Estimation of Energy Gains through Modelling and Simulation of Multiple Effect Evaporator System in a Paper Mill

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In this present investigation comparisons between split feed with and without condensate flash and product flash are attempted. As usual the models are based on steady state mass balance, enthalpy balance and heat transfer rate equations interlinked with overall heat transfer coefficient obtained from Gudmundson's model (12) and suitable correlations of physicothermal properties of black liquor as well as the BPR values as a function of temperature and concentration. A programme is developed in FORTRAN-77 language. The numerical techniques used is Newton-Raphson method with Jacobian matrix and method of Gauss elimination with partial pivoting supplemented with LU decomposition with the aid of Hilbert norms. The gain in SE, reduction in SC and area requirement are quantitatively estimated. The algorithm developed is general in nature which can be used for any other sequences practiced in Indian mills with the required modification. Anticipated steam saving is cited.

INTRODUCTION

Mathematical models are important, now a days, for optimization, simulation and control of any process and operation of any industry. A very few models on evaporator operation are available in literature on these topics. Kern (1) has given a model for concentration of a commercial soda black liquor from a paper mill. Later Mathur(2) and Goel (3) also developed models and solved the problems for kraft black liquor concentration using the procedures documented in Holland (4). All the above works suffer from many limitations, someway or the other and do not, in fact, take care of simulation of multiple effect evaporator (MEE) system practiced in paper industry. In Mathur's works condensate falsh utilization is not incorporated whereas Goel' s design is based on backward feed sequence with no return of condensate from first body which is invariably used as boiler feed water. Though Kern's models is good he used a very weak soda liquor instead of kraft black liquor as feed to a six effect evaporator system. In addition, he has solved the problem by trial and error (Badger-McCabe) method. There are limitations of this method as every time when there are changes of sequences or variation in input data, exhaustive trial and error calculations need to be done. No general correlation of physico-thermal properties of overall heat transfer coefficient (U) is used. Hence it can not be employed for general design. However, it appears that the data of physico-thermal properties of soda liquor are of experimental origin and U, values are reported from a working soda mill. Therefore, the data are expected to be reliable and the design is correct for this specific system only. Numerical techniques, using computer programme, on the other hand, is flexible and can accommodate any change in the system, less time consuming, can give sufficient accuracy, generate large number of data and can handle any system for any industry. Holland's data are far from satisfactory as far as kraft black liquor is concerned. Besides, the data of physico-thermal properties and overall heat transfer coefficient (U) are assumed constant in order to demonstrate the applicability of Newton-Raphson method. Singh(5) has developed steady state mathematical models for both backward feed and split feed sequences for kraft black liquor. In order to develop models, optimum number of effects has been determined with annual cost minimizing scheme following the general models proposed by Ray (1). Models are developed for various sequences in a effect evaporator system. These are validated with the Kern's data for soda liquor for a system of six body evaporator. The systems are simulated with the range of input data globally used by the pulp and paper mills including India. Some of the results are already published in literature(7 -10). In this present investigation, a part of the research work is presented, that is a comparison between the split feed with and without flashing of condensate plus product flash on steam consumption, steam economy and area requirement. Therefore, this present study is an extension of the previous work. Split feed indicates a backward feed sequence where the feed is splitted and distributed equally to the last two bodies. This is considered on priority as it has been established in previous publications (7-10) that this sequence is better than truly backward feed sequence in terms of energy saving. Also many North American mills use this sequence. In this present study correlations of physico-thermal properties are taken from Ray et. al (11) and the overall heat transfer coefficient from Gudmundson's model (12) for simulation.

Analysis of the System

The modeling usually starts with identifying the degree of freedom arising out of the total number of variables and number of correlated equations. It is a fact that the number of evaporator bodies in MEE is to be identified before approaching for modeling. In earlier communication (7), it has been estimated that based on current market prices sextuple effect evaporator system is the right set for Indian conditions. Once it is found out, the next step is to evaluate the number of equations required per evaporator body. Generally, there are four equations such as component mass balance, heat transfer equations and equilibrium relationship for BPR for a single effect. Therefore, for sextuple effect evaporator, 25 equations including overall heat mass balance are required. This has excluded the equations for heat transfer coefficient and physico-thermal properties for black liquor with and without considering the condensate flash and product flash. In our study, the BPR and physico-thermal properties (11) are separated and put in a subprogramme. Overall mass balance equations and also component mass balance equations, L_iX_i are included in the main programme in terms of liquor flow rates. Therefore, the number of equations without flashing for split feed will be again 12 but with condensate flash, it will be 17. When flashing from product is added the number of equations will be 18. However in this present study, product flash is separately estimated. Slight variation of temperature of product from that of the same body to which this flash vapour is directed does not affect the value too much. Therefore, without erring widely this flash vapour, being not very sensitive to these changes, can be assumed as constant value. Hence equations even with product flash remains only 17 in numbers.

Modelling

The modeling will be more meaningful if certain case studies are made based on industrial MEE system. The detailed mathematical model of sextuple effect evaporator system with split feed is given in earlier publication (8). The algorithm for Gudmundson's model has also been shown therein. In this investigation only the studies on split feed and the same with condensate flash and product flash are considered more elaborately and as accurate as possible. These are shown in diagram (Appendix-I). The details of the development of models are depicted in Appendix-II. It is evident that for simple split feed there are 12 equations in 12 unknowns (case-I) 'without considering flash vapour, whereas for flash utilization case, the number of equations have been included to 17 in 17 unknowns (Case-II & Case III). These sequences are abundant in practice, especially in North American mills. For better understanding of the model solution, a logical sequence (Appendix-III) is presented here indicating the mathematical sequences,

Table -1 Parameters for MEE systems

Parameter	Range	Target Value
Steam Temperature, Ts, °C	130-140	137.78
Feed Temperature, T_f,°C	70-80	76.67
Last Effect Temperature, T_n, °C	50-60	51.67
Feed Concentration, X_f	0.12-0.16	0.152
Feed Flow Rate, F, kg/s	18-28	18.144

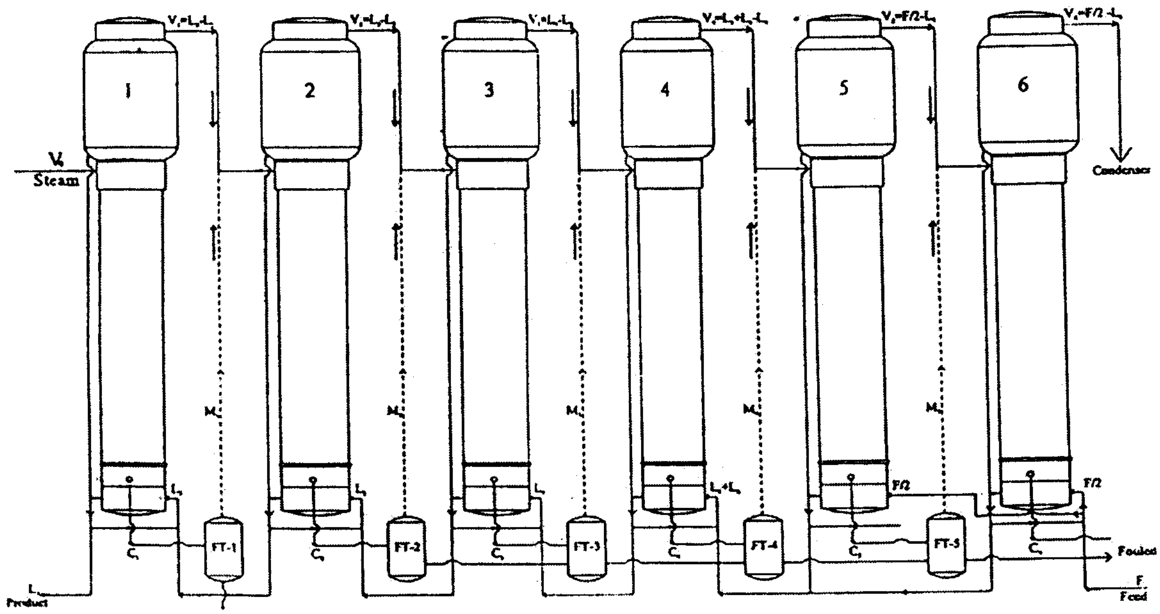


Fig.1A

Sextuple Effect Evaporator System With Split Feed and With Condensate Flash Tank

$\left(\begin{smallmatrix}5\\6\end{smallmatrix}\!>4\rightarrow3\rightarrow2\rightarrow1\right)$

that are involved.

Solution on the Model

Like in the previous work, the Newton-Raphson method with Jacobian-matrix and Gauss elimination with partial pivoting and LU decomposition with Hilbert norms as the parameter for convergence are used. The scaling techniques are also shown therein.

As indicated, present mathematical models involve 17 non-linear algebraic equations which are difficult to solve to achieve reasonable accuracy within limited time.However, using the same techniques, it is possible to solve even these set of 17 non-linear equations. For simulation purpose of different cases the following data are used.

The above set of data agrees quite well within the limit of present practice in pulp and paper mill. The results of simulation are discussed here under for the following purposed options.

Options

- D ⟶ Split feed only
- E ⟶ Split feed with flashing of condensate

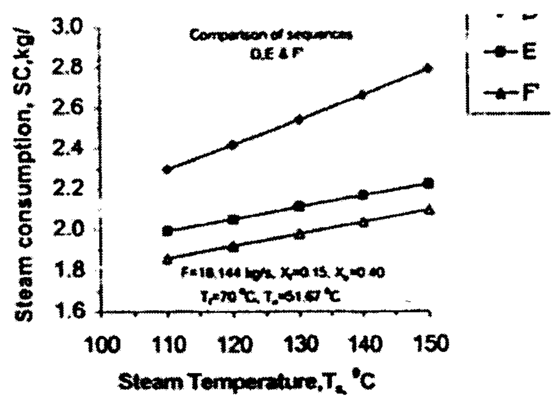


Fig-1 Influence of Steam Temperature on Steam Consumption

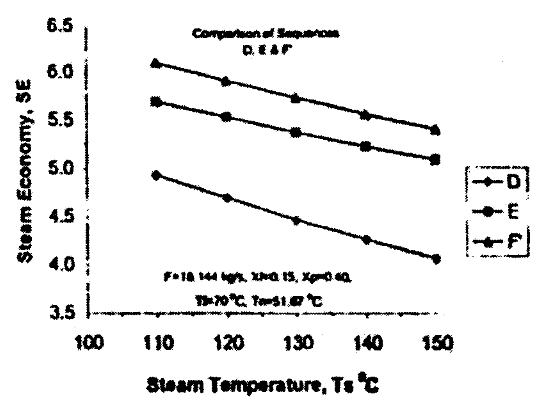


Fig-2 Influence of Steam Temperature on Steam Economy

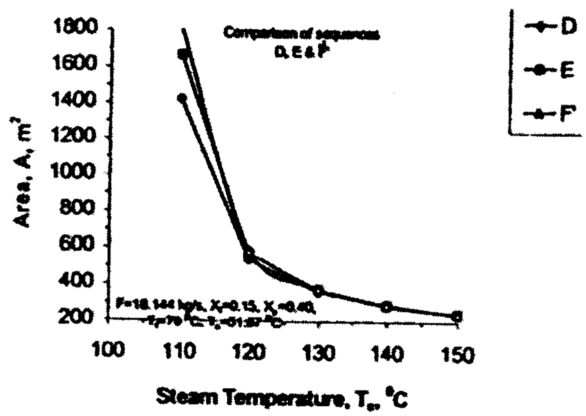


Fig-3 Influence of Steam Temperature on Area

- F′ ⟶ Split feed with flashing of condensate & product flash.

RESULTS AND DISCUSSION

Comparison of Steam Consumption, SC, Steam Economy, SE and Area, A .

Fig. 1-15 are drawn for only split feed sequence (D), split feed with condensate flash (E) and split feed with condensate flash plus product flash (F) to show the effect of various input parameters on SC, SE and A: The operating conditions are depicted in Table 1.

APPENDIX - II

The case studies presented here is a Sextuple effect backward MEE with feed splitted and equally distributed to sth and. 6th bodies of evaporator set.

1. Case-I: Mathematical model for a sextuple effect evaporator system with spilt feed:

$$(5>4\longrightarrow 3\longrightarrow 2\longrightarrow 1)$$
$$6$$

For the design procedure of a sextuple effect evaporator system with split feed sequence as shown in the above structure, the model gives rise to a set of 12 independent nonlinear algebraic equations in 12 unknowns.

For the 1st effect

$$g_1 = l_2\, Ts\{CP_2 (u_2 + BPR_2/Ts) - CP1 (u_1 + BPR_1/Ts)\} /\lambda s + v_0 (\lambda_0 + CPv\, BPR_0)\, \lambda s - (l_2-l_1)$$
$$\{(\lambda l + CPv\, BPR_1) - CP_1\, Ts\, (u_1+BPR_1/Ts)\} /\lambda s - (l_2-l_1)\, (\alpha u_1 + \beta/Ts)\, Ts/ \lambda s \quad \ldots(1)$$

$$g_2 = U_1\, Ts\, a_1\, \{1.0- (u_1 +BPR_1/Ts) \}/50.\lambda s - v_0(\lambda o + CPv\, BPR_0) /\lambda s \quad \ldots(2)$$

For the IInd & IIIrd effect

$$g_i = l_{n+1}Ts\{CPn+l\, (un+1 + BPR_{n+1}/Ts) - CPn\, (u_n + BPR_n/Ts)\} /\lambda s +(l_n-l_{n-1})\, (\lambda n\text{-}1+CPv\, BPRn\text{-}1)/\lambda s$$
$$- (l_{n+1}-l_n)\, \{(\lambda_n + CP_v\, BPR_n) - CP_n\, T_s(u_n+BPR_n/T_s)\}/\lambda s - (l_{n+1}-l_n)\, (\alpha u_n + \beta/T_s)\, T_s/\lambda_s \quad \ldots(3)$$

$$g_{i+1}= U_n\, T_s\, a_n\, \{ u_{n-1}\, (u_n+BPR_n/T_s)\}/50.\ \lambda_s-(l_n-l_{n-1})(\lambda_{n-1}+CP_v\, BPR_{n-1})/\lambda_s \quad \ldots(4)$$

(i=3 S . n=2 3

For the IVth effect

$$g_7 = l_5\, T_s\{CP_5\, (u_5 + BPR_5/T_s) -CP_4\, (u_4 + BPR_4/T_s) \}/\lambda s +l_6\, T_s\{CP_6\, (u_6 + BPR_6/T_s) -$$
$$CP_4\, (u_4 +BPR_4/T_s)\}/\lambda_s+(l_4-l_3)(\lambda_3+ CP_v\, BPR_3)/\lambda_s - (l_5 + l_6-l_4)\{(\lambda_4 +CP_vBPR_4) -$$
$$CP_4T_s\, (u_4+BPR_4/T_s)\}/\lambda_s-(l_5+l_6-l_4)\, (\alpha u_4+\beta/T_s)\, T_s/\lambda_s \quad \ldots(5)$$

$$g_8= U_4\, T_s\, a_4\, \{u_3\text{-}(u_4+BPR_5/T_s)\}/50.\ \lambda_s-(l_4-l_3)(\lambda_3+CP_v\, BPR_3)/\lambda s \quad \ldots(6)$$

For the Vth effect

$$g_9 = 0.5T_s\{CP_f\, (u_f+ BPR_f/T_s) - CP_5(u_5 + BPR_5/T_5)\} /\lambda s +(l_5 +l_6 -l_4)\, (\lambda_4 + CP_v\, BPR_4) /\lambda_s$$
$$- (0.5 -l_5)\, \{(\lambda_5 + CP_v\, BPR_5) - CP_5\, T_s\, (u_5+BPR_s/T_s)\}/\lambda s - (0.5 -l_5)\, (\alpha u_5 + \beta/T_s)\, T_s/\lambda_s \quad \ldots(7)$$

$$g_{10} = U_5\, T_s\, a_5\, \{u_4\text{-}\, (u_5 +BPR_5/T_s)\} / 50.\ \lambda_s - (l_5 +l_6\text{-}\, l_4)\, (\lambda_4 + CP_v\, BPR_4)/\lambda_s \quad \ldots(8)$$

For the VIth effect

$$g_{11} = 0.5T_s\, \{CP_f(u_f+ BPR_f/T_s) - CP_6(u_6 + BPR_6/T_s)\}/\lambda_s +(0..5 -l_5)\, (\lambda_5 + CP_v\, BPR_5) /\lambda_s$$
$$- (0.5 -l_6)\, \{(\lambda_6 + CP_v\, BPR_6) - CP_6\, T_s\, (u_6+BPR_6/T_s)\} /\lambda_s - (0.5 -l_6)\, (\alpha u_6 + \beta/T_s)\, T_s/\lambda_s \quad \ldots(9)$$

$$g_{12} = U_6\, T_s\, a_6\{u_5\text{-}\, (u_6 +BPR_6/T_s)\} /50.\ \lambda_s - (0.5\text{-}\, l_5)\, (\lambda_5 + CP_v\, BPR_5) /\lambda_s \quad \ldots(10)$$

2. Case-II: Mathematical model for a sextuple effect evaporator system with spilt feed with flashing of condensate:

$$\left(6 \overset{5}{>} 4 \rightarrow 3 \rightarrow 2 \rightarrow 1\right)$$

For the design procedure of a sextuple effect evaporator system with split feed with the flashing of condensate as shown in the above structure, the model gives rise to a set of 17 independent nonlinear algebraic equations in 17 unknowns.

For the 1st effect

$$g_1 = l_2 T_s\{CP_2 (u_2 + BPR_2/T_s) - CP_1 (u_1 + BPR_1/T_s)\} /\lambda_s + v_0 (\lambda_0 + CP_v BPR_0) /\lambda_s - (l_2-l_1) \{(\lambda_1 + CP_v BPR_1) - CP_1 T_s (u_1+BPR_1/T_s)\}/\lambda_s - (l_2-l_1) (\alpha u_1 + \beta/T_s) T_s/\lambda_s \quad ...(11)$$

$$g_2 = U_1 T_s a_1 \{1.0- (u_1 +BPR_1/T_s)\} /50.\ \lambda_s - v_0 (A_0 + CP_v BPR_0) /\lambda_s \quad ...(12)$$

For the IInd & IIIrd effect

$$g_i = l_{n+1} T_s\{CP_{n+1} (u_{n+1} + BPR_{n+1}/T_s) - CP_n (u_n + BPR_n/T_s)\} /\lambda_s + (l_n l_{n-1} + m_{n-1}) (\lambda_{n-1} + CP_v BPR_{n-1}) /\lambda_s - (l_{n+1}-l_n) \{(\lambda_n + CP_v BPR_n) - CP_n T_s (u_n+BPR_n/T_s)\} /\lambda_s - (l_{n+1}-l_n) (\alpha u_n + \beta/T_s) T_s/\lambda_s \quad ...(13)$$

$$g_{i+1} = U_n T_s a_n \{U_{n-1} - (u_n +BPR_n/T_s)\} /50.\ \lambda_s - (l_n - l_{n-1} m_{n-1}) (\lambda_{n-1} + CP_v BPR_{n-1}) /\lambda_s \quad ...(14)$$

(i=3, 5 ; n=2, 3)

For the IVth effect

$$g_7 = l_5 T_s\{CP_5 (u_5 + BPR_5/T_s) - CP_4 (u4 + BPR_4/T_s)\} /\lambda_s + l_6 T_s \{CP_6 (U_6 + BPR_6/T_s) - CP_4 (u_4 + BPR_4/T_s)\} /\lambda_s + (l_4-l_3+m_3) (\lambda_3 + CP_v BPR_3) /\lambda_s - (l_5 + l_6-l_4) \{(\lambda_4 + CP_v BPR_4) - CP_4 T_s (u_4+BPR_4/T_s)\} /\lambda_s - (l_5 +l_6 -l_4) (\alpha u_4 + \beta/T_s) T_s/\lambda_s \quad ...(15)$$

$$g_8 = U_4 T_s a_4\{u_3 - (u_4 +BPR_5/T_s)\} / 50.\ \lambda_s - (l_4 - l_3+m_3) (\lambda_3 + CP_v BPR_3) /\lambda_s \quad ...(16)$$

For the Vth effect

$$g_9 = 0.5T_s \{CP_f (u_f+ BPR_f/T_s) - CP_5 (u_5 + BPR_5/T_s)\} /\lambda_s + (l_5 +l_6 -l_4+m_4) (\lambda_4 + CP_v BPR_4) /\lambda_s - (0.5 -l_5) \{(\lambda_5 + CP_v BPR_5) - CP_5 T_s \{ (u_5+BPR_5/T_s)\} /\lambda_s - (0.5 -l_5) (\alpha u_5 + \beta/T_s) T_s/\lambda_s \quad ...(17)$$

$$g_{10} = U_5 T_s a_5 \{u_4 - (u_5 +BPR_5/T_s)\} /50.\ \lambda_s - (l_5 +l_6 -l_4+m_4) (\lambda_4 + CP_v BPR_4) /\lambda_s \quad ...(18)$$

For the VIth effect

$$g_{11} = 0.5T_s \{CP_f (u_f + BPR_f/T_s) - CP_6 (u_6 + BPR_6/T_s)\} /\lambda_s + (0.5 -l_5+m_5)(\lambda_5 + CP_v BPR_5) /\lambda_s - (0.5 -l_6) \{(\lambda_6 + CP_v BPR_6) - CP_6 T_5 (u_6+BPR_6/T_s)\} /\lambda_s - (0.5 -l_6) (\alpha u_6 + \beta/T_s) T_s/\lambda_s \quad ...(19)$$

$$g_{12} = U_6 T_s a_6 \{u_5 - (u_6 +BPR_6/T_s)\}/50.\ \lambda_s - (0.5- l_5) (\lambda_5 + CP_v BPR_5) /\lambda_s \quad ...(20)$$

Equations for condensate flash tank

For 1st condensate flash tank

$$g_{13} = (v_0\, \alpha\, T_s /\lambda_s) (1.0- u_1) - (m_1 T_s/\lambda_s) (Y u_1 + Z/T_s) \quad ...(21)$$

For IInd to Iyth condensate flash tank

$$gi = \{(l_n-l_1+m_1)\, \alpha\, T_s/\lambda_s\} (u_{n-1}- u_n) - (m_n T_s/\lambda_s) (Y u_n + Z/T_s) \quad ...(22)$$

(i=14,15,16; n=2,3,4)

For VIth condensate flash tank

$$g_{17} = \{(l_5+l_6-l_1+m_1)\, \alpha T_s/\lambda_s\} (u_4-u_5) - (m_5 T_s/\lambda_s) (Yu_5+Z/T_s) \quad ...(23)$$

Influence of Steam Temperature

The dependences. of SC, SE & A on T_s are shown in Fig.1-3. From the figures the following observations are made:

SC increases linearly (but with different slopes) with the increase of steam temperature SE also decreases nearly in the same manner.

The area, A unlike SC and SE displays a sharp downward trend with strong curvilinear characteristics. The steam consumption drops to a value, on an average of 18.52 % from D to E, 6.0% from E to F' and 23.41 % from D to F', enhancement of steam economy are found to be of the order of 22.67%, if one, changes from D to E, 6.38% from E to F' and 30.50 % from D to F'. The gain in economy and steam saving are quite large in proportion when compared to the extra heating surface requirements, which is of the order of 3.38 %, for the

3. Case-III: Mathematical model for a sextuple effect evaporator system with spilt feed with flashing of condensate and product flash tank

$$(5 > 4 \longrightarrow 3 \longrightarrow 2 \longrightarrow 1)$$
$$6$$

For the design procedure of a sextuple effect evaporator system with split feed with the flashing of condensate as well as with the product flash as shown in the above structure, the model gives rise to a set of 17 independent nonlinear algebraic equations in 17 unknowns, where in the product flash amount is added in the third effect. Note that there are changes in the model equations from 1st to IIIrd effect. However due to this extra addition of product flash utilization there will be change of models in the subsequent bodies, namely IV, V & VI effects. The equations for condensate flash tank will also be same for Ist to IIIrd effects discussed in sections 2..

For the IVth effect

$$g_7 = l_5 T_s\{CP_5 (u_5 + BPR_5/T_s) - CP_4 (u_4 + BPR_4/T_s)\}/ \lambda_s + l_6 T_s\{CP_6 (u_6 + BPR_6/T_s) - CP_4 (u_4 + BPR_4/T_s)\} /\lambda_s + (l_4 - l_3 + m_3 + m_p)(\lambda_3 + CP_v BPR_3) /\lambda_4 - (l_5 + l_6 - l_4) \{(\lambda_4 + CP_v BPR_4) - CP_4 T_s (u_4 + BPR_4/T_s)\} /\lambda_s - (l_5 + l_6 - l_4) (\alpha u_4 + \beta/T_s) T_s/\lambda_s \quad \ldots(24)$$

$$g_8 = U_4 T_s a_4 \{u_3 - (u_4 + BPR_5/T_s)\} /50./\lambda_s - (l_4 - l_3 + m_3 + m_p) (\lambda_3 + CP_v BPR_3) /\lambda_s \quad \ldots(25)$$

For the Vth effect:

$$g_9 = 0.5T_s \{CP_f(u_f + BPR_f/T_s) - CP_5(u_5 + BPR_5/T_s)\} /A_s + (l_5 + l_6 - l_4 + m_4 + m_p) (\lambda_4 + CP_v BPR_4) /\lambda_s - (0.5 - l_5)\{(\lambda_5 + CP_v BPR_5) - CP_5 T_s \{ (u_5 + BPR_5/T_s)\} /\lambda_s - (0.5 - l_5) (\alpha u_5 + \beta/T_s) T_s/\lambda_s \quad \ldots(26)$$

$$g_{10} = U_5 T_s a_5 \{u_4 - (u_5 + BPR_5/T_s)\} /50. \lambda_s - (l_5 + l_6 - l_4 + m_4) (\lambda_4 + CP_v BPR_4) /\lambda_s \quad \ldots(27)$$

For the VIth effect:

$$g_{11} = 0.5T_s \{CP_f(u_f + BPR_f/T_s) - CP_6(u_6 + BPR_6/T_s)\} /\lambda_s + (0.5 - l_5 + m_5) (\lambda_5 + CP_v BPR_5) /\lambda_s - (0.5 - l_6)\{(\lambda_6 + CP_v BPR_6) - CP_6 T_s (u_6 + BPR_6/T_s)\}/\lambda_s - (0.5 - l_6) (\alpha u_6 + \beta/T_s) T_s/\lambda_s \quad \ldots(28)$$

$$g_{12} = U_6 T_s a_6 \{u_5 - (u_6 + BPR_6/T_s)\}/50. \lambda_s - (0.5 - l_5) (\lambda_5 + CP_v BPR_5) /\lambda_s \quad \ldots(29)$$

Equations for condensate flash tank

There will be a change of equation for bodies IVth and Vth condensate flash tank as shown below:

For IVth condensate flash tank

$$g_i = \{(l_4 - l_1 + m_1 + m_p) \alpha T_s/\lambda_s\} (u_3 - u_4) - (m_4 T_s/\lambda_s) (Y u_4 + Z/T_s) \quad \ldots(30)$$

For VIth condensate flash tank:

$$g_{17} = \{(l_5 + l_6 - l_1 + m_1 + m_p) \alpha T_s/\lambda_s\} (u_4 - u_5) - (m_5 T_s/\lambda_s) (Y u_5 + Z/T_s) \quad \ldots(31)$$

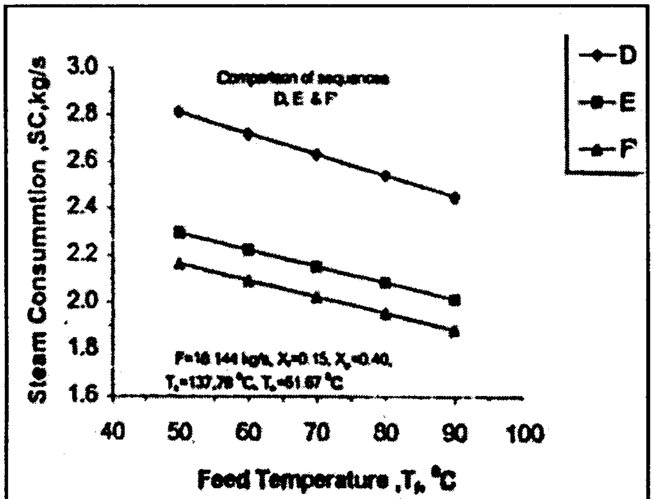


Fig-4 Effect of Feed Temperature on Steam Consumption

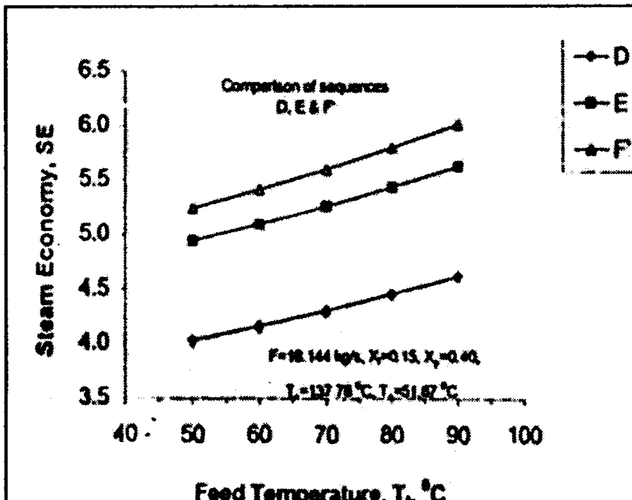


Fig-5 Effect of Feed Temperature on Steam Economy

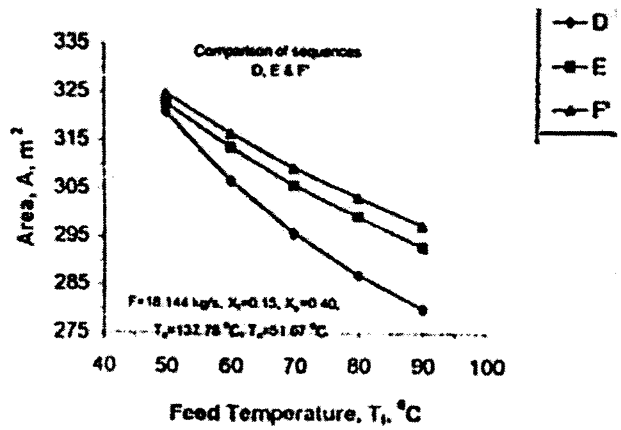


Fig-6 Effect of Feed Temperature on Area

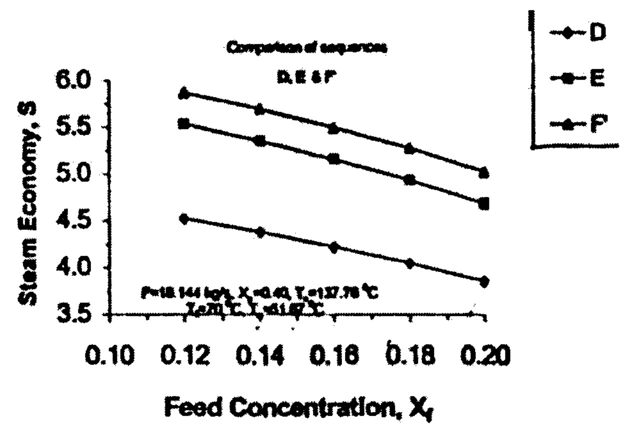


Fig-8 Influence of Feed Concentration on Steam Economy

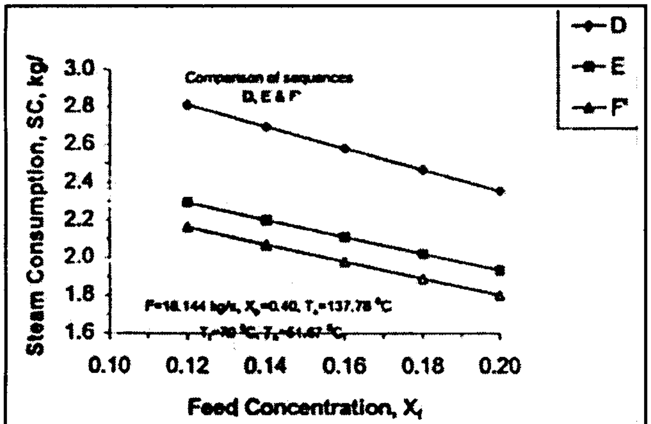


Fig-7 Influence of Feed Concentration on Steam Consumption

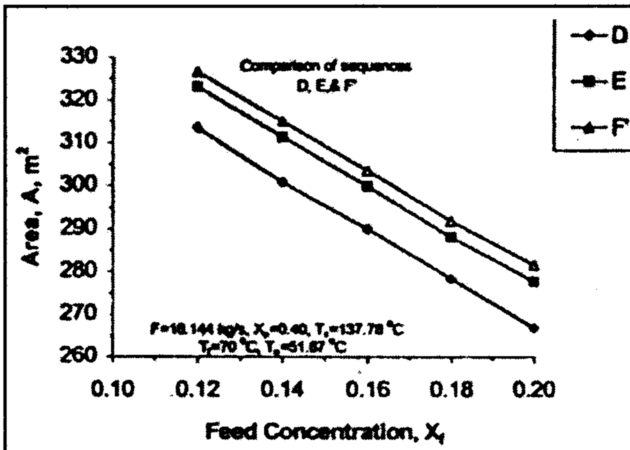


Fig-9 Influence of Feed Concentration on Area

change from D to E, 1.13% from E to F' & 4.56 % from D to F', indicating the scoring over the loss due to capital cost by the gain due to energy savings.

Effect of Feed Temperature

Variations of steam consumption, steam economy and area demand with variation of temperature of feed and the alternative designs (D, E &F) are depicted in Fig. 4-6. Reverse trends are noticed between SC and SE values though the nature are distinctly linear in both parameters.

With the increase of feed temperature, the steam consumption decreases to a value, on an average of 18.03% from D to E, 6.26 % from E to F' & 23.17 % from D to F', 22 % increase of SE from D to E, 6.67% from E to F' & 30.08 % from D to F', are also noted. This indicates an enormous quantum of steam saving. On the other hand, extra heating surface requirements increase by only 4.2% from D to E, 1.36% from E to F', 5.59 % from D to F'. It is evident that the increases in area demand are very small compared to the gain in economy due to reduction in steam consumption.

Influence of Feed Concentration, X_f

The effects of feed concentration, X_f on SC, SE and A have been plotted in Fig.7-9. It is revealed from the figures that with the increase of X_f at the fixed values of input parameters given in Table-1, namely, F, Xp, Ts, T_f and Tn, SC and A decrease linearly but SE decreases in a non-linear way.

a. For X_f fixed at 0.14, the saving of SC if one desires to go from D to , an extent of 18.22%, is anticipated. It is interesting to note that if feed concentration is increased by 0.02 (i.e. X_f)at 0.16, the quantum of saving from sequence D $\longrightarrow$ F' remains around 23.2 % indicating that there is not much gain obtained

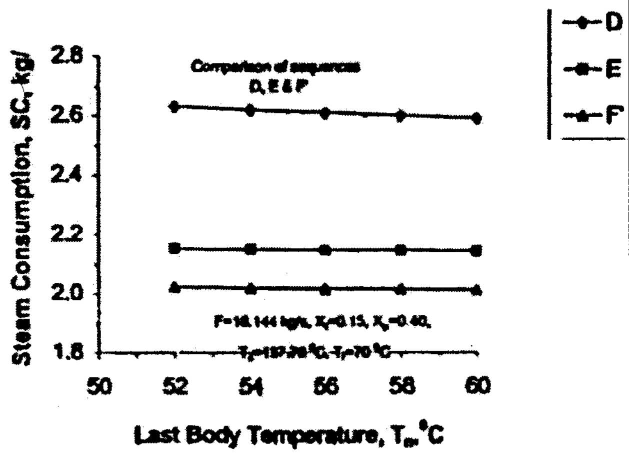


Fig-10 Effect of Last Body Temperature on Steam Consumption

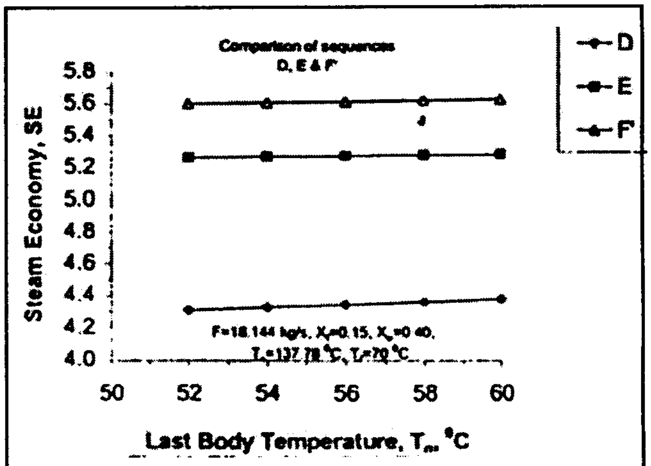


Fig-11 Effect of Last Body Temperature on Steam Economy

Table -2

O.P.	Split Feed No flash, D	With. condensate flash, E	With condensate & product flash,F	Diff. D-E, kg/s D$\rightarrow$E, %	Diff. E-F ,kg/s E$\rightarrow$F , %	Diff. D-F',kg/s D$\rightarrow$F', %
SC, kg/s,	2.5671	2.1024	1.9721	0.4647 18.102%	0.2003 6.21%	0.595 23.1 7%
SE, kg/s,	4.417	5.391	5.747	0.974 22.051%	0.356 6.60%	1.33 30.11 %
A, m^2	292.463	303.712	307.822	11.249 3.846%	4.11 1.35%	15.359 5.25%

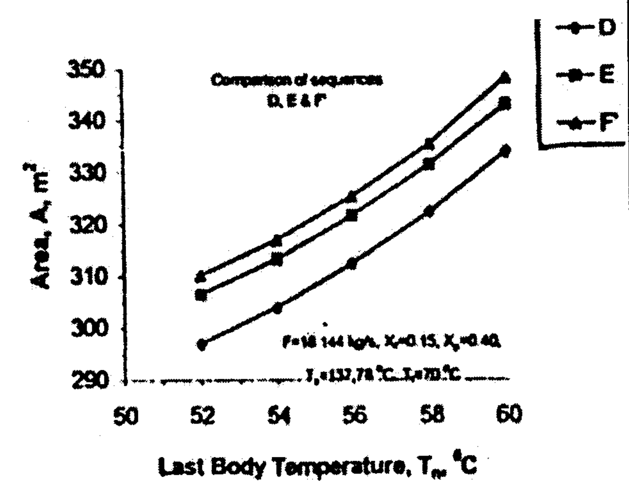


Fig-12 Effect of Last Body Temperature on Area

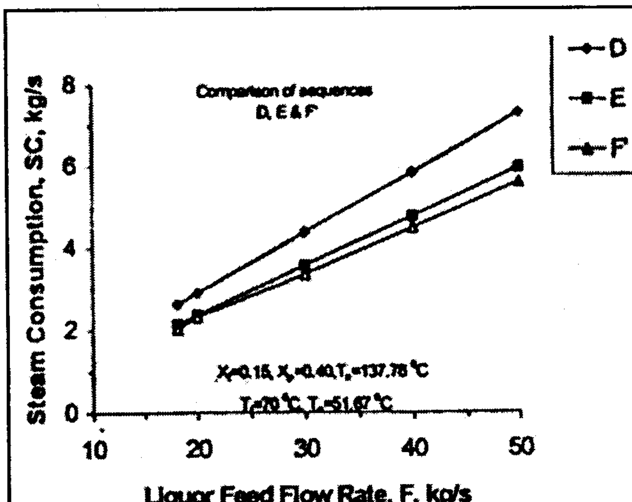


Fig-13 Effect of Liquor Flow Rate on Steam Consumption

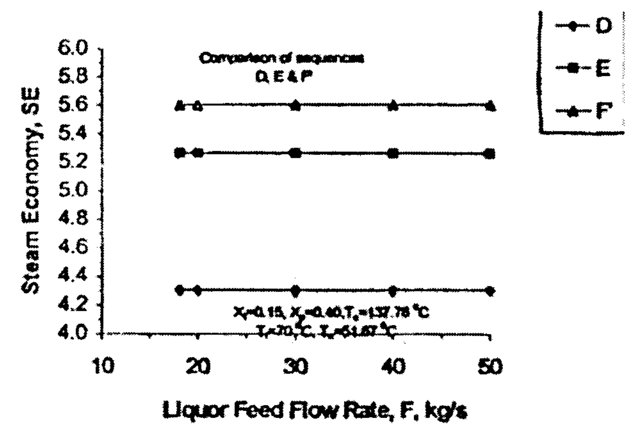


Fig-14 Effect of Liquor Flow Rate on Steam Economy

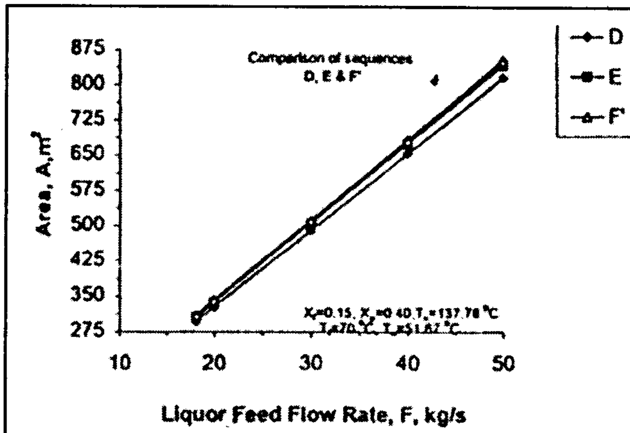


Fig-15 Effect of Liquor Flow Rate on Area

percentage-wise but there might be a considerable saving when estimating steam consumption on an annual basis for an industry This, in turn, earns a lot of profit.

b. If one proceeds from D to E there is a dramatic enhancement of SE noticed (22.07%) from E to F' only 6.59 % & 30.11 % for X_f at 0.16. This amply clear that enormous gain in economy from flashing of condensate and product can be obtained.

c. There is an approximate requirement of extra 3.37 % of A for changes in configuration from D to E, 1.24% from E to F' & 4.65% from D to F' for X_f =0.16. The lower value of additional heating surface requirement, at X_f of 0.16 favours the higher concentration of feed values. This further encourages the designer for the overall cost reduction due to flashing as the capital cost in terms of extra addition of A is overshadowed by the cost . Benefits due to increase of SE and saving of steam.

Effect of Last Body Temperature

Fig. 10-12 portary the influence of last body temperature on the values of SC, SE and A. It is evident from the plots that there are displays of opposite trend of linearity by SC and SE values but upward concavity for variation of area demand is noted, if T_n is used as a parameter.

The insignificant decrease of SC further points out that SC is almost independent on Tn and there is substantial amount of steam saving if one increases the last body temperature. It is, therefore, suggested that normal working temperature of 51. 7°C (corresponding to last body absolute pressure, 13.27 kN/m^2) may be kept fixed as the safe value. The relative differences between D, E & F' indicates that much gain is obtained by shifting from D$\longrightarrow$E, E$\longrightarrow$F' & D$\longrightarrow$F'. From the analysis of these alternations in design, the following observations are noted,

a. Reductions of SC, on an average of 18.15% for shifting design from D to E, 6.05% from E to F' & 23.10% from D to F' are achieved.

b. Enhancements of SE for the same change, is found of the order of 22.13% from the change of design from D to E, 6.44% from E to F' & 22.99% from D to F' are obtained.

c. Area demand, A increases by 3.12% from D to E, 1.19% from E to F' & 4.44% from D to F' for the above cases.

It is very much clear that flashing of condensate with product flash can bring large amount of steam saving vis a vis a profit to the industry.

Effect of Liquor Feed Rate

From scrutiny of data & plots (Fig. 13-15) the following critical comments can be made:

a. Steam saving for shifting from D to E by 18.2 %, E to F' by 6.05% & D to F' by 23,14 % can be obtained.

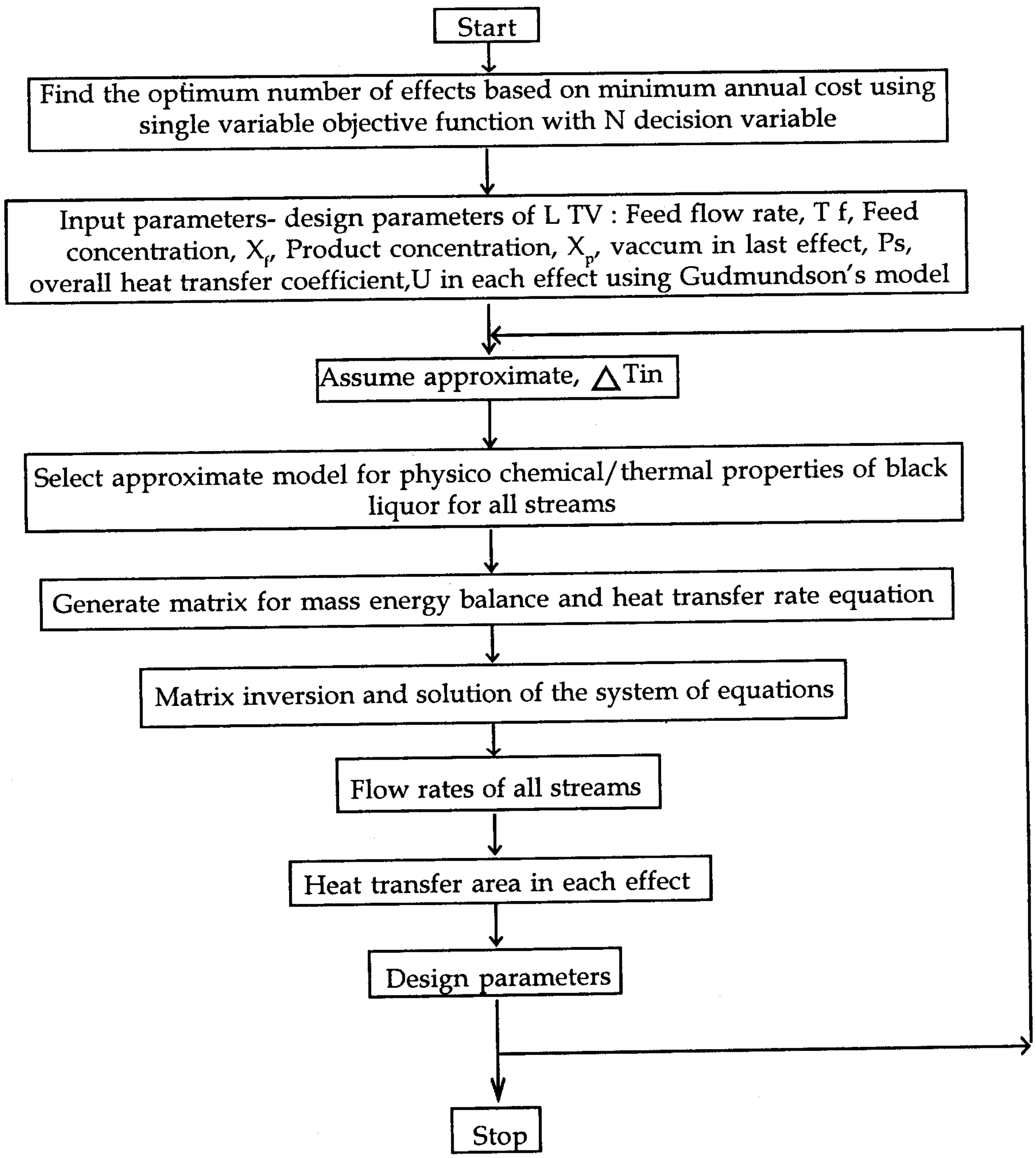
b. Increases of SE for the above changes go up to 22.2% from D to E, 6.44% from E to F' & 30.06% from D to F'.

c. The additional area, ΔA demands of 3.2% (9.6m^2), 1.2%, 4.48% for the above alternations of design respectively are required.

As found earlier, the gain in steam saving i.e. benefits of operational charges overpowers the loss in extra area

APPENDIX-III

LOGICAL SEQUENCE OF CALCULATIONS



demand (capital expenditure). Therefore, flashing of condensate with product flash can contribute significant capital gain to the industry. For better clarity, a few noteworthy results one shown in the following Table:

The sufficient gain in reduction of steam consumption and increase in steam economy is clearly evident. The extra heating surface requirements are much less in comparison to the gain of steam economy obtained. This, if calculated annually will be of significance to the industry,

CONCLUSION

From the analysis of the computer simulation of the models the following conclusions can be made.

• The main advantageous point is to increase the feed temperature. Around 22.05% steam saving is possible at normal working conditions at 80°C with condensate flash in comparison to those from a system without flash. With flashing of condensate plus product flash saving of steam to an extent of 30.11 % is possible.

• It is noticed that in the split feed and the same with condensate flash options, E is always better than D. As expected F' is better than E. The developed mathematical models can be extended to many other chemical and process industries which use backward feed multiple effect evaporator system or systems with split feed for estimating steam . consumption, steam economy and area requirement.

NOMENCLATURE

A Area of evaporator body, heat transfer area, m^2

a Fractional heating area of the effect, defined by $a_j=A/(50.F)$ sm^2/kg

BPR Boiling point rise, °C ,or Kelvin

C Condensate from steam chest

C_p Specific heat of liquor, kJ/kg °C

F Liquor feed rate, kg/s

f Fraction of first cost as repairs and maintenance charges per annum

g A function defined by $g_j=f_j/\lambda_s$

H Specific enthalpy of the vapour, kJ/kg

h Specific enthalpy of liquor, kJ/kg

L Liquor flow rate from the effect, kg/s

M Flash vapour, kg/s

n Number of effects in MEE set

Q Rate of heat transfer across the tube from the steam/ water vapour to the liquor

T Saturation temperature of water at pressure, P, °C

U Overall heat transfer coefficient, W /m^2K

V Vapour flow rate from the effect, kg/s

x Mass fraction of solute in the liquor

l,m,u and v are scaled liquor flow rate, flash vapour rate, temperature and vapour flow rate defined by $lj=L_i/F$, $m_j=M_j/F$, $uj=T_j/F$ and $v_j=V_j/F$.

SUBSCRIPTS AND GREEK LETTERS

f Feed concentration

p Final or output product

s Steam, saturation

v Vapour

A Latent heat of vaporization, kJ/kg

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