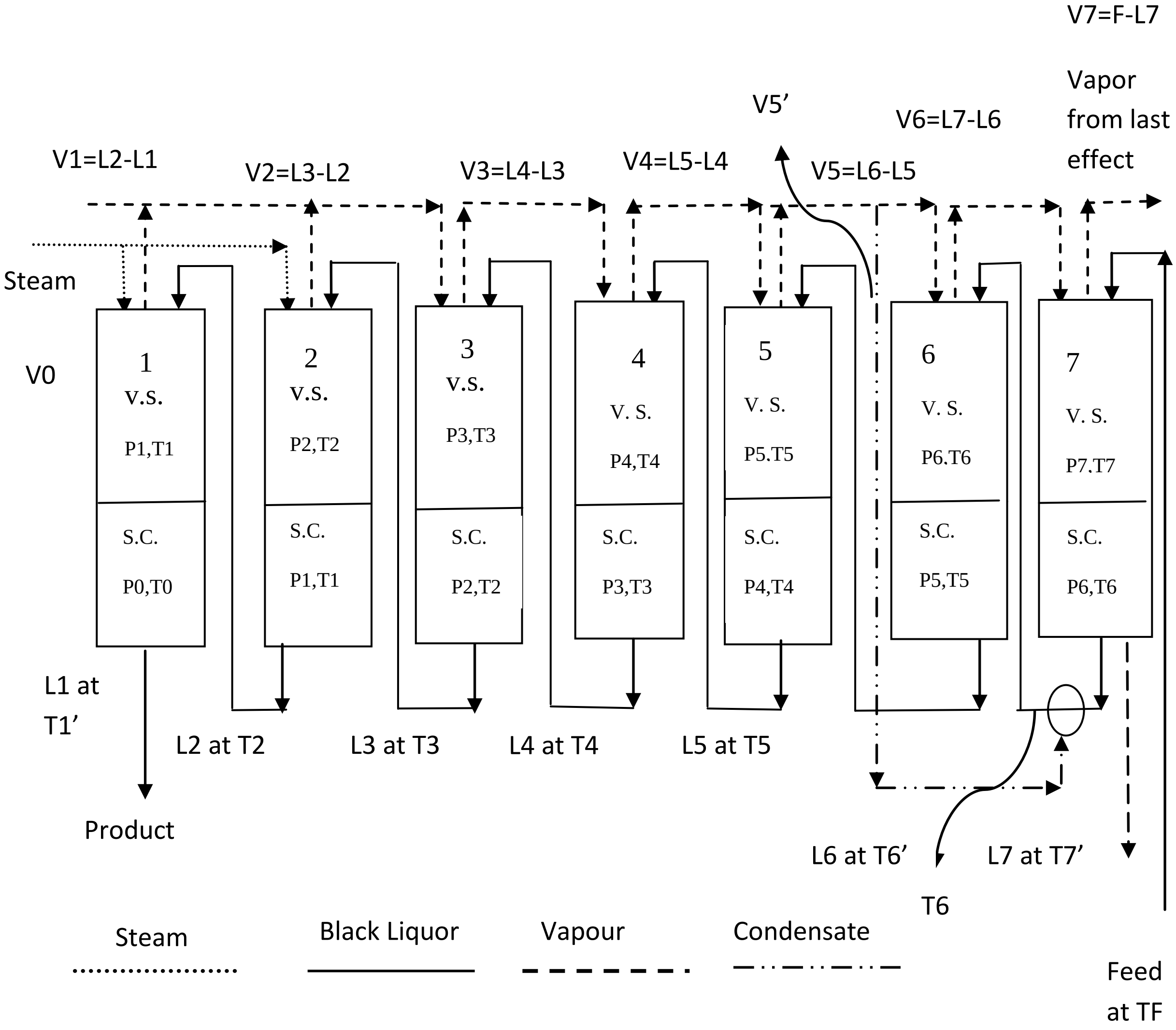

Figure 4.9: Schematic diagram of seven effect evaporator systems with considering vapor bled from vapor generated in fifth effect

5th effect

$$F9= [L6*CP6*(T5)] - [L5*CP5*(T5 + t5)] + (L5 - L4)*\lambda4 - [(L6 - L5)*(\lambda5 + (4.2*T5)] \tag{4.84}$$

$$F10=U5*A5*(T4 + t4 - T5 - t5) - (L5 - L4)*\lambda4 \tag{4.85}$$

6th effect

$$F12= [L7*CP7*(T6)] - [L6*CP6*(T6 + t6)] + (L6 - L5 - V'5)*\lambda5 - [(L7 - L6)*(\lambda6 + (4.2*T6)] \tag{4.86}$$

$$F13=U6* A6*(T5 + t5 - T6 - t6) - (L6 - L5 - V'5)*\lambda5 \tag{4.87}$$

F14= V'5* λ5 – L7*CP7*(T6 + t6 – T7 – t7) (4.88)

Further, another configuration of vapor bleeding where one pre heaters are placed is considered. It is referred as Conf-6. In this configuration one pre-heaters are placed at same position as indicated in Fig. 4.9. However, in this case vapor streams are bled from V5. In this configuration liquor streams L6 are preheated up to the temperatures (T6+T7)/2, respectively. These liquor streams are heated up to average temperatures only as sufficient driving force is required to transfer the heat from bled vapor to liquor. The model, developed for Conf-6 is Mod-8.

Summarize the model

In Mod-8, the 15 equations, 15 unknown variables and 33 known variables are involved. It is referred as Conf-6. In this model one pre-heater are placed between6rdand 7theffect at same position as indicated in Fig. 4.9.

4.4.1.8 Model of seven effect evaporator system for preheating of liquor using condensate

A pre-heater is placed between 2thand 7th effect. Instead of vapor bled, condensate is used which like heating medium. Here Condensate is employed to pre heat the liquor, this is entering into that effect using a counter heat exchanger. In this figure 4.10, the condensates of vapor chest of first and second (live steams) C01 and C02 are used to pre heat the liquor coming from the third and fourth. This respective model is named as Mod-9.

Energy balance

1st effect

F1 = [L2*CP2*(T2 + t2)] – [0.5*V01*λ01] – [L1*CP1*(T1 + t1)] – [(L2 – L1)*(λ1 + (4.2*T1)]

(4.89)

F2 = [U1*A1*(T01 – T1 - t1)] – [0.5*V01*λ1] (4.90)

2nd effect

$$F3 = [L3*CP3*(T2 - 8)] - [0.5*V02*\lambda02] - [L2*CP2*(T2 + t2)] - [(L3 - L2)*(\lambda2 + (4.2*T2)] \tag{4.91}$$

$$F4 = [U2*A2*(T2 - T1 - t1)] - [0.5*V02*\lambda2] \tag{4.92}$$

3rd effect

$$F5 = [L4*CP4*T3] - [L3*CP3*(T3 + t3)] + [(L2 - L1)*\lambda1] + [(L3 - L2)*\lambda2] - [(L4 - L3)*(\lambda3 + (4.2*T3)] \tag{4.93}$$

$$F6 = U3*A3*((T1+T2)/2) - T3 - t3) - [(L2 - L1)*\lambda1] - [(L3 - L2)*\lambda2] \tag{4.94}$$

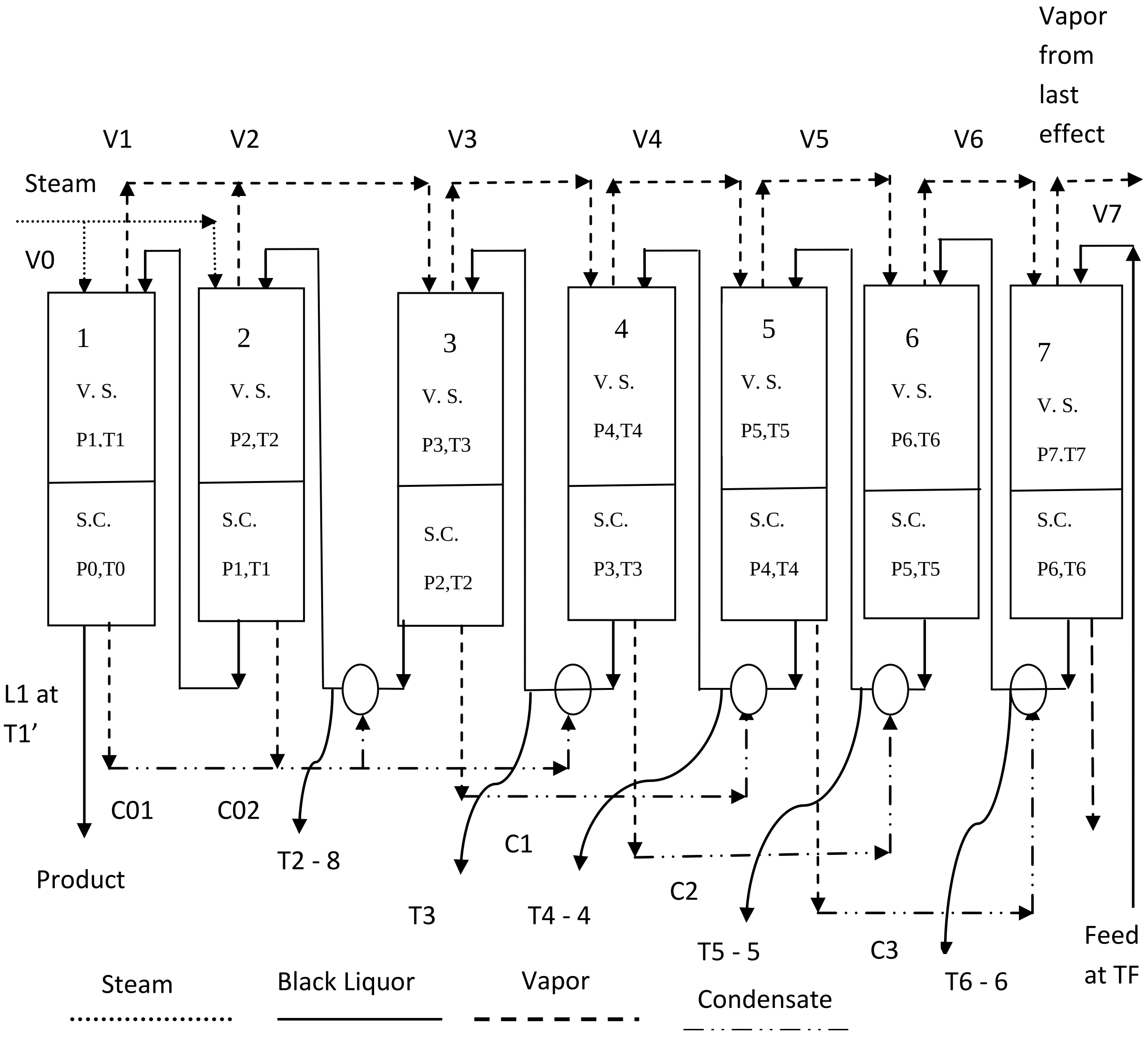

Figure 4.10: Schematic diagram of seven effect evaporator system pre heating of liquor using condensate

Equations of 2nd effect can be derived using figure 4.11

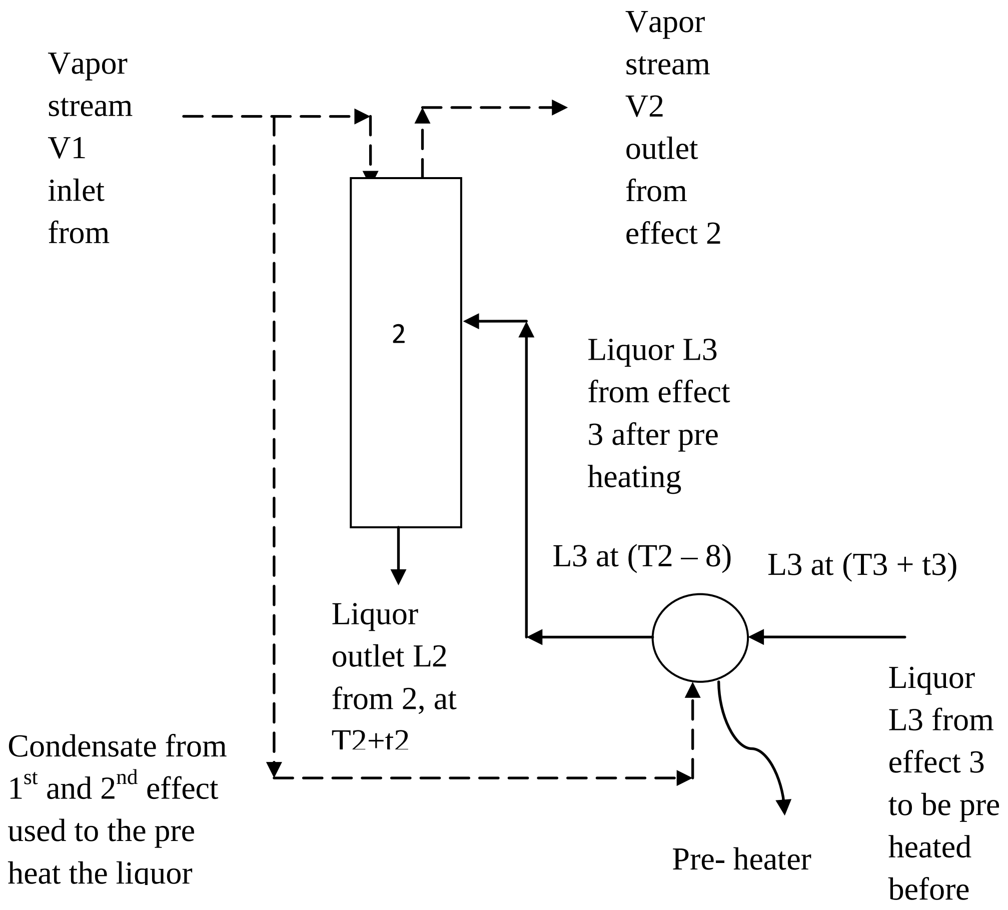

Figure 4.11: Schematic diagram of 2nd effect with pre heating using

4th effect

$$F7 = [L5*CP5*(T4 - 4)] - [L4*CP4*(T4 + t4)] + [(L4 - L3)*\lambda 3] - [(L5 - L4)*(\lambda 4 + (4.2*T4)] \tag{4.95}$$

$$F8 = [U4*A4*(T3 - T4 - t4)] - [(L4 - L3)*\lambda 3] \tag{4.96}$$

5th effect

$$F9 = [L6*CP6*(T5 - 5)] - [L5*CP5*(T5 + t5)] + [(L5 - L4)*\lambda 4] - [(L6 - L5)*(\lambda 5 + (4.2*T5)] \tag{4.97}$$

$$F10 = [U5*A5*(T4 - T5 - t5)] - [(L5 - L4)*\lambda 4] \tag{4.98}$$

6th effect

$$F11 = [L7*CP7*(T6 - 6)] – [L6*CP6*(T6 + t6)] + [(L6 – L5)*\lambda5] - [(L7 – L6)*(\lambda6 + (4.2*T6)] \tag{4.99}$$

$$F12 = [U6*A6*(T5 – T6 – t6)] – [(L6 – L5)*\lambda5] \tag{4.100}$$

7th effect

$$F13 = [F*CPf*Tf] – [L7*CP7*(T7 + t7)] + [(L7 – L6)*\lambda6] - [(F – L7)*(\lambda5 + (4.2*T7)] \tag{4.101}$$

$$F14 = [U7*A7*(T6 – T7 – t7)] – [(L7 – L6)*\lambda6] \tag{4.102}$$

Further, in this model where five pre heaters are placed is considered. It is referred as Mod 9. Instead of vapor bled, condensate is used which like heating medium. Here Condensate is employed to pre heat the liquor. In this model, five pre-heaters are placed at same position as indicated in Fig. 4.10.

Summarize the model

In Mod-9, the 14 equations, 14 unknown variables and 31 known variables are involved. In this model, five pre-heaters are placed at same position as shown in Fig. 4.10.Instead of vapor bled, condensate is used which like heating medium.

4.4.2 Model for ten effect evaporator system

These are specific heat capacity of liquor, Cp latent heat of vaporization, λ, enthalpy of vapor and BPR. In this model live steam, divided equally in first and second effects as shown in Fig. 4.12, is also accounted. The vapor exiting from 1stand 2ndeffects enter to third effect.

4.4.2.1 Model with variation in physical properties, BPR and steam splitting in ten effect evaporator system.

In actual scenario the properties of liquor continuously vary with temperature and concentration. Therefore, the present model of seven effects evaporator system, Mod-10, is modified to incorporate - variations in physical properties.

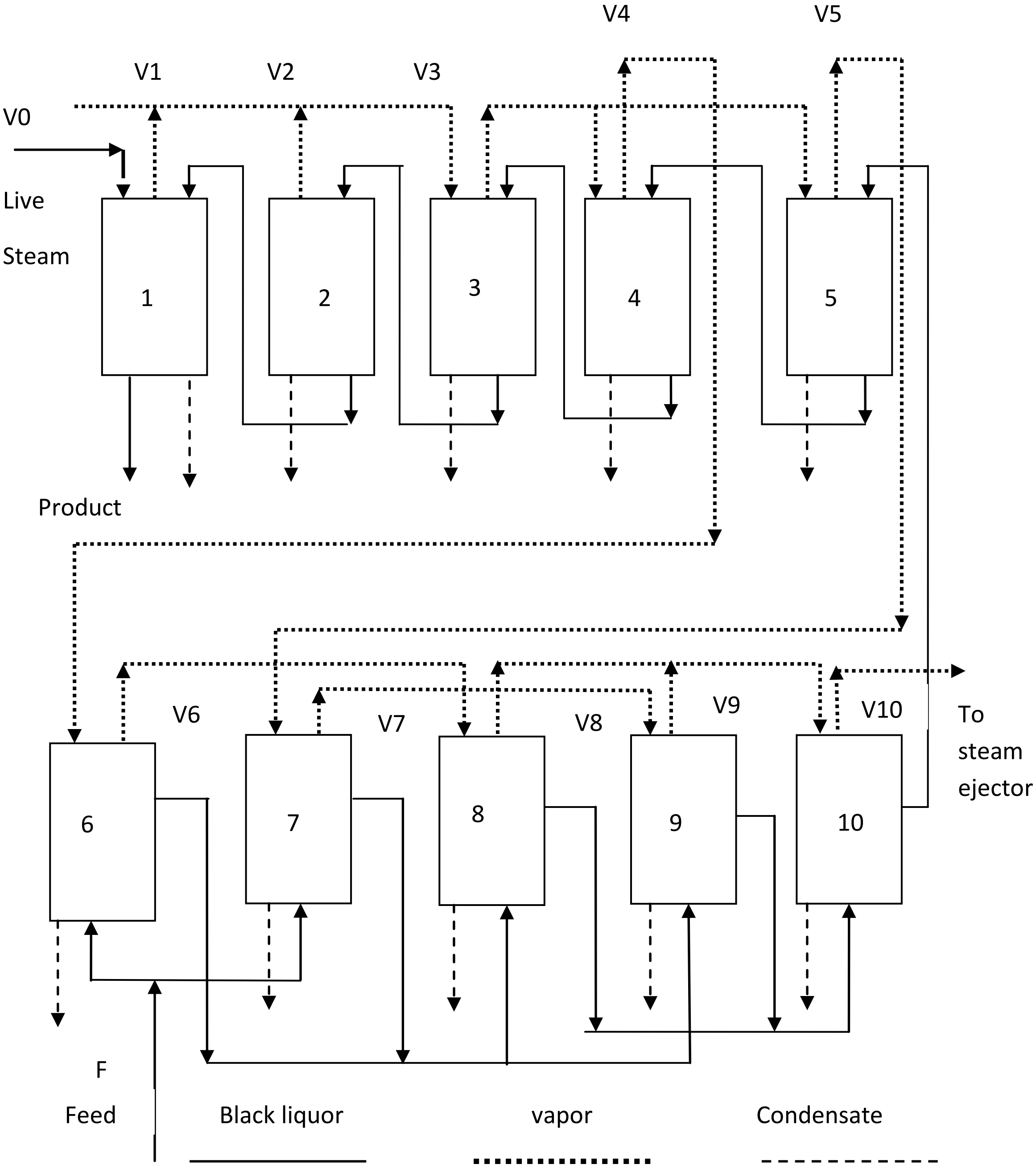

Figure 4.12: Schematic diagram of ten effect evaporator system with steam splitting

The model developed for present simplified system is named as Mod-10. Governing equations of 1st and 10th effects are derived based on material and energy balances as carried out for Mod-10. The steam is divided equally and then enters to 1stand 2nd effect simultaneously. Therefore, in Eq. 4.101 to 4.120 amount of steam, V0, with factor 0.5 is used. The equations for 1stand 2ndeffects are shown

Energy balance:-

1steffect

$$F1= [L2*CP2*(T2+t2)] + [0.5*V01*\lambda 01] - [L1*CP1*(T1+ t1)] - [(L2 - L1)*(\lambda 1+ 4.2*T1)] \tag{4.103}$$

$$F2 = U1*A1*(T01 - T1 - t1)] - (0.5*V01*\lambda 01) \tag{4.104}$$

2nd effect

$$F3= [L3*CP3*(T3+t3)] + [0.5*V02*\lambda 02] - [L2*CP2*(T2+ t2)] - [(L3 - L2)*(\lambda 2+ 4.2*T2)] \tag{4.105}$$

$$F4 = U2*A2*(T02 - T2 - t2)] - (0.5*V02*\lambda 02) \tag{4.106}$$

3rd effect

$$F5 = [L4*CP4*(T4 + t4)] - [L3*CP3*(T3 + t3)] + (L2 - L1)*\lambda 1 + (L3 - L2)*\lambda 2 - [(L4 - L3)*(\lambda 3 + 4.2*T3)] \tag{4.107}$$

$$F6 = U3*A3*((T1+T2)/2) - T3 - t3) - (L2 -L1)*\lambda 1 - (L3 - L2)*\lambda 2 \tag{4.108}$$

4th effect

$$F7 = [L5*CP5*(T5 + t5)] - [L4*CP4*(T4 + t4)] + (L4 - L3)*\lambda 3 - [(L5 - L4)*(\lambda 4 + 4.2*T4)] \tag{4.109}$$

$$F8 = U4*A3*(T3 - T4 - t4) - (L4 - L3)*\lambda 3 \tag{4.110}$$

5th effect

$$F9 = [L10*CP10*(T10 + t10)] - [L5*CP5*(T5 + t5)] + 0.5*(L4 - L3)*\lambda 4 - 0.5*(L4 - L3)*\lambda 5 - [(L10 - L5)*(\lambda 5 + 4.2*T5)] \tag{4.111}$$

$$F10 = U5*CP5*(T4 - T5 - t5) - 0.5*(L4 - L3)*\lambda 4 + 0.5*(L4 - L3)*\lambda 5 \tag{4.112}$$

6th effect

$$F11 = [0.5*F*CPf*Tf] - [L6*CP6*(T6 + t6)] + (L10 - L5)*\lambda 5 - [(0.5*F - L6)*(\lambda 6 + 4.2*T6)] \tag{4.113}$$

$$F12 = U6*CP6*(T5 - T6 - t6) - (L10 - L5)*\lambda 5 \tag{4.114}$$

7th effect

$$F13 = [0.5*F*CPF*Tf] - [L7*CP7*(T7 + t7)] + (L5 - L4)*\lambda 4 - [(0.5*F - L7)*(\lambda 7 + 4.2*T7)] \tag{4.115}$$

$$F14 = U7*CP7*(T6 - T7 - t7) - (L5 - L4)*\lambda 6 \tag{4.116}$$

8th effect

$$F15 = [L6*CP6*(T6 + t6)] + [L7*CP7*(T7 + t7)] - [L8*CP8*(T8 + t8)] + (0.5*F - L6)*\lambda 6 - [(0.5*L6 + 0.5*L7 - L8)*(\lambda 8 + 4.2*T8)] \tag{4.117}$$

$$F16 = U8*CP8*((T6+T7)/2) - T8 - t8) - (0.5*F - L6)*\lambda 6 \tag{4.118}$$

9th effect

$$F17 = [L6*CP6*(T6 + t6)] + [L7*CP7*(T7 + t7)] - [L9*CP9*(T9 + t9)] + (0.5*F - L7)*\lambda 7 - [(0.5*L6 + 0.5*L7 - L9)*(\lambda 9 + 4.2*T9)] \tag{4.119}$$

$$F18 = U9*CP9*((T6+T7)/2) - T9 - t9) - (0.5*F - L7)*\lambda 7 \tag{4.120}$$

10th effect

$$F19 = [L8*CP8*(T8 + t8)] + [L9*CP9*(T9 + t9)] - [L10*CP10*(T10 + t10)] + [(0.5*(L6 + L7) - L8))*\lambda 8] + [(0.5*(L6 + L7) - L9))*\lambda 9] - [(L8 + L9 - L10)*(\lambda 10 + 4.2*T10)] \tag{4.121}$$

$$F20 = U10*CP10*((T8+T9)/2) - T10 - t10) - [(0.5*(L6 + L7) - L8))*\lambda 8] + [(0.5*(L6 + L7) - L9))*\lambda 9] \tag{4.122}$$

Summarize the model

In Mod-10, the 20 equations, 20 unknown variables and 43 known variables are involved. The present model of seven effects evaporator system, Mod-10, is modified to incorporate - variations in physical properties at same position as shown in Fig. 4.13.

4.4.2.2 Model of ten effect evaporator system with vapor bleeding

As the seven effect evaporator system is being operated with backward sequence, feed enters to an effect at lower temperature. Further, feed acquires the temperature of effect using heat from vapor entering to that effect. Such heating of feed an also be carried out using vapor bleeding. Usually, vapor generated in one effect is completely utilized in next effect. However, in the present work a part of vapor generated in one effect, which is called bled vapor, is utilized to preheat the liquor exiting from subsequent effects. This effect is considered in the model and hence, Mod-10 is modified model and named as Mod-11. The Fig. 4.13 is shown the schematic of vapor bleeding in SEE.

Energy balance around each effect is shown as:

[Sensible heat of liquor (L4)] + [latent heat of vapour (V1)] + [latent heat of vapour (V2)] -[latent heat of vapour (V’2)] = [Sensible heat of liquor (L3)] + [latent heat of vapour (V3)]

1steffect

$$F1= [L2*CP2*(T2+t2)] + [0.5*V0*\lambda 01] - [L1*CP1*(T1+ t1)] - [(L2 - L1)*(\lambda 1+ 4.2*T1)] \qquad (4.123)$$

$$F2 = U1*A1*(T01 - T1 - t1)] - (0.5*V0*\lambda 01) \qquad (4.124)$$

2nd effect

$$F3= [L3*CP3*(T3+t3)] + [0.5*V0*\lambda 02] - [L2*CP2*(T2+ t2)] - [(L3 - L2)*(\lambda 2+ 4.2*T2)] \qquad (4.125)$$

$$F4 = U2*A2*(T02 - T2 - t2)] - (0.5*V0*\lambda 02) \qquad (4.126)$$

3rd effect

$$F5 = [L4*CP4*(T3 + t3)] - [L3*CP3*(T3 + t3)] + (L2 - L1)*\lambda 1 + (L3 - L2)*\lambda 2 - V'2*\lambda 2 - [(L4 - L3)*(\lambda 3 + 4.2*T3)] \tag{4.127}$$

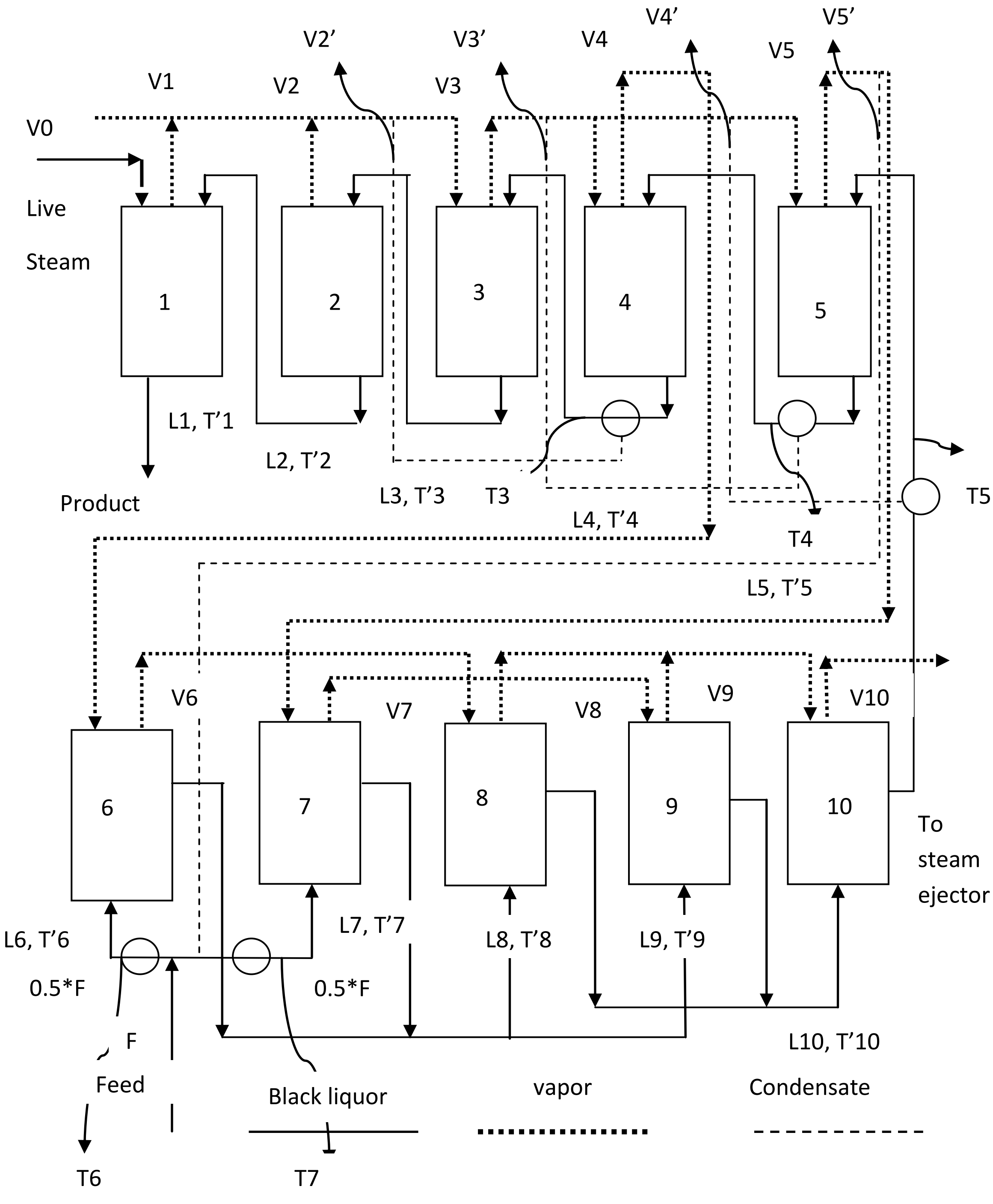

Figure 4.13: Schematic diagram of ten effect evaporator system with vapor bleeding

$$F6 = U3*A3*((T1+T2)/2) - T3 - t3) - (L2 - L1)*\lambda 1 - (L3 - L2)*\lambda 2 + V'2*\lambda 2 \tag{4.128}$$

$$F7 = V'2*\lambda 2 - L4*CP4*(T3 + t3 - T4 - t4) \tag{4.129}$$

4th effect

$$F8 = [L5*CP5*(T4 + t4)] - [L4*CP4*(T4 + t4)] + 0.5*(L4 - L3)*\lambda 3 + V'3*\lambda 3 - [(L5 - L4)*(\lambda 4 + 4.2*T4)] \tag{4.130}$$

$$F9 = U4*A3*(T3 - T4 - t4) - 0.5*(L4 - L3)*\lambda 3 + V'3*\lambda 3 \tag{4.131}$$

$$F10 = V'3*\lambda 3 - L5*CP5*(T4 + t4 - T5 - t5) \tag{4.132}$$

5th effect

$$F11 = [L10*CP10*(T5 + t5)] - [L5*CP5*(T5 + t5)] + 0.5*(L4 - L3)*\lambda 3 - [(L10 - L5)*(\lambda 5 + 4.2*T5)] \tag{4.133}$$

$$F12 = U5*CP5*(T3 - T5 - t5) - 0.5*(L4 - L3)*\lambda 3 \tag{4.134}$$

6th effect

$$F13 = [0.5*F*CPf*(T6+t6] - [L6*CP6*(T6 + t6)] + (L5 - L4)*\lambda 4 - V'4*\lambda 4 - [(0.5*F - L6)*(\lambda 6 + 4.2*T6)] \tag{4.135}$$

$$F14 = U6*CP6*(T4 - T6 - t6) - (L5 - L4)*\lambda 4 + V'4*\lambda 4 \tag{4.136}$$

$$F15 = V'4*\lambda 4 - 0.5F*CPf*(T6 + t6 - Tf) \tag{4.137}$$

7th effect

$$F16 = [0.5*F*CPf*(T7+t6)] - [L7*CP7*(T7 + t7)] + (L10 - L5)*\lambda 5 - V'5*\lambda 5 - [(0.5*F - L7)*(\lambda 7 + 4.2*T7)] \tag{4.138}$$

$$F17 = U7*CP7*(T5 - T7 - t7) - (L10 - L5)*\lambda 5 + V'5*\lambda 5 \tag{4.139}$$

$$F18 = V'5*\lambda 5 - 0.5F*CPf*(T7 + t7 - Tf) \tag{4.140}$$

8th effect

$$F19 = [0.5L6*CP6*(T6 + t6)] + [0.5L7*CP7*(T7 + t7)] - [L8*CP8*(T8 + t8)] + (0.5*F - L6)*\lambda 6 - [(0.5*L6 + 0.5*L7 - L8)*(\lambda 8 + 4.2*T8)] \tag{4.141}$$

$$F20 = U8*CP8*(T6 - T8 - t8) - (0.5*F - L6)*\lambda 6 \tag{4.142}$$

9th effect

$$F21 = [0.5L6*CP6*(T6 + t6)] + [0.5L7*CP7*(T7 + t7)] - [L9*CP9*(T9 + t9)] + (0.5*F - L7)*\lambda 7 - [(0.5*L6 + 0.5*L7 - L9)*(\lambda 9 + 4.2*T9)] \tag{4.143}$$

$$F22= U9*CP9*(T7 - T9 -t9) - (0.5*F - L7)*\lambda 7 \tag{4.144}$$

10th effect

$$F23 = [L8*CP8*(T8 + t8)] + [L9*CP9*(T9 + t9)] - [L10*CP10*(T10 + t10)] + [(0.5*(L6 + L7) - L8)*\lambda 8] + [(0.5*(L6 + L7) - L9))*\lambda 9] - [(L8 + L9 - L10)*(\lambda 10 + 4.2*T10)] \tag{4.145}$$

$$F24 = U10*CP10*((T8+T9)/2) - T10 - t10) - [(0.5*(L6 + L7) - L8))*\lambda 8] - [(0.5*(L6 + L7) - L9)*\lambda 9] \tag{4.146}$$

Further, another configuration of vapor bleeding where four pre heaters are placed is considered. It is referred as Mod-11. In this configuration four pre-heaters are placed at same position as indicated in Fig.4.13.However, in this case vapor streams are bled from V3, V4, V5, V6, V7,V8 and V9 instead of V2, V3, V4, V5, V6, V7 and V8. In this configuration liquor streams L4, L5, L6, L7, L8, L9 and L10 are preheated up to the temperatures (T3+T4)/2, (T4+T5)/2, (T5+T6)/2 a (T6+T7)/2, (T7+T8)/2,(T8+T9)/2and (T9+T10)/2 respectively. These liquor streams are heated up to average temperatures only as sufficient driving force is required to transfer the heat from bled vapor to liquor.

Summarize the model

In Mod-11, the 24 equations, 24 unknown variables and 45 known variables are involved. In this model, four pre-heaters are placed between 3rd and 4thand so on till 10th effects. The vapor bled from the vapor come out from 2ndeffect which is employed to the pre heat the black liquor before it enters the 3rd effect with a pre-heater placed between 3rd and 4theffect. Others are placed consecutively at same position as shown in Fig. 4.13.

4.4.3 SUMMARY OF THE MODELS

Table 4.2 shows 11 models which are represented as Mod-1, Mod-2, Mod-3, Mod-4, Mod-5, Mod-6, Mod-7, Mod-8, Mod-9, Mod-10 and Mod-11 and 6 numbers of configurations shown as Conf-1, Conf-2, Conf-3, Conf-4, Conf-5 and Conf-6 . Table 4.2 indicates that numbers of equations, known variables and unknown variables for different models are different.

Table 4.2: Model Analysis

Model name	Description	Configuration	No. of equations	Known variables	Unknown variables
Mod-1	Model of simple seven effect evaporator system		14	Cp1-7, λ1-7, U1-7, A1-7, T7, F, Tf	V0,L1,L2, L3,L4,L5,L6,L7,T1,T2,T3,T4,T5, T6
Mod-2	Model with steam splitting and variable physical properties and BPR		14	Cp1-7, λ1-7, U1-7, A1-7, T7, F, Tf, T01, T02	V0,L1,L2, L3,L4,L5,L6,L7,T1,T2,T3,T4,T5, T6
Mod-3	Model of seven effect evaporator system with vapor bleeding with configuration 1	Conf-1	18	Cp1-7, λ1-7, U1-7, A1-7, T7, F, Tf, T01, T02	V0,L1,L2, L3,L4,L5,L6,L7,T1,T2,T3,T4,T5, T6,V2,V3, V4,V5
Mod-4	Model of seven effect evaporator system with vapor bleeding with configuration 2	Conf-2	18	Cp1-7, λ1-7, U1-7, A1-7, T7, F, Tf, T01, T02	V0,L1,L2, L3,L4,L5,L6,L7,T1,T2,T3,T4,T5, T6,V3,V4, V5,V6
Mod-5	Model of seven	Conf-3	18	Cp1-7, λ1-7,	V0,L1,L2,

	effect evaporator systems when vapor is bled from second effect			U1-7, A1-7, T7, F, Tf, T01, T02	L3,L4,L5,L6,L7,T1,T2,T3,T4,T5, T6,V2,V3, V4,V5
Mod-6	Model of seven effect evaporator systems when vapor is bled from third effect	Conf-4	17	Cp1-7, λ1-7, U1-7, A1-7, T7, F, Tf, T01, T02	V0,L1,L2, L3,L4,L5,L6,L7,T1,T2,T3,T4,T5, T6,V3,V4, V5
Mod-7	Model of seven effect evaporator systems when vapor is bled from fourth effect	Conf-5	16	Cp1-7, λ1-7, U1-7, A1-7, T7, F, Tf, T01, T02	V0,L1,L2, L3,L4,L5,L6,L7,T1,T2,T3,T4,T5, T6,V4,V5
Mod-8	Model of seven effect evaporator systems when vapor is bled from fifth effect	Conf-6	15	Cp1-7, λ1-7, U1-7, A1-7, T7, F, Tf, T01, T02	V0,L1,L2, L3,L4,L5,L6,L7,T1,T2,T3,T4,T5, T6,V5
Mod-9	Model of seven effect evaporator system for preheating of liquor using condensate		14	Cp1-7, λ1-7, U1-7, A1-7, T7, F, Tf	V0,L1,L2, L3,L4,L5,L6,L7,T1,T2,T3,T4,T5, T6
Mod-10	Model for ten effect evaporator system		20	Cp1-10, λ1-10, U1-10, A1-10, T10, F, Tf	V0,L1,L2, L3,L4,L5,L6,L7,T1,T2,T3,T4,T5, T6,V3,V4, V5,V6

Mod-11	Model of ten effect evaporator system with vapor bleeding		24	Cp1-10, λ1-10, U1-10, A1-10, T10, F, Tf, T01, T02	V0,L1,L2, L3,L4,L5,L6,L7,L8,L9,L10,T1,T2,T3,T4,T5, T6,T7,T8,T9,V2,V3,V4,V5

CHAPTER 5

SOLUTION TECHNIQUES

In Chapter 4, the solutions techniques of mathematical models are used to be developing at many conditions for the SEE system. The number of parameters is required to be solution in these models like heat capacity, enthalpy, BPR, overall heat transfer coefficient, variable physical properties, etc. these unknown intermediate temperature depend on number of parameters. The non linear equations group is calculated to be developed by Systems of Non- Linear Equations software. In the models, the series of steps is explained detailed algorithm (not clear, please re-write). The steps of series are given as below:

1: From Table 3.1 the values of operating parameters are found.

2: To estimated temperature and liquor flow rates for each effect, the equal vaporization and temperature are considered originally for each effect. Then to start the calculation for everybody effect the original values of U is made.

3: The material and component balance are employed in order to obtain calculate to compositions of intermediate streams and the flow rates inside the operation.

4: The compositions are handled to calculate BPEs and specific heat of the solution. The composition and temperature computed in step 2 and 3 are handled to obtain enthalpy values.

5: The incorporation of variations such as steam splitting, variation in specific heat capacity, BPR, latent heat of vaporization, preheating of liquor using condensate and vapor bleeding is assumed.

6: Based on values of U set of non linear equations are developed that are solved to get the revised values of temperatures and liquor flow rates of each effect. In this system, the solver “system of non linear equations software” is used.

7: Revised values of U are estimated considering temperature, flow rate and concentration of each effect.

8: The values of U are compared with the previous iteration values. If difference of U fall within (± 40%). Then the calculations from step 3 to 10 are repeated with revised values of U, temperature and flow rates and U until the operation complete.

9: Steam economy of the MEE system is computed.

CHAPTER 6

RESULTS AND DISCUSSION

The present investigation focuses on the optimization of multiple effect evaporators (MEE) system considering effect of vapor bleeding. For this purpose nonlinear models are developed under Section 4.4.1 based on steam splitting, vapor bleeding and variable physical properties. The correlations for physical properties and BPR of liquor are discussed under Section 4.4.2. The set of nonlinear equations present in model developed in this work is solved using software "Systems of nonlinear Equations". To use the developed model two different MEE systems are employed. These are seven and ten effect MEE systems, being used in typical Indian pulp and paper industries for concentration of black liquor. Details of these systems are discussed in Chapter 3.

6.1. SIMPLE SEVEN EFFECT SYSTEM WITH VARIABLE PHYSICAL PROPERTIES

The present model of seven effects evaporator system, Mod-1, is modified to incorporate - variations in physical properties. In this, 14 equations are involved. The physical properties are latent heat of vaporization, λ, enthalpy of vapor and specific heat capacity of liquor, Cp. where feed enters to 7th effect and product exists from 1st effect. Steam of amount, V0, enters the steam chest of 1st effect and exits it in the form of condensate. The produced vapor in 1st effect goes to vapor chest of second effect. While the produced vapor of second effect go to the vapor chest of the third effect and so on up to seventh effect. In the table 3.1, the operating parameters is used solve to the model. Table 6.1 indicates that final results are found in 10thiteration, in which are solved the values U in two consecutive till the values of U fall up to ±40% range. For this model the SE is 4.230 while SC is 2.872 kg/s, respectively.

Tab.-6.1 Results for the SSEEs in backward sequence.

Iteration No	Effect	T, ^{o}C	X	L, kg/s	Economy	U, kW/m^{2o}C	Diff. of U,%
1	1	127.430	0.600	3.070		0.364	
	2	114.860	0.379	4.862		0.261	
	3	102.286	0.277	6.653		0.703	
	4	89.700	0.218	8.445		0.683	
	5	77.140	0.180	10.236		0.6803	
	6	64.700	0.153	12.030		0.6834	
	7	52.000	0.133	13.820		0.6890	
2	1	122.635	0.455	3.950	3.070	0.236	19.00
	2	135.137	0.347	5.190		0.418	42.30
	3	90.112	0.226	7.983		0.212	20.30
	4	87.482	0.188	9.612		1.096	67.40
	5	72.716	0.163	11.128		0.542	69.80
	6	67.014	0.147	12.395		1.184	37.50
	7	52.000	0.126	14.552		0.558	35.10
3	1	127.915	0.342	5.354	3.152	0.354	33.33
	2	143.480	0.313	5.856		0.428	02.33
	3	90.265	0.215	8.527		0.188	11.32
	4	89.690	0.184	9.984		1.066	70.33
	5	70.070	0.159	11.571		0.520	04.05
	6	68.276	0.153	12.069		1.170	01.18
	7	52.000	0.122	15.195		0.526	05.73
4	1	128.042	0.357	5.060	3.978	0.360	01.66
	2	149.878	0.291	6.223		0.404	05.60
	3	98.937	0.209	8.672		0.196	04.08
	4	84.895	0.168	10.795		0.548	92.24
	5	77.615	0.163	11.182		0.986	47.26
	6	61.220	0.145	12.594		0.512	56.23
	7	52.000	0.125	14.625		0.824	36.16
5	1	126.404	0.549	3.286	1.046	0.260	27.77
	2	137.040	0.259	6.972		0.572	29.37
	3	92.171	0.211	8.566		0.214	08.41
	4	83.560	0.185	9.784		0.820	33.17
	5	79.394	0.157	11.565		1.492	33.91
	6	61.892	0.145	12.576		0.484	05.46
	7	52.000	0.127	14.421		0.778	05.58
6	1	120.574	0.342	5.307	1.037	0.322	19.25
	2	144.180	0.272	6.679		0.416	27.27
	3	95.543	0.207	8.786		0.210	01.86
	4	81.495	0.174	10.465		0.500	39.02
	5	76.983	0.163	11.213		1.396	06.43

	6	67.863	0.147	12.506		0.812	40.39
	7	52.000	0.132	13.948		0.532	31.61
7	1	126.474	0.549	4.693	1.799	0.262	18.63
	2	133.763	0.259	6.935		0.654	36.39
	3	98.316	0.211	7.453		0.260	19.23
	4	81.668	0.185	10.962		0.490	02.00
	5	78.957	0.155	11.718		2.096	33.39
	6	69.745	0.149	12.241		0.808	00.49
	7	52.000	0.124	14.753		0.490	07.89
8	1	127.227	0.331	5.599	3.933	0.364	28.02
	2	141.411	0.299	5.428		0.390	40.36
	3	94.958	0.250	7.193		0.206	20.76
	4	87.201	0.182	9.898		0.890	44.94
	5	70.471	0.159	11.391		0.494	76.43
	6	63.315	0.142	12.829		0.984	17.88
	7	52.000	0.134	13.653		0.696	29.59
9	1	126.096	0.413	4.372	4.130	0.308	15.38
	2	144.278	0.288	6.278		0.590	00.25
	3	98.700	0.252	7.188		0.212	02.83
	4	86.671	0.165	10.988		0.634	28.76
	5	72.759	0.157	11.560		0.572	13.63
	6	64.494	0.145	12.596		0.876	10.97
	7	52.000	0.135	13.582		0.642	07.75
10	1	127.839	0.525	3.461	4.230	0.250	18.83
	2	131.873	0.331	5.499		0.672	12.20
	3	91.644	0.227	8.391		0.236	10.16
	4	82.178	0.171	10.653		0.768	17.44
	5	70.575	0.153	11.965		0.662	13.59
	6	65.382	0.146	12.548		1.280	31.56
	7	52.000	0.122	15.085		0.614	04.36

In Table 6.1,the effect from 1 to 7 are shown at the temperature 127.839, 131.873, 91.644, 82.178, 70.575, 65.382 and 52°C. According to the model, the effects dependent on the temperature. The temperature of effect 1 is lower than that of effect 2. Then on moving towards effect 7, the temperature keeps on decreasing.

Table 6.1 shows that the effect from 1 to 7 are located at flow rate 3.461, 5.499, 8.391, 10.653, 11.965, 12.548 and 15.085 kg/s. The pattern of liquor flow rate is obvious as it decreases from 7th to 1st effect. As we move from effect 1 to 7, the liquor flow rate increases from 3.461 to 15.085 kg/s.the effect from 1 to 7 is situated at overall heat transfer coefficient 0.250, 0.672, 0.236, 0.768, 0.662, 1.280 and 0.614. In this model, the effect from 1to 7 varies different U. the effect from 1 to 7 are located at solid mass fraction 0.525, 0.331, 0.227, 0.171, 0.153, 0.146 and 0.122. According to the model, the effects dependent on the solid mass fraction. As we move from effect 1 to 7 as mass fraction decreases from 0.525 to 0.122.

6.2. SEES WITH STEAM SPLITTING, BPR AND VARIABLE PHYSICAL PROPERTIES

In this model, Mod-2, is modified to incorporate - variations in physical properties. In which is involved 14 equations. These are latent heat of vaporization, λ, BPR, specific heat capacity of liquor, Cp and enthalpy of vapor. In this model live steam, divided equally in 1st and 2nd effects in which is shown in Figure. 4.2, is also accounted. The vapor exiting from 1st and 2nd effects enter to third effect. In this model, the SE is 4.334 and SC is 2.296 kg/s respectively.

In Figure 6.1,the effect from 1to 7 are shown at the 113.694, 135.082, 90.916, 83.414, 73.266, 66.364 and 52°C. According to the model, the effects dependent on the temperature. The temperature of effect 1 is lower than that of effect 2. Then on moving towards effect 7, the temperature keeps on decreasing.

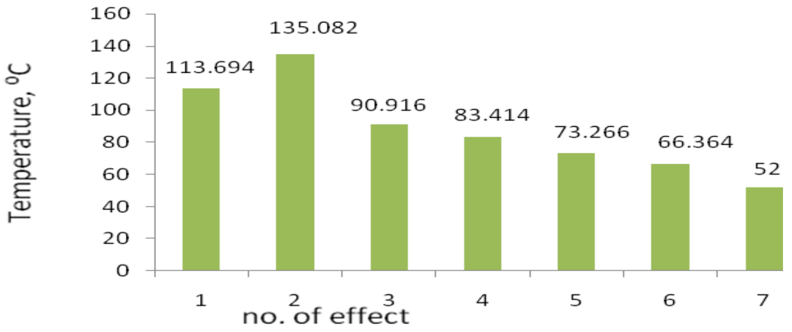

Fig.6.1: variations between temperature and effect in the steam splitting model.

In the figure 6.2. the effect from 1to 7 are located at flow rate 5.006, 6.088, 7.717, 9.728,11.696, 12.792 and 14.384. According to the model, the effects dependent on the liquor flow rate. As we move from effect 1 to 7, the liquor flow rate increases from 5.006 to 14.384.

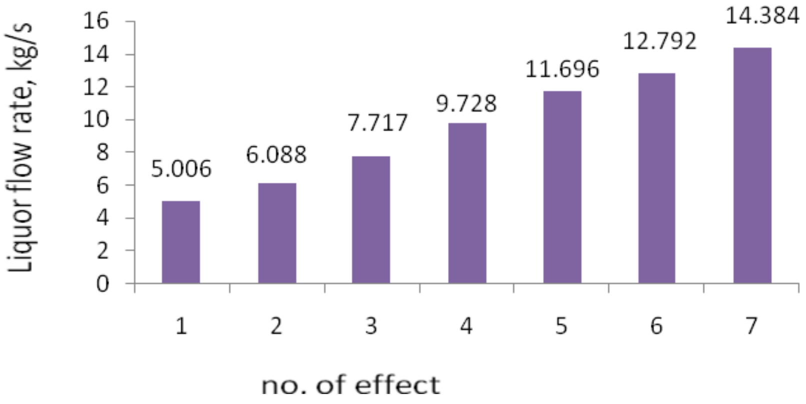

Fig.6.2: variations between flow rate and effect of the steam splitting model

In the figure 6.3, the effect from 1 to 7 is situated at overall heat transfer coefficient 0.302, 0.517, 0.225, 1.119, 0.824, 1.182 and 0.614. In this model, the effect from1to 7 varies different overall heat transfer coefficient.

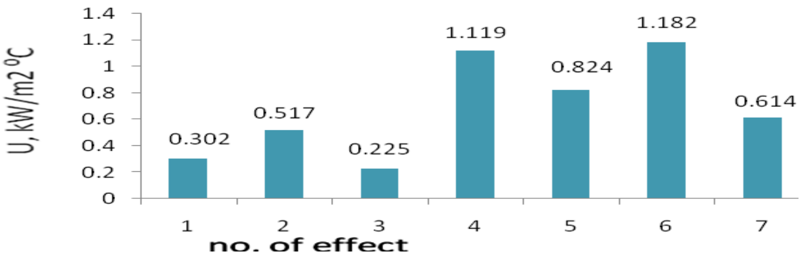

Fig.6.3: variations between U and effects of the steam splitting model with the previous model.

6.2.1: COMPARISON OF THE STEAM SPLITTING SYSTEM WITH THE SIMPLE MODEL.

Figure 6.4 shows the comparison between the previous model and the splitting model. In this model, the splitting model is better than the previous. So, the economy and steam consumption of the splitting model is 5.81% more than the SE and 17.75 % lesser SC. The PC of the previous models is more than the steam splitting system.

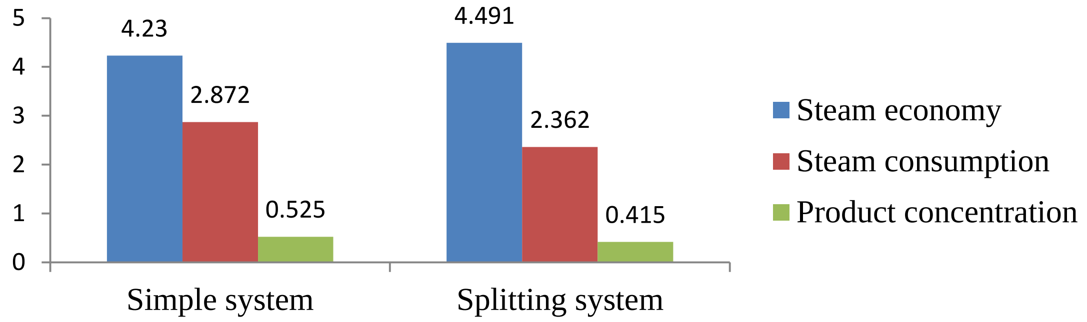

Fig 6.4: Comparison of simple system with steam splitting system

6.3. SEE SYSTEM WITH VAPOUR BLEEDING

In this model, Mod-2 is modified model and named as Mod-3. The pre heaters placed among 2ndand 3rd, 3rd and 4th, 4th and 5th, 5th and 6th effects are needed vapor and are bled vapor from V_2,V_3, V_4, V_5. In the table 6.9 is shown final results of this model. This model shows that the bled vapor flow rates are 0.2423, 0.0288, 0.1099 and 0.0743 kg/s from streams V'2, V'3, V'4 and V'5. The total evaporation rate is 11.387 kg/s. Table 6.2 is shown final results, in which are solved the values U in two consecutive till the values fall up to ±40% range. The SC is obtained 1.574 kg/s and SE is 4.774.

Table 6.2: Result of SEE system with vapor bleeding (conf.S-1).

Effect No.	1	2	3	4	5	6	7
U, $kW/m^{2\,o}C$	0.285	0.994	0.214	1.115	0.576	0.845	0.828
L , kg/s	4.224	6.738	8.041	10.566	11.961	12.510	14.963
X	0.516	0.270	0.227	0.173	0.153	0.147	0.123
Ƭ, ^{o}C	7.589	2.738	2.138	1.490	1.280	1.220	0.994

Amount of vapor bled, kg/s		0.2423	0.0288	0.1099	0.0743		
T, °C	117.301	141.976	94.672	87.262	72.149	62.175	52.000

Table 6.2 shows that the effect from 1 to 7 are located at the temperature 117.301, 141.976, 94.672, 87.262, 72.149, 62.175 and 52°C. According to the model, the effects dependent on the temperature. For first two effect viz. effect1 and effect2 temperature rises from effect1 to effect2 and then from effect2 to effect7 temperature decreases consistantly. The effect from 1 to 7 is situated at overall heat transfer coefficient 0.285, 0.994, 0.214, 1.115, 0.576, 0.845 and 0.828. In this model, the effect from1to 7 varies different overall heat transfer coefficient.

In the second configuration, the pre heaters placed among 3rdand 4th, 4thand 5th, 5th and 6th, 6thand7th effects are needed vapor and are bled vapor from V_3, V_4, V_5, V_6.

The model developed for Conf-2 is Mod-4. This model shows that the bled vapor flow rates are 0.0578, 0.0592, 0.1457 and 0.1579 kg/s from streams V'_3, V'_4, V'_5 and V'_6. The total evaporation rate is 9.613 kg/s. The SE and SC is 4.937 and 1.947kg/s. while steam economy and steam consumption is 4.230 and 2.872 kg/s for simple model. Due to the driving force (ΔT), the steam economy increase for sensible heating with higher latent heat and low pressure vapor. According to its position, the units of steam economy increases. Table 6.3 shows final results from which are solved the values U in two consecutive till the values of U fall up to ±40% range.

Tab.- 6.3: Results of SEE system with vapor bleeding (conf.- 2)

Effect No.	1	2	3	4	5	6	7
U, kW/m^2 °C	0.232	0.675	0.210	0.750	1.211	0.646	0.701
L , kg/s	5.998	6.892	7.196	8.181	10.491	12.123	14.991
X	0.484	0.262	0.251	0.221	0.173	0.150	0.122
τ, °C	6.821	2.620	2.464	2.060	1.490	1.250	0.985

Amount of vapor bled, kg/s			0.0578	0.0592	0.1457	0.1579	
T, ^{o}C	109.099	139.356	92.230	80.851	77.794	64.310	52.000

Table 6.3 indicates that the effect from 1to 7 are located at the temperature 109.099, 139.356, 92.280, 80.851, 77.794, 64.310 and 52. According to the model, the effects dependent on the temperature. For first two effect viz. effect1 and effect2 temperature rises from effect1 to effect2 and then from effect2 to effect7 temperature decreases consistantly, the effect from 1 to 7 is situated at overall heat transfer coefficient 0.23, 0.675, 0.210, 0.750, 1.211, 0.646 and 0.701. In this model, the effect from1to 7 varies different overall heat transfer coefficient.

6.3.1COMPARISON BETWEEN CONFI.-1 AND CONF.-2 FOR SYSTEM WITH VAPOR BLEEDING

The comparison between configuration 1 and configuration 2 is shown in figure 6.5. It is considered that configuration 2 is better than configuration 1. The steam economy of the configuration 2 is 14.44% more than steam economy of the configuration 1. Whereas the steam consumption of the configuration 2 is 18.36% more in comparison to configuration 1.In this model, the product concentration in the confi.-1 is more than the confi.-2.

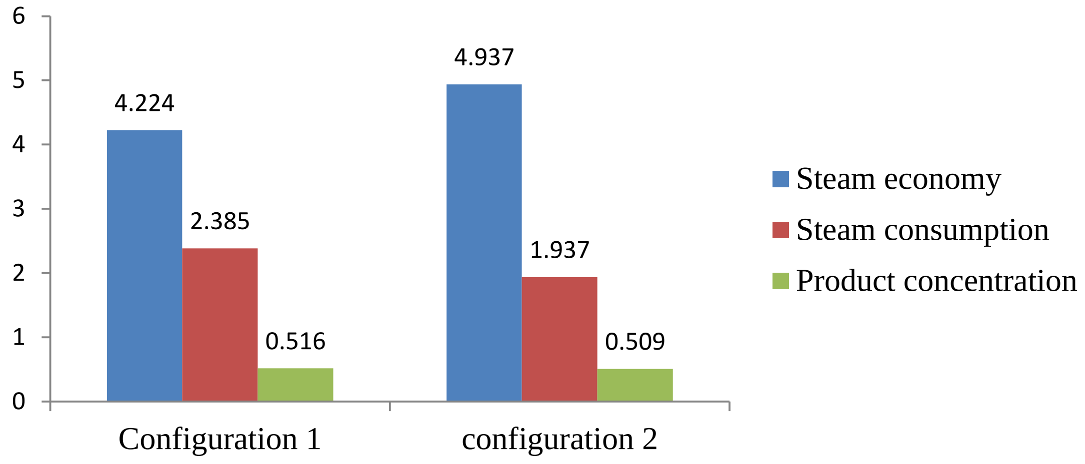

Figure 6.5: Variation between confi.-1 and confi.-2 for system with vapor bleeding.

6.4. SEVEN EFFECT EVAPORATOR SYSTEM CONSIDERING VAPOR BLED FROM VAPOR GENERATED IN SECOND EFFECT

A pre-heater is placed between 3rd and 4theffect where vapor bled from 2nd effect. This configuration and respective model is named as Conf-3 and Mod-5. In this configuration liquor stream L4 is heated from T4 to T3. In showing section 6.4, the comparisons of model for simple system operate with the Mod-5. This model shows that the bled vapor flow rates are 0.0455kg/s from streams $V'_{2.}$ The total evaporation rate is 12.188 kg/s. The SC is obtained 1.462 kg/s and SE is 5.598.

In the figure 6.6, it is shown that the effect from 1to 7 are located at the temperature 106.587, 137.846, 94.188, 89.849, 72.866, 69.177 and 52. In this model, According to the model, the effects dependent on the temperature. For first two effect viz. effect1 and effect2 temperature rises from effect1 to effect2 and then from effect2 to effect7 temperature decreases consistantly.

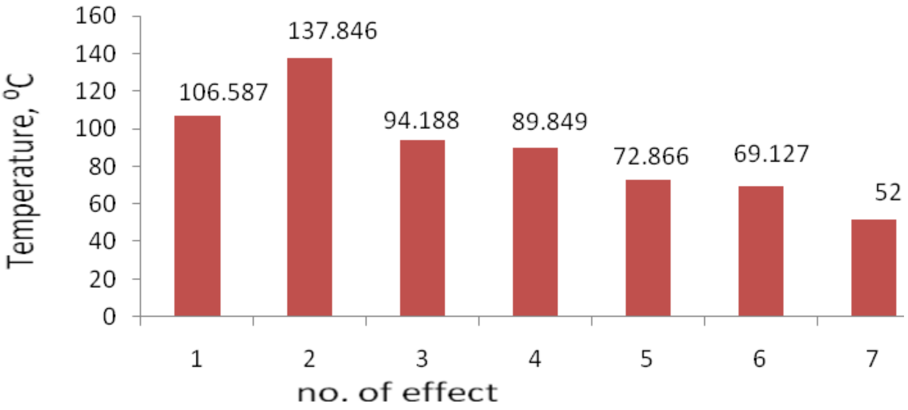

Fig.6.6: variations between temperature and effect in considering vapor bled from vapor generated in second effect.

In the figure 6.7, the effect from 1 to 7 is situated at overall heat transfer coefficient 0.184, 0.595, 0.230, 1.975, 0.519, 1.188and 0.528. In this model, the effect from1to 7 varies different overall heat transfer coefficient.

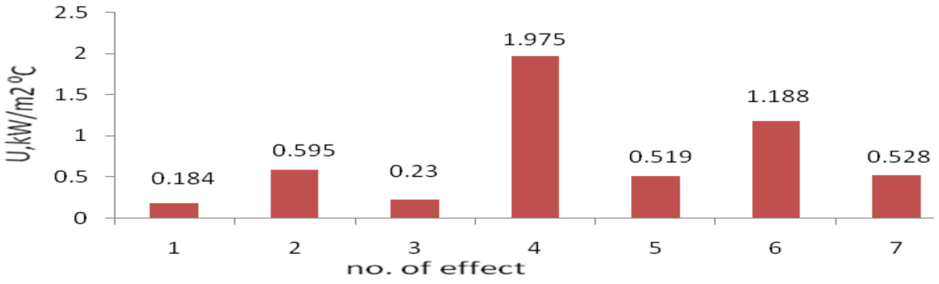

Fig.6.7: variations between film heat transfer coefficient and effect in considering vapor bled from vapor generated in second effect.

6.4.1COMPARISON BETWEEN SIMPLE MODEL AND MODEL CONSIDERED VAPOR BLED FROM SECOND EFFECT

Figure 6.8 developed the comparison between the previous model and the considering vapor bled generated in second effect model. In this model, it indicates that the considering vapor bled from second effect model is better than the previous.

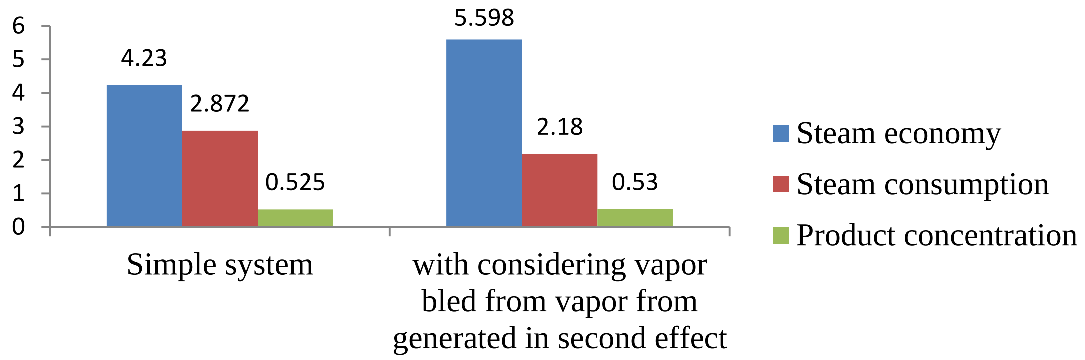

Figure 6.8: Variation between simple system with considering vapor bled from second effect

So the economy and steam consumption of the considering vapor bled generated in second effect models 24.37% more than the SE and 24.09 % decrease SC. The PC in the present and previous is approximately equal.

6.5 SEVEN EFFECT EVAPORATOR SYSTEM CONSIDERED VAPOR BLED FROM THIRD EFFECT

It is the seven effect evaporator system when single pre-heater is placed between 4thand 5theffect. The heating of liquor stream, L4, takes place from T5 to T4 using vapor bled from 3rd effect. The present configuration and model is referred as Conf-4 and Mod-6. Table shows that total evaporation is 11.901 kg/s and 12.150kg/s for simple system. While total evaporation rate is reduced with vapor bleeding, it is found to be by consuming 2.219 kg/s of steam. This is 22.73% less in comparison to simple model. In Table 6.4 is shown final results in which are solved the values U in two consecutive till the values of U fall up to ±40% range. This model shows that the bled vapor flow rates are 0.0384 kg/s from stream V'_3. The total rate of evaporation is 11.901 kg/s. The SC and SE are obtained 1.473kg/s and 5.363.

Tab.- 6.4 Results for the SEE system with considered vapor bled from third effect.

Effect No.	1	2	3	4	5	6	7
U, kW/m^2 ^{o}C	0.218	0.537	0.238	0.635	0.829	0.584	0.767
L , kg/s	3.710	6.888	7.198	8.003	9.057	10.985	12.755
X	0.386	0.264	0.253	0.228	0.202	0.168	0.144
Ƭ, ^{o}C	4.723	2.649	2.492	2.151	1.824	1.436	1.190
Amount of vapor bled, kg/s			0.0384				
T, ^{o}C	118.712	135.271	94.869	81.385	79.182	63.134	52.000

Table 6.4 shows that the effect from 1to 7 are located at the temperature 118.712, 135.271, 94.869, 79.182, 63.134 and 52°C. According to the model, the effects dependent on the temperature. The temperature of effect 1 is lower than that of effect 2. Then on moving towards effect 7, the temperature keeps on decreasing, the effect from 1 to 7 is situated at overall heat transfer coefficient 0.218, 0.537, 0.238, 0.635, 0.829, 0.584 and 0.767. In this model, the effect from1to 7 varies different overall heat transfer coefficient

6.5.1COMPARISON BETWEEN SIMPLE MODEL AND MODEL CONSIDERED VAPOR BLED FROM THIRD EFFECT

Figure 6.9 developed the comparison between the previous model and. the considering vapor bled generated in third effect model. In this model, the considered vapor bled from third effect model is better than the previous. So the SE and SC of the considered vapor bled from third effect model is 21.11% more than the steam economy and 22.73% less steam consumption. The PC of the previous model is more than the considered vapor bled vapor from third effect.

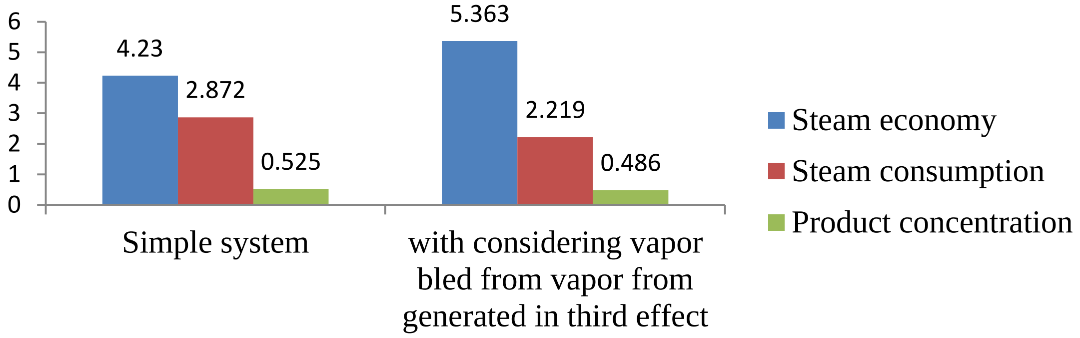

Fig.6.9: Variation between simple system with considered vapor bled from third effect.

6.6. SEVEN EFFECT EVAPORATOR SYSTEM CONSIDERING VAPOR BLED FROM VAPOR GENERATED IN FOURTH EFFECT

In this case single pre-heater is placed between 5thand 6theffect in which vapor bled from from fourth effect is used. Consequently, liquor stream, L5, is heated from T6 to T5. The schematic of the present system is shown in Fig. 4.8. The present configuration and model is referred as Conf-5 and Mod-7. Table shows that total evaporation is 11.709 kg/s and 12.150kg/s for simple system. While evaporation rate is reduced from vapor bleeding, it is found to be by consuming 2.333 kg/s of steam. This is 18.76 % lesser comparison than that of simple model. This model shows that the bled vapor flow rates are 0.0185 kg/s from stream V'_4.The evaporation rate is 5.018 kg/s. The SC and SE are 1.536 kg/s and 5.018.

The effect from 1to 7 are located at the temperature 103.068, 131.560, 96.794, 88.436, 70.852, 66.259 and 52°C as shown in Figure 6.10. In this model, According to the model, the effects dependent on the temperature. For first two effect viz. effect1 and effect2 temperature rises from effect1 to effect2 and then from effect2 to effect7 temperature decreases consistantly.

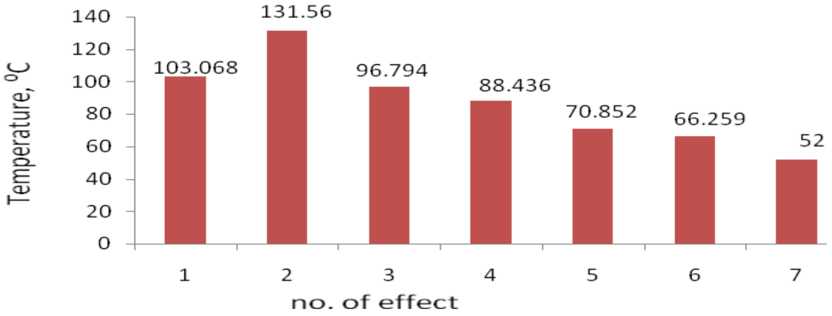

Fig.6.10: variations between temperature and effects in considered vapor bled from fourth effect.

In the figure 6.11 it is shown that the effect from 1 to 7 has values of overall heat transfer coefficient as 0.213, 0.460, 0.272, 1.012, 0.498, 1.884 and 0.617 kW/m^2°C. In this model, the effect from1to 7 varies different overall heat transfer coefficient

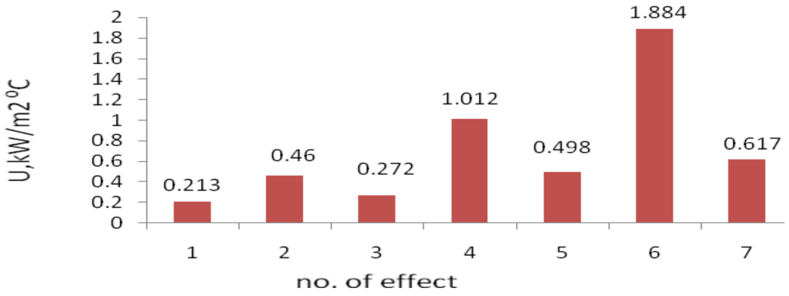

Fig.6.11: variations between U and effect in considered vapor bled from fourth effect.

6.6.1COMPARISON BETWEEN SIMPLE MODEL AND MODEL CONSIDERED VAPOR BLED FROM FOURTH EFFECT

Figure 6.12 developed the comparison between the previous model and the considering vapor bled from fourth effect model. In this model, the considering vapor bled generated in fourth effect model is better than the previous. So the SE and SC of the considered vapor bled from fourth effect model is 15.70% more than the SE and 18.76 % lesser SC. The PC in simple system and considered vapor bled from fourth effect is approximately equal.

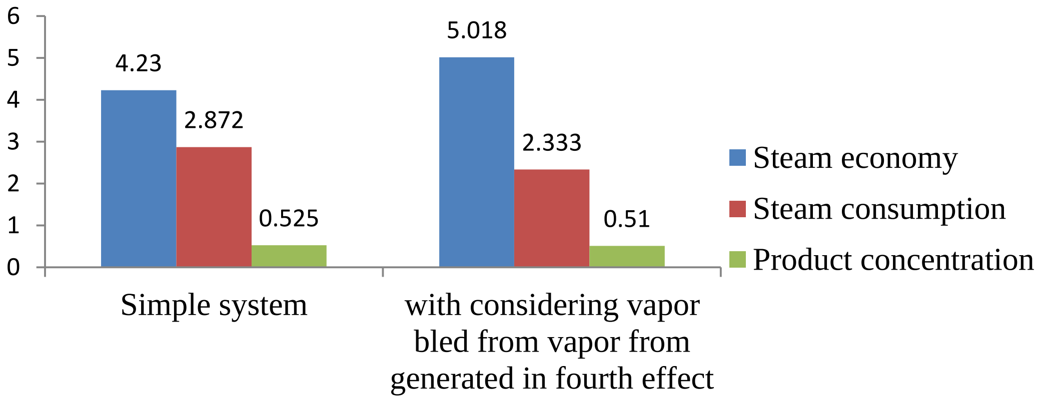

Fig.6.12: Comparison of simple system with considering vapor bled from vapor generated in fourth effect.

6.7. SEVEN EFFECT EVAPORATOR SYSTEM CONSIDERING VAPOR BLED FROM VAPOR GENERATED IN FIFTH EFFECT

A pre-heater is placed between 6thand 7th effect where vapor bled from 5theffect is used as heating medium. The schematic of the system is shown in Fig. 4.9. This configuration and respective model is named as Conf-6 and Mod-8. In this configuration liquor stream L6 is heated from T7 to T6.

Table 6.5 shows that total evaporation is 10.948 kg/s and 12.150 kg/s for present and simple system. While total evaporation rate is reduced with vapor bleeding, it is found by consuming 2.242 kg/s of steam. This is 21.93 % less in comparison to simple model. This model shows that the bled vapor flow rates are 0.2527 kg/s from stream V'_5. The evaporation rate is 10.948 kg/s. The SC and SE are obtained 1.422 kg/s and 4.883. Table 6.5 shows final results that are solved values U in two consecutive till value of U fall up to ±40% range.

Tab.- 6.5 Results for the SEE system with considered vapor bled from fifth effect.

Effect No.	1	2	3	4	5	6	7
U, kW/m^2 ^{o}C	0.224	0.490	0.276	0.499	0.825	0.799	0.691
L , kg/s	4.663	6.353	7.526	8.537	9.505	10.601	10.095
X	0.427	0.285	0.241	0.213	0.192	0.173	0.152
Ƭ, ^{o}C	5.554	2.964	2.325	1.959	1.705	1.490	1.270
Amount of vapor bled, kg/s					0.2527		
T, ^{o}C	103.569	133.173	99.007	81.504	71.357	64.455	52.000

Table 6.5 shows that the effect from 1to 7 are located at the temperature 103.569, 133.173, 99.007, 81.504, 71.357, 64.455 and 52. The effects dependent on the temperature. For first two effect viz. effect1 and effect2 temperature rises from effect1 to effect2 and then from effect2 to effect7 temperature decreases consistantly, the effect from 1 to 7 is situated at overall heat transfer coefficient0.224, 0.490, 0.276,

0.499, 0.825, 0.799 and 0.691. In this model, the effect from1to 7 varies different overall heat transfer coefficient

6.7.1COMPARISON BETWEEN SIMPLE MODEL AND MODEL CONSIDERED VAPOR BLED FROM FIFTH EFFECT

Figure 6.13 developed the comparison between the previous model and the considered vapor bled from fifth effect model. In this model, the considered vapor bled from fifth effect model is better than the previous. So the SE and SC of the considering vapor bled from fifth effect model is 4.90% more than the SE and 21.93 % lesser SC. The PC in previous model and the considered vapor bled from fifth effect model is not equal.

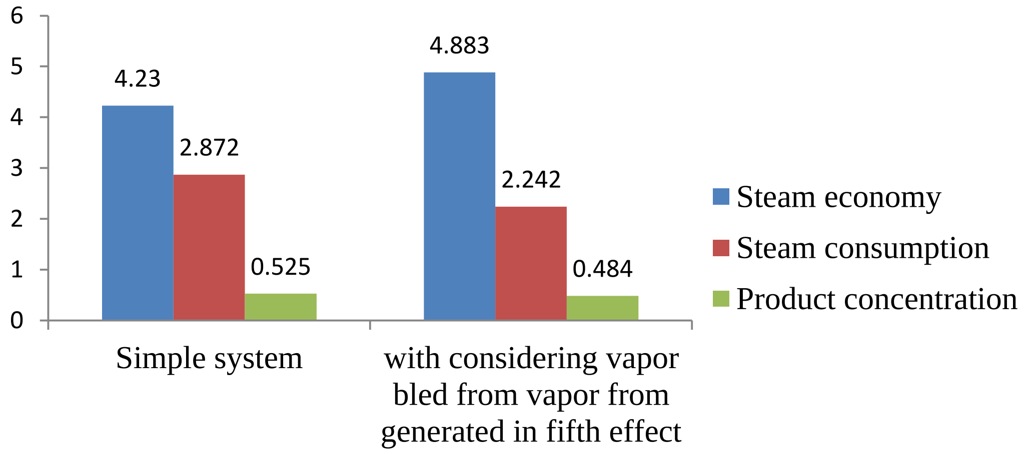

Fig.6.13: Comparison of simple system with considered vapor bled from fifth effect.

6.8 SEE SYSTEMS CONSIDERING PREHEATING OF LIQUOR USING CONDENSATE.

A pre-heater is placed between 2thand 7theffect. Instead of vapor bled, condensate is used which like heating medium. Here Condensate is employed to pre heat the black liquor, In this figure 4.10, the condensates of chest of 1st and 2nd (live steams) C01 and C02 are handled to pre heat the liquor which come from the 3rd and 4th effects. This respective model is named as Mod-9.In this model, total rate is 12.582 kg/s;

While, the rate is 12.150 kg/s for simple system. The SC and SE are obtained 2.097kg/s and 5.999.

Figure 6.14 shows that the effect from 1to 7 are located at the temperature 102.27to 52. According to the model, the effects dependent on the temperature. For first two effect viz. effect1 and effect2 temperature rises from effect1 to effect2 and then from effect2 to effect7 temperature decreases consistantly.

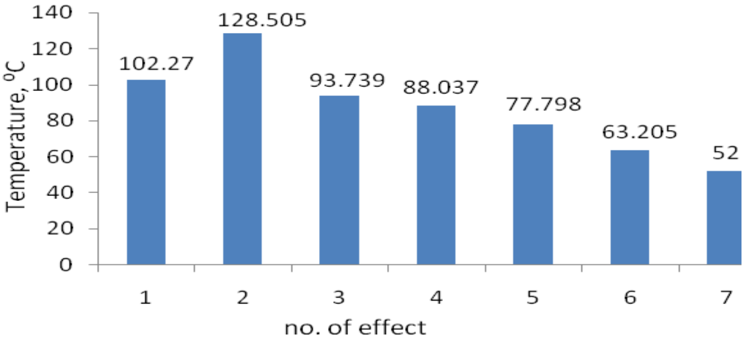

Fig.6.14: variations between temperature and effect in considering preheating of liquor using condensate.

The effect from 1 to 7 is situated at overall heat transfer coefficient 0.352, 0.592, 0.290, 1.306, 0.832, 0.606 and 0.762 as shown in Figure 6.15. In this model, the effect from1to 7 varies different overall heat transfer coefficient.

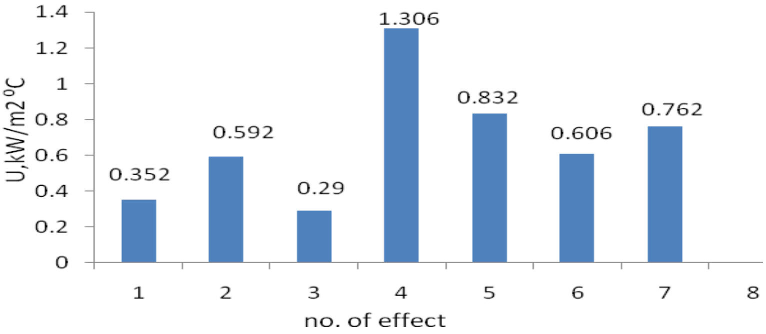

Fig.6.15: variations between U and effect in considering preheating of liquor using condensate

6.8.1COMPARISON OF MODEL CONSIDERED PREHEATING OF LIQUOR USING CONDENSATE WITH SIMPLE MODEL

Figure 6.16 developed the comparison between the previous model and the considered liquor preheating using condensate model. In this model, the considered liquor preheating using condensate model is better than the previous. So the SE and SC of the considered liquor preheating using condensate model is 29.48% more than the SE and 26.98 % decrease SC in compared of previous model. The PC in previous model and the considered liquor preheating using condensate model are not equal.

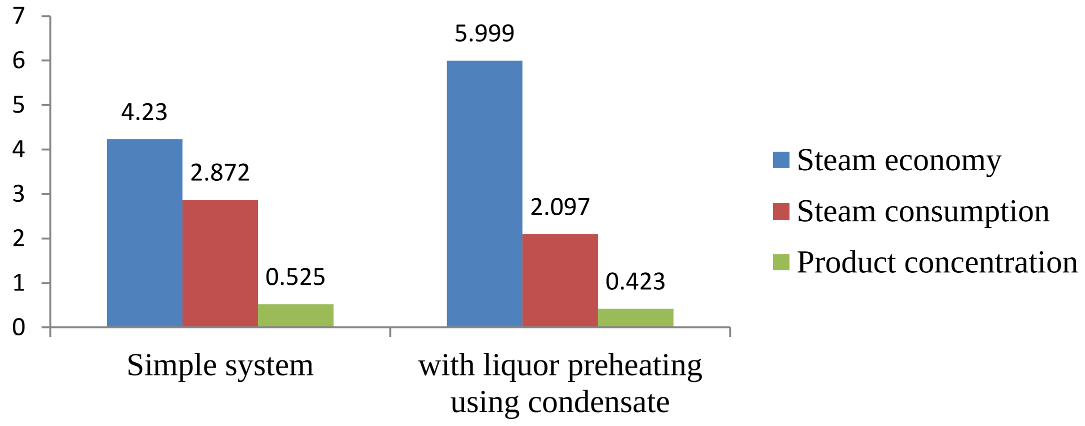

Fig. 6.16: Comparison between the previous model and considered liquor preheating using condensate.

6.9 TEE WITH VARIABLE STEAM SPLITTING, BPR AND PHYSICAL PROPERTIES

In actual scenario the properties of liquor continuously vary with temperature and concentration. Therefore, the present model of ten effects evaporator system, Mod-10, In Fig. 4.12, in this model live steam, divided equally in first and second effects is also accounted. The vapor exiting from 1st and 2ndeffects enter to third effect. By this method all iterations are determined. Till the values of U are < ± 30 % range. In this model, the SC and SE are 1.569kg/s and 7.730.

Table 6.6: Results of TEE system with variable steam splitting, C_P, Ƭ, U and λ

Effect No.	1	2	3	4	5	6	7	8	9	10
U, kW/m^2 °C	0.640	1.113	0.707	0.681	0.514	0.953	0.676	0.496	0.546	0.905
L , kg/s	11.54	12.04	14.74	15.65	16.43	22.83	21.64	19.46	18.73	17.93
X	0.329	0.313	0.255	0.240	0.229	0.165	0.174	0.193	0.201	0.210
Ƭ, °C	3.68	3.41	2.53	2.32	2.17	1.40	1.50	1.72	1.81	1.92
T, °C	128.2	134.5	117.1	102.4	97.2	92.61	82.87	72.07	64.48	57.60

Table 6.6 indicates that the effects dependent on the temperature. For first two effect viz. effect1 and effect2 temperature rises from effect1 to effect2 and then from effect2 to effect7 temperature decreases consistantly.

6.10 TEN EFFECT EVAPORATOR SYSTEM WITH VAPOUR BLEEDING

Mod-10 is modified model and named as Mod-11. Fig. 4.13 is four pre-heaters placed between 3rd and 4thand so on till 10theffects. The rate is 11.866 kg/s. The SC and SE are obtained 1.471 kg/s and 8.066. It is solved the values U in two consecutive till the values of U fall up to ±30% range.

In the figure 6.17, it is shown that the effect from 1 to 10 are located at the temperature 127.80 to 57.6. According to the model, the effects dependent on the temperature.the temperature of effect 1 is lower than that of effect 2. Then on moving towards effect 10, the temperature keeps on decreasing.

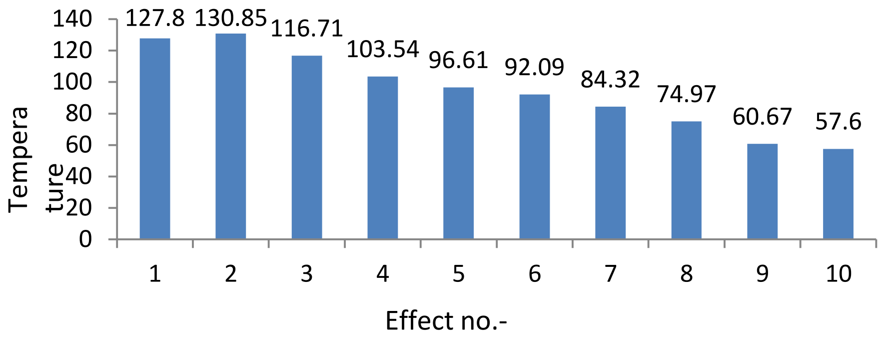

Fig.6.17: variations between temperature and effect in ten effect system with vapor bleeding

6.10.1 COMPARISON BETWEEN MODELS OF STEAM SPLITTING AND VAPOR BLEEDING IN TEN EFFECT SYSTEM

Figure 6.18 developed the comparison between the previous model and the vapor bleeding in ten effect system. In this model that the vapor bleeding in ten effect system is better than the previous. So the SC and SE of the vapor bleeding in ten effect system is 4.34 more than the SE and 6.66 % decrease SC in compared of previous model. The product concentration in the previous and vapor bleeding in ten effect system is around equal.

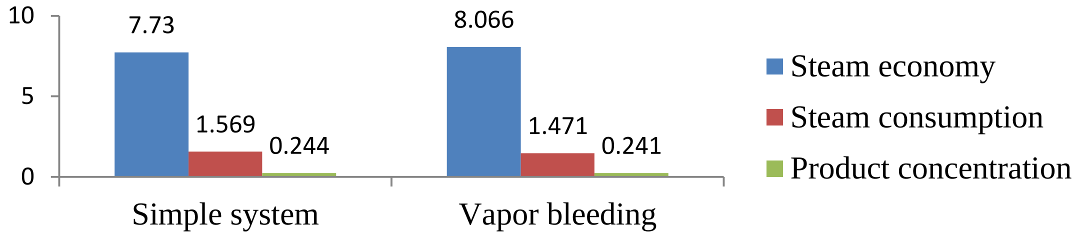

Fig. 6.18: Comparison between models of steam splitting model and vapor bleeding in ten effect system

Summarize model:-

Table 6.7 shows that numbers of models is 11, in which best model in seven and ten effect evaporator systems are Mod-9 and Mod-11, respectively. Because of the steam economy for best model in SEE is more in comparison to that of other eight models. The SE for best model in SEE is 5.999, whereas that TEE system is 8.099. Thus, Mod-9 and Mod-11 are selected as best models in the present study.

Table no.6.7 Model details for seven and TEE systems.

S. No.	Model details	Model no.	Economy
1	SEE (Simple seven effect system for backward flow)	Mod-1	4.230
2	SEE system for variable steam splitting , C_p, Ꚍ, U and λ	Mod-2	4.334
3	SEE system for vapor bleeding (confi-1).	Mod-3	4.774
4	SEE system for vapor bleeding (confi-2).	Mod-4	4.937
5	SEE system for considered vapor bled from second effect	Mod-5	5.598
6	SEE system for considered vapor bled from third effect	Mod-6	5.363
7	SEE system for considered vapor bled from fourth effect	Mod-7	5.018
8	SEE system for considered vapor bled from fifth effect	Mod-8	4.883
9	SEE system with considered preheating of liquor	Mod-9	5.999

	using condensate.		
10	TEE system for variable steam splitting , C_p, Ƭ, U and λ	Mod-10	7.730
11	TEE system for vapor bleeding	Mod-11	8.066

6.11 SCHEMATIC OF MOD-9 FOR SEE (SEVAEN EFFECT EVAPORATOR)

A pre-heater is placed between 2thand 7th effect as shown in Figure 6.19. Instead of vapor bled, condensate is used as heating medium in pre-heaters. Here Condensate is entering into pre-heater in counter current manner.

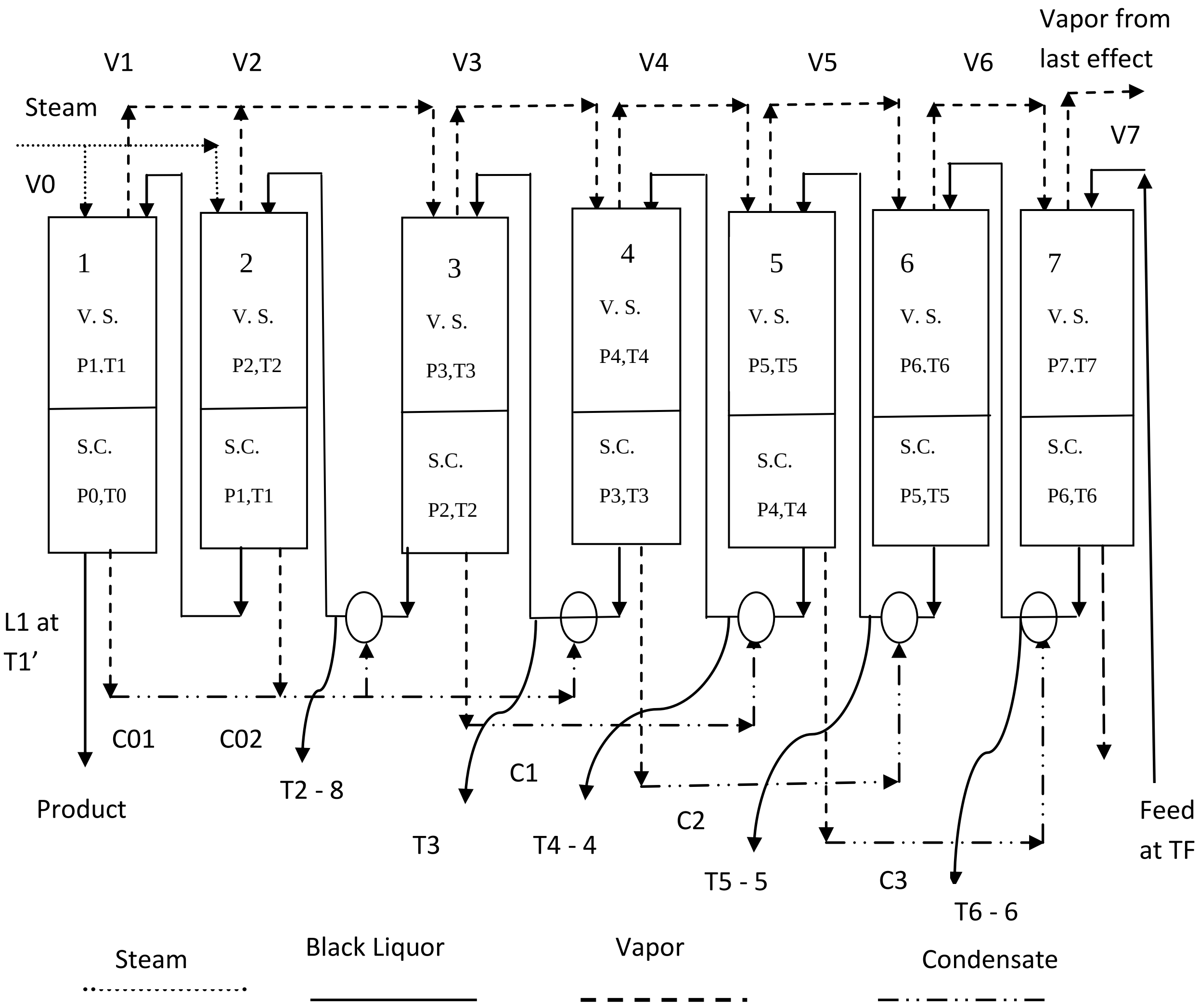

Figure 6.19: Schematic diagram of seven effect evaporator system best model (pre heating of liquor using condensate)

6.12 COMPARISON BETWEEN PUBLISHED MODEL AND BEST MODEL FOR SEVEN EFFECT EVAPORATOR SYSTEM

Figure 6.20 shows the comparison between the published model ***(Bhargava et al. 2008)*** and the best model found in the present work for seven effect evaporator system. When the steam economy is calculated for best model it is found as 7.151% more than that of published model and steam consumption is 1.917% lesser in comparison to the published model. The PC (product conc.) of best models is 21.66% less than that of published.

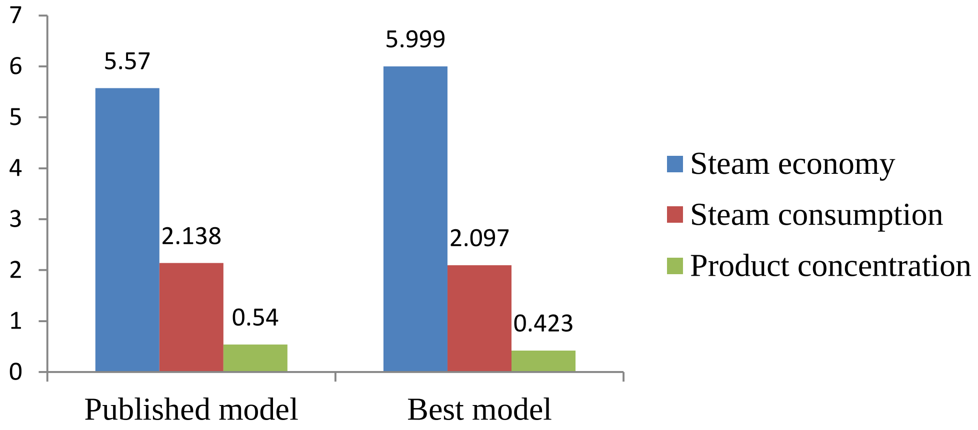

Fig. 6.20: Comparison between the published model and the best model for seven effect evaporator system.

6.13 SCHEMATIC OF MOD-11 FOR TEE (TEN EFFECT EVAPORATOR)

In mill, the ten effect evaporator is handled to withdrawn for black liquor. These effects are FFEs system. This model is found a by- product of the raw material digesting system. These are obtained raw wood compound by disaster process.

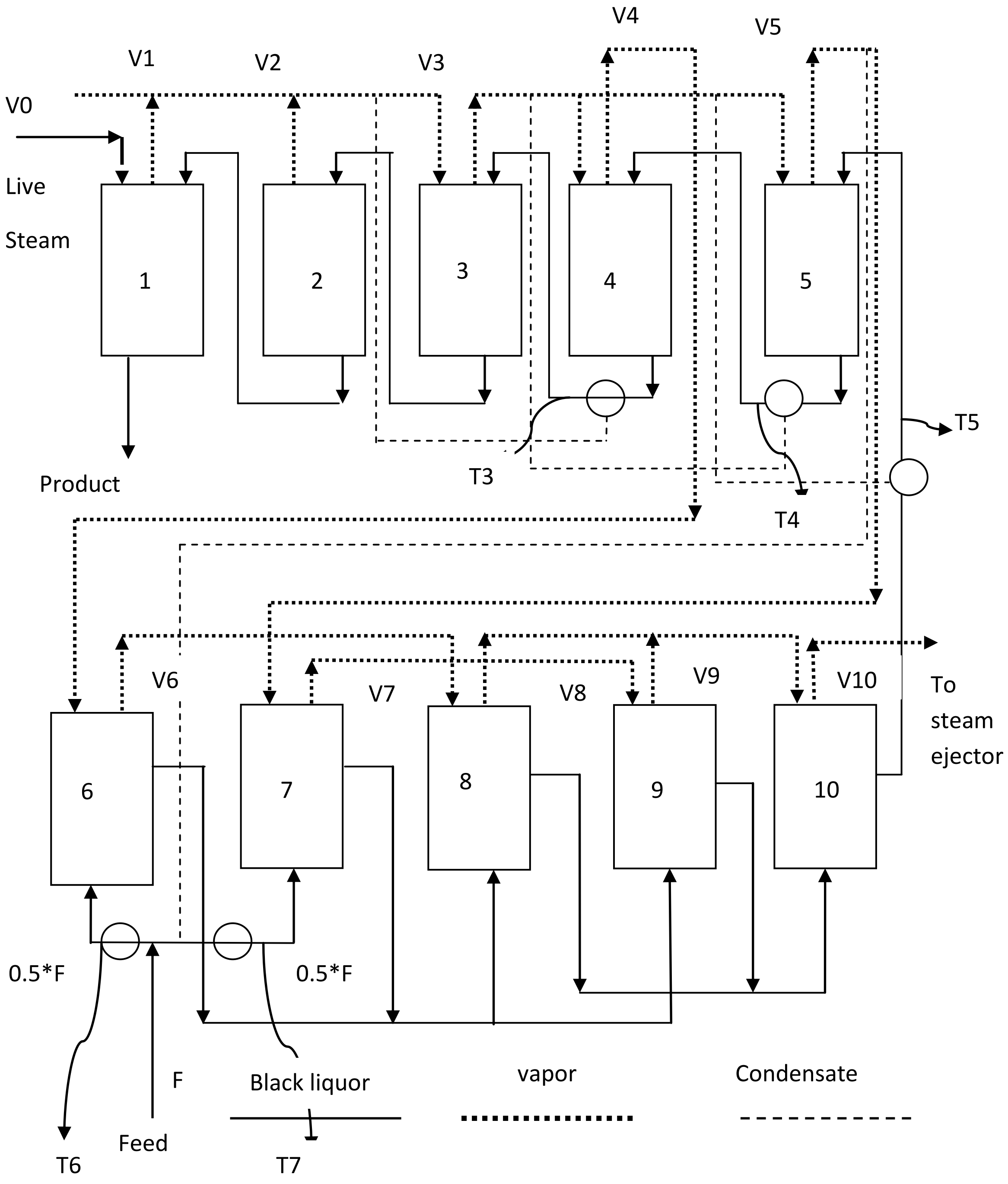

Figure 6.21: Schematic diagram of ten effect evaporator system

6.14 COMPARISON BETWEEN PUBLISHED MODEL AND BEST MODEL FOR TEN EFFECT EVAPORATOR SYSTEM

Figure 6.22 shows the comparison between the published model ***(Mohanty et al. 2010)*** and the best model found for ten effect evaporator system. The SE and SC is found as 14.31% more and 40.27% less, respectively, in comparison to that for published model

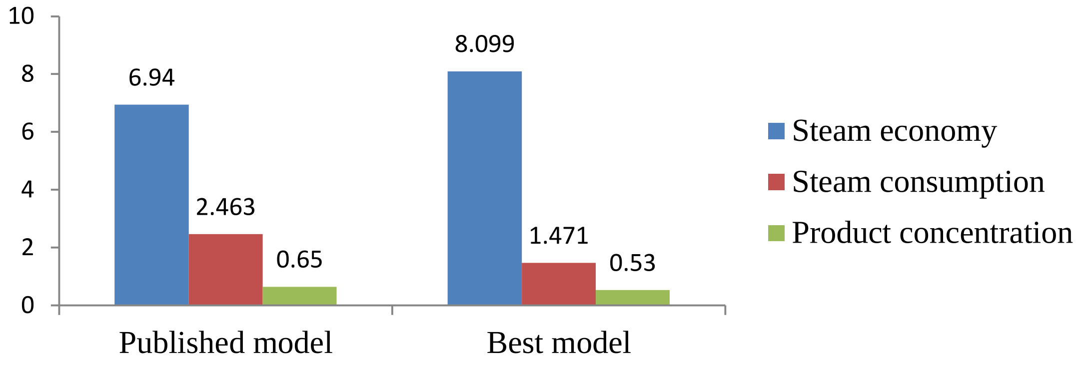

Fig. 6.22: Comparison between the published model and the best model for ten effect evaporator system

CHAPTER 7

CONCLUSION

A mathematical model for a MEE is developed in present work. The mathematical model assumes the variation of thermo physical properties in the system.

The a few conclusions of this process are as below:

1-The model developed based on set of nonlinear equations, directs almost all difficulties of real MEE system such as variation in physical properties, BPR, steam splitting, feed, product and vapor bleeding, considering vapor bled from vapor generated in second, third, fourth, fifth and pre heating of liquor.

2-The economy of simple seven effects evaporator system is 4.230 which increase by 17.75%, 14.44%, 24.37%, 14.90, 15.70, 21.11, 24.37 and 29.48% by inducting steam splitting, first configuration of vapor bleeding, considering vapor bled from vapor generated in second configuration of vapor bleeding, considering vapor bled from vapor generated in fifth, fourth, third, second effects and pre heating of liquor with condensate.

4-The confi-1 and confi-2 for vapor bleeding in SEE systems is assumed and also done comparison. These show that SE for confi-2 is more compared to confi-1.

5-Considered steam splitting in SEE, the steam economy is increased 17.75% and steam consumption is decreased 5.81% in comparison to simple system.

6-Considered the best configuration of vapor bleeding in seven effects evaporator system, the steam economy is increased 14.44% and steam consumption is decreased 18.36% in comparison to simple system.

7-Considered the vapor bled from vapor generated in second effect of seven effects evaporator system, the steam economy is increased 24.37% and steam consumption is decreased 24.09% in comparison to simple system.

8-Considered the vapor bled from vapor generated in third effect of seven effects evaporator system, the steam economy is increased 21.11% and steam consumption is decreased 22.73% in comparison to simple system.

9-Considered the vapor bled from vapor generated in fourth effect of seven effects evaporator system, the steam economy is increased 15.70 % and steam consumption is decreased 18.76% in comparison to simple system.

10-Considered the vapor bled from vapor generated in fifth effect of seven effects evaporator system, the steam economy is increased 14.90% and steam consumption is decreased 21.93% in comparison to simple system.

12-Considered the preheating of liquor with condensate in seven effects evaporator system, the steam economy increases 29.48% and steam consumption decreases 26.98% in comparison to simple system.

13-Liquor heating using sensible heat of condensate is used mostly to decrease steam consumption. Further, that obtains reduce complex MEE system in comparison to other model.

14- Considered TEE system, The SE increases 4.34% and SC decreases 6.66% in comparison to simple system

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APPENDIX

SAMPLE CALCULATION

Sample calculation for design of schematic diagram of seven effect evaporator system

1.1 The following data were considered operating parameters for the design of schematic diagram of seven effect evaporator system

S.NO.	Parameters	Values
1	Total no. of effects	7
2	Numbers of effects supplied with live steam	2
3	Feed flow rate of black liquor	56,200 kg/hr
4	Feed flow sequence	Backward
5	Vapor temperature of last effect	52 °C
6	Live steam temperature in effect 1	140 °C
7	Live steam temperature in effect 2	147 °C
8	Inlet concentration of black liquor	0.118
9	Inlet temperature of black liquor	64.7 °C
10	Area of 1st effect and 2nd effect	540 m^2
11	Area of 3rd effect and 6th effect	660 m^2
12	Area of 7th effect	690 m^2

1.2 Equal temperature drop and equal vaporization in each effect were considered to solve temperatures and liquor flow rates for each effect in the design of schematic diagram of seven effect evaporator system.

Equal temperature:

$\Delta T = \frac{Ts - T7}{n}$

ΔT = (140 -57)/7 = 12.57 °C

T1 = Ts - ΔT = 140 – 12.57 = 127.43°C

T2 = T1 - ΔT = 127.43 – 12.57 = 114.86 °C

T3 = T2 - ΔT = 114.86 – 12.57 = 102.28 °C

T4 = T3 - ΔT = 102.28 – 12.57 = 89.714 °C

T5 = T4 - ΔT = 89.714 – 12.57 = 77.143 °C

T6 = T5 - ΔT = 77.143 – 143 = 64.57 °C

The overall component balance

F*xf =L1*x1

L1 = (F*xf)/x1 = (15.611*0.118)/0.6 = 3.07 kg/s

Equal vaporization was assumed

V1= V2 = V3 = V4 = V5 = V6 =V7 = ((F – L1)/n) = ((15.611- 3.07)/7)

= 1.792 kg/s

L7 = 15.611 -1.792 = 13.82 kg/s

L6 = 13.82 – 1.792 = 12.03 kg/s

L5 = 12.03 – 1.792 = 10.236 kg/s

L4 = 10.236 – 1.792 = 8.44kg/s

L3 = 8.44 – 1.792 = 6.653kg/s

L2 = 6.653 – 1.792 = 4.862kg/s

1.3 Calculation of composition of liquor, boiling point rise, specific heat, heat of vaporization and overall heat transfer coefficient

Composition of the liquor:

$X7 = (15.611*0.118)/13.82 = 0.133$

$X6 = (13.82*0.133)/12.03 = 0.153$

$X5 = (12.03*0.153)/10.236 = 0.180$

$X4 = (10.236*0.180)/8.44 = 0.218$

$X3 = (8.44*0.218)/6.653 = 0.276$

$X2 = (6.653*0.276)/4.862 = 0.377$

X1 = 0.6 (given data)

Boiling point rise:

Ʊ7 = $20*(0.1$ Ʊ7$+ 0.133)^2 = 1.0886^{o}C$

Ʊ6 = $20*(0.1$ Ʊ7$+ 0.153)^2 = 1.280^{o}C$

Ʊ5 = $20*(0.1$ Ʊ7$+ 0.180)^2 = 1.568^{o}C$

Ʊ4 = $20*(0.1$ Ʊ7$+ 0.218)^2 = 2.022^{o}C$

Ʊ3 = $20*(0.1$ Ʊ7$+ 0.276)^2 = 2.827^{o}C$

Ʊ2 = $20*(0.1$ Ʊ7$+ 0.377)^2 = 4.550^{o}C$

Ʊ1 = $20*(0.1$ Ʊ7$+ 0.118)^2 = 9.80^{o}C$

Specific heat:

$Cp_7 = 4.187*(1- 0.54*0.133) = 3.885$ kJ/kg K

$Cp_6= 4.187*(1- 0.54*0.153) = 3.841$ kJ/kg K

$Cp_5 = 4.187*(1- 0.54*0.180) = 3.780$ kJ/kg K

$Cp_4 = 4.187*(1- 0.54*0.218) = 3.694$ kJ/kg K

$Cp_3 = 4.187*(1- 0.54*0.276) = 3.362$ kJ/kg K

Cp_2 = 4.187*(1- 0.54*0.377) = 3.330 kJ/kg K

Cp_1= 4.187*(1- 0.54*0.6) = 2.830 kJ/kg K

Heat of vaporization:

$\lambda 7 = (-0.0028*52^2) – (2.1207*52) +2496.1 = 2378.25$ kJ/kg

$\lambda 7 = (-0.0028*64.571^2) – (2.1207*64.571) +2496.1 = 2347.49$kJ/kg

$\lambda 7 = (-0.0028*77.143^2) – (2.1207*77.143) +2496.1 = 2315.84$ kJ/kg

$\lambda 7 = (-0.0028*89.714^2) – (2.1207*89.714) +2496.1 = 2283.30$ kJ/kg

$\lambda 7 = (-0.0028*102.286^2) – (2.1207*102.286) +2496.1 = 2249.88$ kJ/kg

$\lambda 7 = (-0.0028*114.857^2) – (2.1207*114.857) +2496.1 = 2215.58$ kJ/kg

$\lambda 7 = (-0.0028*127.429^2) – (2.1207*127.429) +2496.1 = 2180.39$kJ/kg

Difference of temperatures:

ΔT7 = (64.57 – 52 – 1.0886) = 11.48°C

ΔT6 = (77.143 – 64.57 – 1.282) = 11.291°C

ΔT5 = (89.714 – 77.143 – 1.567) = 11.004°C

ΔT4 = (102.286 – 89.714 – 2.024) = 10.548°C

ΔT3 = (114.857 – 102.286 – 2.841) = 9.730°C

ΔT2 = (140 – 114.857– 4.587) = 20.556°C

ΔT1 = (140 – 127.429 – 9.800) = 2.771°C

Average of the liquor:

F7 = (15.611+ 13.82)/2 = 14.716 kg/s

F6 = (13.82 + 12.028)/2 = 12.924 kg/s

F5 = (12.028 + 10.236)/2 = 11.132 kg/s

F4 = (10.236 + 8.444)/2 = 9.340 kg/s

F3 = (8.444 + 6.653)/2 = 7.5485 kg/s

F2 = (6.653 + 4.861)/2 = 5.757 kg/s

F1 = (4.861 + 3.070)/2 = 3.9655 kg/s

Average of the composition:

X7 = (0.118 + 0.133)/2 = 0.1255

X6 = (0.133 + 0.153)/2 = 0.1430

X5 = (0.153 + 0.180)/2 = 0.1660

X4 = (0.180 + 0.218)/2 = 0.1990

X3 = (0.218 + 0.277)/2 = 0.2475

X2 = (0.277 + 0.379)/2 = 0.3280

X1 = (0.379 + 0.600)/2 = 0.4895

Overall heat transfer coefficient:

$U_7/2$= 0.1369*((11.48/40) ^ (-0.7949))*((0.1255/0.6) ^ 0.0)*((14.716/25) ^ 0.1673)
U7 = 0.689 kW/m^2 K

$U_6/2$= 0.1369*((11.291/40) ^ (-0.7949))*((0.143/0.6) ^ 0.0)*((12.924/25) ^ 0.1673)

U6 = 0.683 kW/m^2 K

$U_5/2$= 0.1369*((11.004/40) ^ (-0.7949))*((0.166/0.6) ^ 0.0)*((11.132/25) ^ 0.1673)

U5 = 0.680 kW/m^2 K

$U_4/2$ = 0.1369*((10.548/40) ^ (-0.7949))*((0.199/0.6) ^ 0.0)*((9.340/25) ^ 0.1673)

U4 = 0.683 kW/m^2 K

$U_3/2$ = 0.1369*((9.730/40) ^ (-0.7949))*((0.247/0.6) ^ 0.0)*((7.548/25) ^ 0.1673)

U3 = 0.7029 kW/m^2 K

$U_2/2$= 0.0604*((20.566/40) ^ (-0.3717))*((0.328/0.6) ^ (-1.2273))*((5.757/25) ^ 0.0748)

U7 = 0.2609 kW/m^2 K

$U_1/2$= 0.0604*((2.771/40) ^ (-0.3717))*((0.489/0.6) ^ (-1.2273))*((3.965/25) ^ 0.0748)

U7 = 0.3640 kW/m^2 K

Table 1: Sample calculation for other effects

Effect no.	Flow rate (kg/s)	Temp (°C)	BPR	X	Cp (KJ/kg K)	λ (kg/s)	U (KW/m^2 K
1	3.070	127.429	9.800	0.600	2.830	2180.39	0.364
2	4.861	114.857	4.587	0.379	3.330	2215.58	0.260
3	6.653	102.286	2.841	0.277	3.561	2249.88	0.702
4	8.444	89.714	2.024	0.218	3.693	2283.30	0.683
5	10.236	77.143	1.567	0.180	3.780	2315.84	0.680
6	12.028	64.571	1.282	0.153	3.840	2347.49	0.683
7	13.819	52.000	1.088	0.133	3.885	2378.25	0.689