Simulation of Multiple Effect Evaporator for Black Liquor Concentration

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ABSTRACT

An attempt has been made in this present investigation to design a sextuple effect black liquor evaporator system for paper industry. This required to develop a system of 12 nonlinear simultaneous equations based on steady state mass and energy balances, heat transfer rate, equilibrium relationships and same physico-chemical/physico-thermal properties of liquor. Numerical techniques using Newton-Raphson-Jacobian matrix method and method of Gauss elimination are employed to solve the problem. A generalised algorithm is developed for the simulation of this multiple effect evaporator systems with backward feed. To process a large body of data within limited time and to generate a data bank a computer program has been developed based on Fortran 77. Normal parameters practiced in Industry are employed to simulate the system. Anticipated saving of steam consumption is indicated. The design procedure developed can bring accuracy in assessing the performance of an existing evaporator system or can help in designing a new system for a green field pulp and paper mill.

INTRODUCTION

Evaporators are essential equipments in paper, sugar and various other chemical industries. These are widely used in the process industry to concentrate solutions and to recover solvents. By multiple staging of evaporator units, the amount, and therefore the cost of externally supplied steam can be reduced. Depending upon the evaporator capital cost, the number of units in the set, and the steam cost, a design based on minimum cost can be determined. Multiple effect evaporators may be arranged in a variety of ways. Forward feed, backward feed and mixed feed are the three general types of evaporator flow sequences.

Many investigators (1,2,4-6) developed equations in steady state conditions based on material and energy balances and heat transfer rate. They also developed some algorithms which reduced the series of nonlinear algebraic equations that governed the evaporator system to a linear form and solved them iteratively by a linear iteration technique. For a given number of stages, the calculation procedure computed design variables such as area (or area ratio between effects), externally supplied steam rate, stage temperature and flows etc. For the evaporator problem, the set of equations could be solved iteratively estimating the effects from the previous solution and solving the linear equations that result (basically by using the Newton - Raphson method). This algorithm is simple, easy to program, inherently stable and virtually guarranted convergence, thereby eliminating the biggest problems with general nonlinear methods. A calculation procedure useful in

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the design of multiple effect evaporator system is presented in this work.

DEVELOPMENT OF MATHEMATICAL MODELS AND ITS SOLUTION

To initiate the modelling and simulation for Indian Industry, multiple effect evaporator comprising of a fixed number of bodies is to be ascertained. This needs optimization with minimum total annual cost as a decision variable. Approximate market costs of the basic items like steam, water, material of construction, labour etc will be enough for the preliminary selection of optimum number of effects.

For developing the models of multiple effect evaporator it is important to know how many evaporator bodies are required to function most optimally.

It is well known to the process engineer that the larger the number of effects in a MEE, the less is the intake of steam by evaporators for the same quantum of evaporation. It appears therefore that for the large number of evaporator bodies the steam economy will be maximum.Economic consideration however sets a limit to the use of unlimited number of bodies.

The total annual cost of evaporation can be modelled to comprise of the following terms:

Total cost (C_T) = Labour Cost (C_L), Supervision charges (C_{SL}) and Overall, Laboratory and administrative expenses (C_{OLA})

+ Periodic cleaning cost (C_C)

+ Fixed charges based on first cost (C_{FC})

+ Repair and maintenance charges ($C_{M\text{-}R}$)

+ Fuel and steam charges (C_S) + Condensing and Cooling water cost (C_{CW}) and Charges on electrical Power (C_P). +Loss of capacity due to BPR (C_{BPR})...(1)

In the above total cost equation except the third term, i.e. C_{FC}, are normally grouped under operating charges although many investigators considered $C_{M\text{-}R}$ and C_P as a part of fixed charges.

TOTAL ANNUAL COST MODEL, C_T

Putting all the model equations for various cost terms developed by Ray (5) and Singh (6), one can obtain the total cost of evaporation C_T as:

$$C_T = (n)^b.P_1\,(E_T/24\,e_I)\,(1+f_i))\,(F+f) + \{E_T/K_1\,(n)^m\}\,D.CS$$

$$+\ E_T/n\,D.W_{\setminus}\,(Cpa_i+Cp_C+rC_W) + j\,(P_i+P_c)_{std}\,(F+f)\,(E_TW/24\,V_{std})^{1/2}$$

$$+\ (Pa)_{std}\,(F+f)\,\frac{\{E_T(1.33+jW)a/\}^{1/2}}{24\,Va_{std})^{1/2}\}}$$

APPENDIX

TABLE 1: COST TERMS/CONSTANTS AND THEIR APPROXIMATE VALUES

S.NO.	COST TERM/CONSTANTS		VALUES	S. NO.	COST TERM/CONSTANTS		VALUES
1	b		1.0	11	A,	m^2	300.00
2	CC,	Rs./m^2	11.0	12	f		0.05
3	$P_{FC,}$	Rs/m^2	30000.0	13	F_1		0.27-0.60
4	$C_{L,}$	Rs/8h	75.0	14	$e_{1,}$	kg/m^2h	130
5	$C_{Pa,}$	Rs./kg of water	1.63E-05	15	K_1		0.15
6	$C_{PC,}$	Rs./kg of water	3.42E-05	16	M		0.682
7	$C_{pi,}$	Rs./kg of water	3.55E-05	17	r		0.10
8	$C_{S,}$	Rs./Tonne	500	18	R		15
9	$C_{W,}$	Rs./m^3	0.05	19	W,	kg/kg	60
10	D,	Days/year	300	20	Y		0.85

TABLE 2: OPERATING PARAMETERS

S.NO.	PARAMETERS		VALUE
1	Liquor feed rate,	kg/s	18.144
2	Liquor feed temperature,	°C	76.67
3	Liquor feed concentration,		0.152
4	Final product concentration		0.405
5	Steam temperature,	°C	137.78
6.	Last body temperature,	°C	51.67
7	Water evaporated from each body,	kg./hm²	130
8	Heat transfer area,	m²	300

$$+ \{(n-2)+2/K\}\ (DE_T/R24e_1)\ K_1C_C+C_L \quad .... (2)$$

The total annual cost of evaporation as depicted in equation (1) can be evaluated with the data given in table-1 and 2 (given in Appendix). A computer program for the above purpose is developed based on **FORTRAN** 77 and is used to estimate the individual costs as well as the total annual cost.

A graph has been plotted to show the variation of total annual cost as a function of number of effects (Fig.1). The profile displays a unimodal function and exhibits one sharp inflexing point as minima. This minimum annual cost corresponds to six number of bodies, thus indicating sextuple effect evaporator is the most feasible MEE set Paper Industry at present.

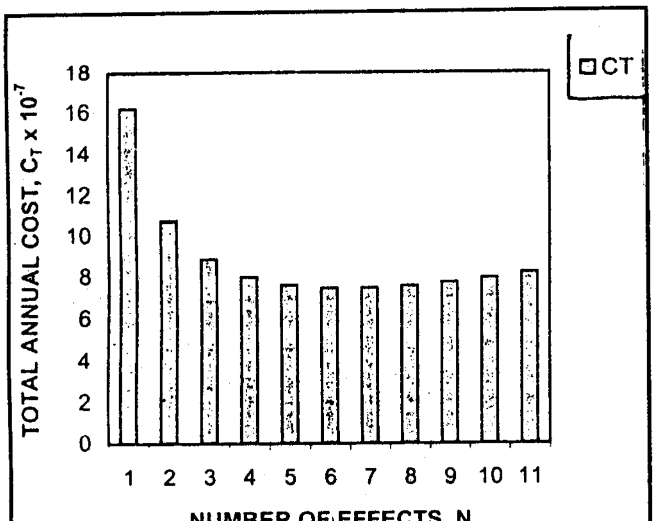

Fig.1 Total annual cost as a function of No. of effects

MATHEMATICAL MODEL FOR A SEXTUPLE EFFECT EVAPORATOR SYSTEM WITH BACKWARD FEED (6→5→4→3→2→1)

The modelling of Sextuple effect evaporator system will start from steady state equations for total mass balance, component mass balance, energy balance, heat transfer rate and equilibrium relations for boiling point rise for all the bodies (Fig.1.1). These are developed below for the first body in detail and a general equation for any number of bodies in the proposed set-up.

(a) Mass and Energy Balance Equations Around First Effect of Evaporator

A. Total Mass balance equation:

$$L_2 = V_1 + L_1 \qquad ...(3)$$

B. Component mass balance:

$$L_2X_2 = L_1X_1 \qquad ...(4)$$

C. An enthalpy balance:

$$Q_1 = V_0H_0 - C_1hc_1$$
$$= V_0(hc_1 + \lambda_0 + C_{pv}BPR_0) - Chc_1$$
$$= V_0\lambda_0 + V_0C_{pv}BPR_0 \qquad ...(5)$$

D. Heat transfer rate:

$$Q_1 = U_1A_1(\Delta T_1)_{eff}$$

Where, $(\Delta T_1)_{eff} = \Delta T_1 - BPR_1$

$$= T_S - T_1 - BPR_1$$

Hence $Q_1 = U_1A_1(T_S - T_1 - BPR_1) \qquad ...(6)$

E. Total mass balance on the steam chest:

$$C_1 = V_0 \qquad ...(7)$$

F. An enthalpy balance on the process:

$$L_2h_2 + Q_1 = V_1H_1 + L_1h_1 \qquad ...(8)$$

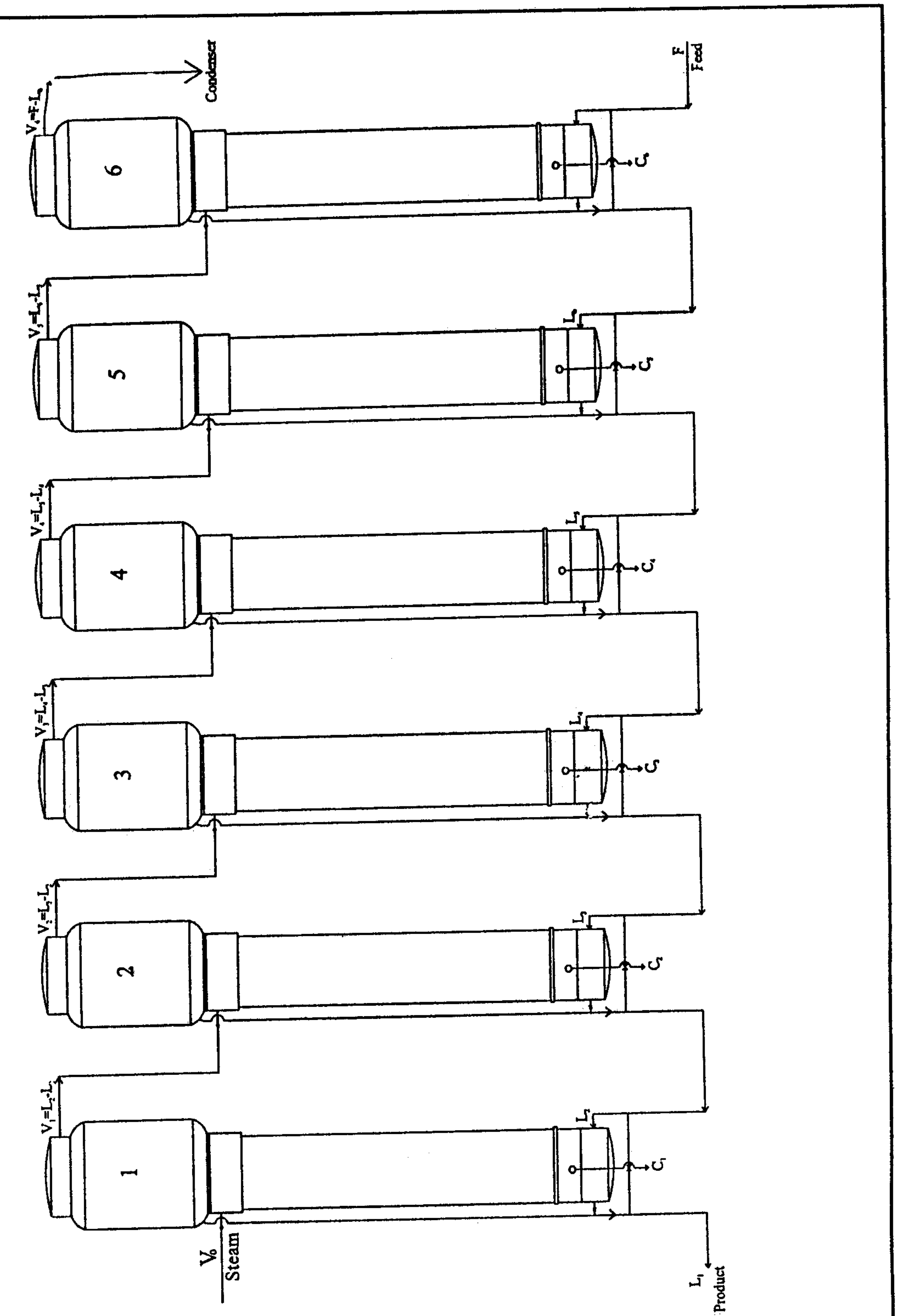

Fig - 1.1
Sextuple Effect Evaporator System With Backward Feed
(6→5→4→3→2→1)

Substituting the value of V_1 from Eq. (3) and Q_1 from Eq. (5) into Eq. (8) gvies

$$L_2h_2 + V_0 H_0 - C_1 hc_1 - (L_2-L_1) H_1-L_1 h_1=0$$

$$L_2(h_2 - h_1) + V_0H_0 - C_1hc_1 - (L_2-L_1) (H_1-h_1)=0 \quad ..(9)$$

Putting $h_j = CP_j (T_j + BPR_j)$,

$H_j = hc_{j+1} + \lambda_j + CP_V BPR_j$ and $hc_{j+1} = AT_j+B$

Where the constants A and B are 4.1832 and 0.127011 respectively.

Putting the values of h_j and hc_j in Eq. (9) the following equations are developed which on simplification gives Eq. (10).

$L_2\{CP_2\ (T_2\ +BPR_2)\ -\ CP_1\ (T_1\ +BPR_1)\}\ +\ V_0\ (hc_1+\lambda_0+CP_V BPR_0)\ -\ Chc_1$

$-(L_2-L_1)\ \{hc_2+\lambda_0+CP_V+BPR_2)\ -\ CP_1\ (T_1\ +BPR_1)=0$

$L_2\{CP_2(T_2+BPR_2)\ -\ CP_1\ (T_1+BPR_1)\}\ +\ (V_0-C_1)\ hc_1+V_0\ (\lambda_0+CP_V+BPR_0)$

$-(L_2-L_1)\ \{hc_2+\lambda_1+CP_V+BPR_1)\ -\ CP_1\ (T_1\ +BPR_1)=0$

$L_2\{CP_2(T_2+BPR_2)\ -\ CP_1(T_1+BPR_1)\}+\ V_0(\lambda_0+CP_V+BPR_0)$

$-(L_2-L_1)\ \{\lambda_1+CP_V+BPR_1)\ -\ CP_1\ (T_1\ +\ BPR_1)\}-(L_2-L_1)(AT_1+B)=$ ...(10)

f_1 is now defined as:

f_1-$L_2\{CP_2(T_2+BPR_2)$- $CP_1\ (T_1+BPR_1)\}$- $V_0(\lambda_1+CP_V BPR_0)$

$-(L_2-L_1)\{\lambda_1+CP_V+BPR_1)-CP_1(T_1+BPR_1)-(L_2-L_1)(AT_1+B)$ ...(11)

Now from Eqs. (5) and (6) and gets

$U_1A_1\ (T_S\ -\ T_1\ -\ BPR_1)\ -\ V_0\ (CP_V BPR_0)=0$ ...(12)

Defining, f_2

$f_2=\ U_1A_1(T_S-T_1-\ BPR_1)-V_0(\lambda_0 CP_V BPR_0)=0$ ...(13)

The above equations need scaling. This has been done following the procedure proposed by Holland (1). These are as follows:

$g_1=l_2T_2/\lambda_0\{CP_2(u_2+BPR_2/T_S-CP_1(u_1+BPR_1/T_S)\}+V_0/\lambda_0\ (\lambda_0+CP_V BPR_0)$

$-(l_1-l_2)/\lambda_0\{(\lambda_1 CP_V BPR_1)$- $CP_1T_1(u_1+BPR_1/T_S)\}$-$(l_2-l_1)/\lambda_0\ (Au_1+B/T_S)T_S$ ...(14)

$g_2=U_1T_Sa_1/50.\lambda_0\{1.0-(u_1+BPR_1/T_S)\}V_0+CP_V BPR_0)$ ...(15)

(b) The general Equations for Mass and Energy Balacne for second to n body of an N body set (Nth effect multiple effect evaporator):

$g_i=l_{n+1}T_S/\lambda_0\{CP_{n+1}(u_{n+1}+BPR_{n+1}/T_S)\}+(l_n-l_{n-1})/\lambda_0$

$(\lambda_{n-1}+CP_V BPR_{n-1})$- $(l_{n+1}-l_n)/\lambda_0\{(\lambda_n+CP_V BPR_n)$- $CP_{n\,T}\ ((u_n+BPR_nT_S)\}$

- $(l_{n+1}-l_n)/\lambda_0\ (Au_n+B/T_S)\ T_S$ (i=3,5,....11) ..(17)

$g_{i+1}=U_nT_Sa_n/50.\lambda_0\{u_n+BPR_n/T_S)\}-(l_n-l_{n-1})/\lambda_0\ (\lambda_{n-1}+CP_V BPR_{n-1})$

(i=3,5, ...11) ...(16)

SOLUTION OF MODELS

TABLE 3: PHYSICO-THERMAL/CHEMICAL PROPERTIES

S.NO.	PARAMETERS	CORRELATIONS	FUNCTION OF
1.	Latent heat of vaporization,	λ = 2519.5-2.653 x T	Temperature
2.	λ, kJ/kg Boiling point rise,	BPR = 41.4 x (TS - 1)^2	Concentration
3.	BPR, K	Cp = {1.0-3.234x (TS/T1)} x 4190	
	Specific heat,	Where T1 = (T x 1.8 + 32)	
4.	Cp, J/kg K		Temperature and
	Thermal	k = (0.504-0.282 x TS + 1.35 x 10^{-03})	concentration
	conductivity, kW/mk	x 1.163	
5.	Pressure, P, kN/m^2	P = 3.73812 - 0.108896 x T1 +	Temperature and
		0.0012806xT1^2-6.69111x10^{-06}x^{T3}+	concentration
		1.99203x10^{-08}xT1^4	Temperature
		where T1 = (Tx1.8+32)	
6.	Density, ρ, kg/m^3	ρ = 1007 - 0.495 x T + 6.0 x TS	
7.	Viscosity, μ,mPas	μ =exp[a+b.(TS)+c. (TS)^2 + d.(TS)^3]	Temperature and
		Where,	concentration
		a=0.4717-0.02472xT+0.7059x10^{-05}xT^2	Temperature and
		b==0.06973-0.5452x10^{-03}+0.1656x10^{-05}xT^2	concentration
		c=0.002046+0.3183x10^{-04}xT+0.9761x10^{-07}xT^2	
		d=0.5793x10^{-04} - 0.1629x10^{-08}xT^2	

In the present investigation the Newton - Raphson - Jacobian matrix method followed by Gauss elimination is used as employed also by Holland (1). It is claimed to be the best to solve the system of non-linear equations because it converges more rapidly than others methods.

COMPUTER SIMULATION

The steady state models developed are now subjected to MEE system with an aim to calculate the energy requirement or how much energy can be saved with this purposed configuration.

In this present investigation FORTRAN-77 Program have been developed using the mathematical technique indicated in Section 3.

The known variables are: Liquor feed rate, F, Liquor feed temperature, T_f, Liquor feed concentration, X_f, Steam temperature, T_s, Last effect saturated temperature, $T_{n\ and}$ Final product concentration X_p (X_1) whereas specified variables are: overall heat transfer coefficients U_1, U_2, U_3, U_4, U_5 and U_6 and boiling point rise (BPR): BPR_1, BPR_2, BPR_3, BPR_4, BPR_5 and BPR_6. The unknown variables are: scaled vapor flow rate V_0, scaled liquor flow rate l_2, l_3, l_4, l_5 and l_6 scaled flash vapor flow rate m_1, m_2, m_3, m_4 and m_5 scaled product flash vapor flow rate, Mp, scaled temperature u_1, u_2, u_3, u_4 and u_5 fractional heating area, a and concentration terms X_2, X_3, X_4, X_5 and X_6.

VALIDITY OF MODELS

To test the validity of present model, Kern's (2) data for six effect evaporator body with backward feed sequence is used. Gudmundson (3) model for estimating overall heat transfer coefficient and suitable model equations for physico-chemical and thermal properties of kraft black liquor such as density, viscosity, specific heat and thermal conductivity etc are employed for easy computational purposes. The model equations are presented in Tables-3. The result obtained from Kern's data compare surprisingly very well with the results from the present model. The comparison of the data from the present investigation and that from Kern clearly indicate that mathematical models, the algorithms and the solutions developed are accurate.

RESULTS AND DISCUSSION

The results predicted from the models are plotted in graphs and the parametric influences are interpreted. Earlier works (4,5,6) have shown that the output parameters viz. steam consumption, SC, steam economy, SE and area, A are quite sensitive to variations in the

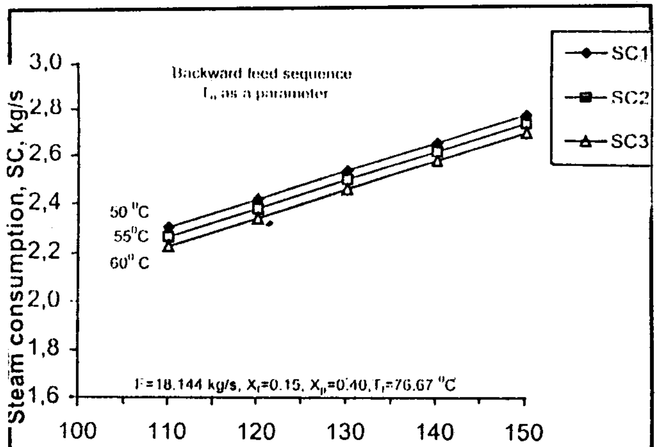

Fig-2 Effect of Steam Temperature on Steam Consumption

steam temperature among other input parameters. Therefore, in this present investigation, the effect of steam temperature along with any one parameter from the rest are shown for mere simplicity reasons where steam temperature variable are kept always common in all evaluations.

EFFECT OF LAST BODY TEMPERATURE

Figures 2 to 4 have been drawn to show the effect of steam temperature on output parameters, namely, steam consumption (SC), steam economy (SE), and area (A) respectively for backward feed sequence with last effect temperature, Tn, as a parameter. In these plots specified variables are feed flow rate F, feed concentration X_f, final product concentration X_p and feed temperature, T_f.

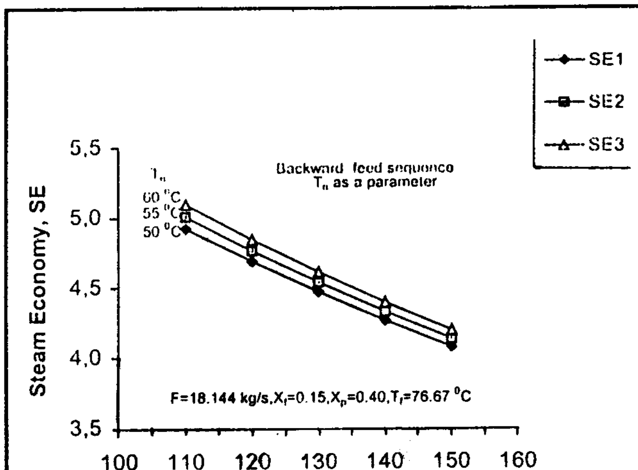

Fig-3 Effect of Steam Temperature on Steam Economy

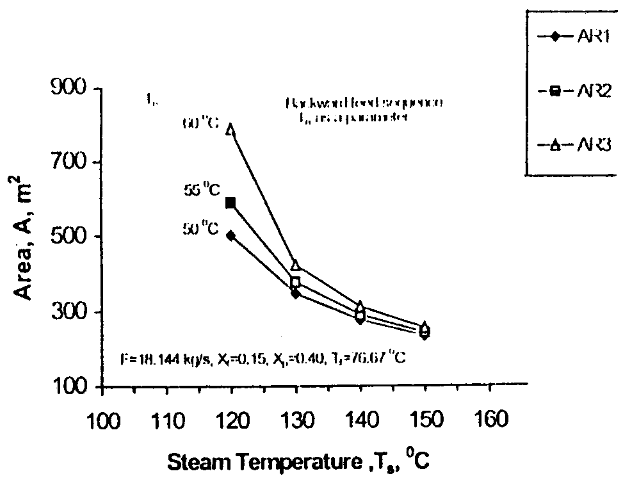

Fig-4 Effect of Steam Temperature on Area

Figure 2 shows that when the steam temperature increases the value of the steam consumption also increases for all the values of last effect temperature. Increase of Tn for a particular value of Ts, SE, however increases (Figure 3).

Rising the last body temperature, Tn, the amount of SC decreases for the entire range of steam temperature, Ts. With the increase of Ts, the SE decreases. Increase of Tn for a particular value of Ts, SE however increases (Figure3).

The effect of Ts on the heating surface area, A, drops very sharply. The slope tends, however to steeper as the temperature of the last body (lowering vacuum) becomes higher. This is shown in Figure 4. At a fixed

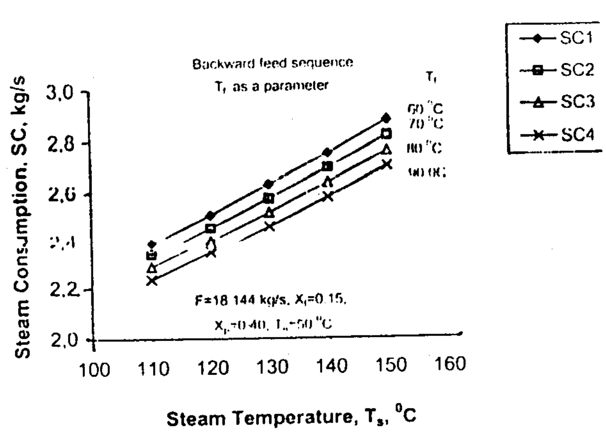

Fig-5 Effect of SteamTemperature on Steam Consumption

Ts, the area requirement increases with the increase of Tn.

Rising of Ts by 10°C (130°C -> 140°C) at 50°C of Tn, the area requirement decreases by 20.2%.

EFFECT OF FEED TEMPERATURE, T_F

The effect of Ts on SC, SE and A with feed temperature T_f as parameter has been shown in Figures 5-7. Figure 5 shows that SC rises with Ts linearly at all values of T_f. At a fixed value of Ts, SC also increases. SE, however, drops (also linearly) with rise in Ts values (Figure 6).

From Figure 6 it is evident that SE decreases by 4.5% with increase of Ts by 10°C(130°C>140°C) whereas for 10°C rise of T_f (80°C> 90°C), the SE

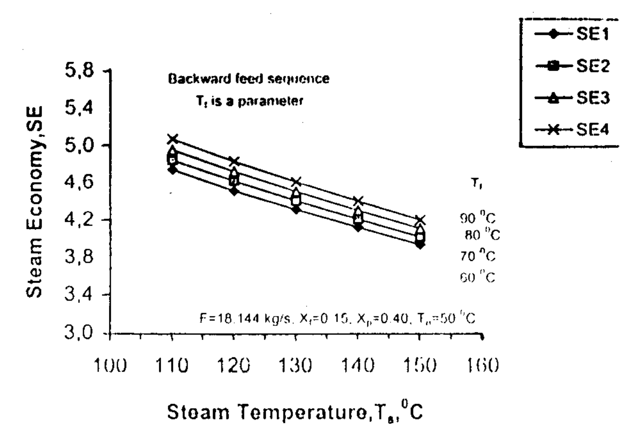

Fig-6 Effect of Steam Temperature on Steam Economy

increases by 2.35%. The above value, however remains virtually constant if one desires to change the T_f in the lower range (60°C>70°C>80°C).

At a fixed value of Ts, SE, rises with the increase of T_f.

Figure-7 indicates that the area requirement, A decreases non-linearly with the variation of Ts. It display the same trend if we increase T_f.

On further examining the results, it is found that the higher feed temperature range (80°C>90°C) gives higher reduction of SC (2.3%) than those from lower temperature range between 70°C>80°C (SC=2.2%).

Based on the findings it can be concluded that for

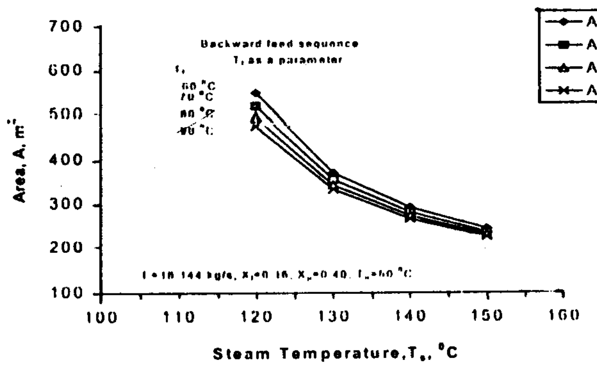

Fig-7 Effect of SteamTemperature on Area

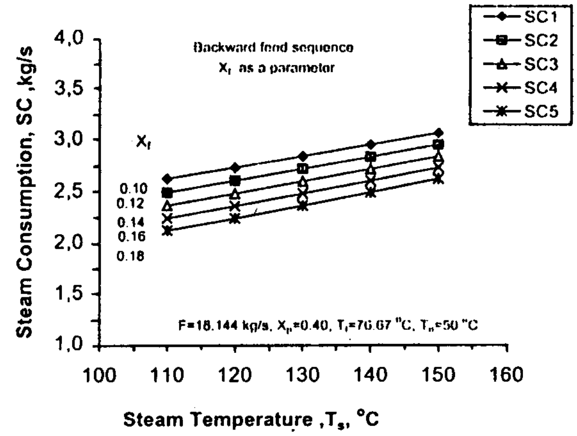

Fig.8 Influence of SteamTemperature on Steam Comsumption

10 rise of feed temperature approximately 2.2-2.3% steam saving is possible at normal working conditions of a mill. For 10°C rise of T_f from 80°C to 90°C, the requirement of A decreases by 2.55% at 140°C of Ts. At T_f equal to 80°C, and for 10°C rise of T_s from 130°C to 140°C, A decreases by 20.07%. This is shown in the given Table-4.

INFLUENCE OF FEED CONDENTRATION, X_f

Figures 8-10 are drawn to show the influences of steam temperature, T_s and feed concentration, X_f on SC, SE and A. As expected, with the increase of T_s and decrease of X_f, SC increases. Further, SE boosts up with both the lowering of T_s and X_s. The relationship exhibits a neârly parallel straight lines for the concentration range (0.10-0.18 with a step change of 0.2) examined.

The heat transfer area requirements also decrease with increase of T_s and also with increase of X_f.

EFFECT OF FEED FLOW RATE, F

Figures 11-13 are plotted to examine the effects of T_s and Feed flow rate, F. It is reflected from the Figures, that with the rise of both T_s and F, increase of SC is evident. The area requirements, A follow the same trend with the increase of F but has reverse trend with rise of T_s. This is an expected phenomena as more feed flow rate increases evaporation capacity, thereby the system demands more area.

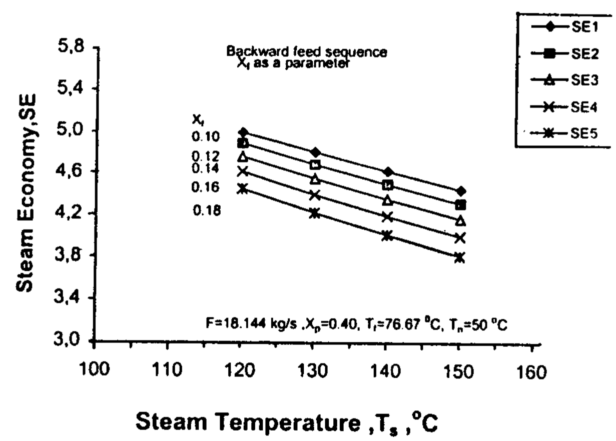

Fig-9 Influence of Steam Temperature on Steam Economy

TABLE-4 EFFECT OF T_s AND T_f ON AREA DEMAND, A, m²

STEAM TEMP., °C	FEED TEMPERATURE °C		Δ A, m²
	80	90	
130	341.4	331.8	9.6
140	272.9	265.9	7.0

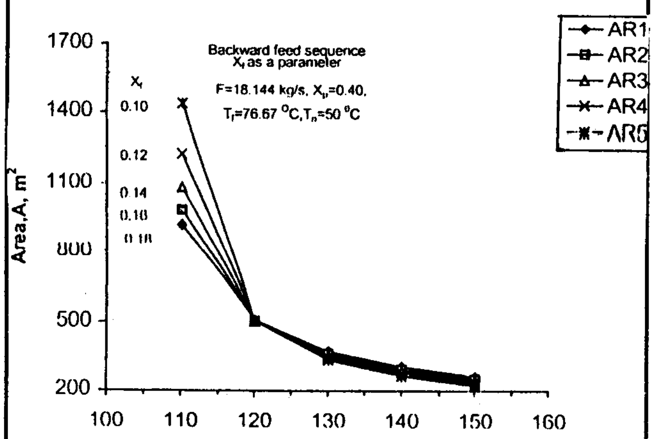

Fig. 10 Influence of Steam Temperature on Area

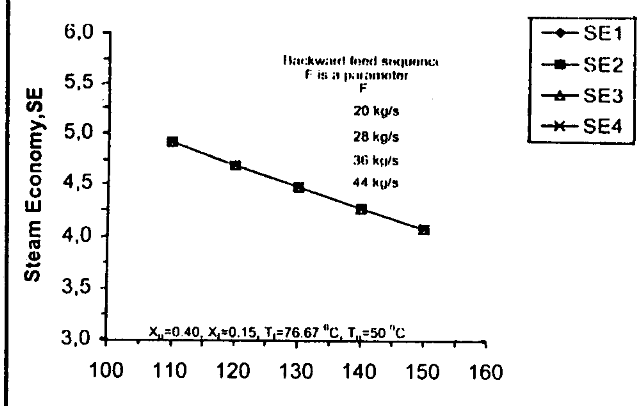

Fig-12 Effect of Steam Temperature on Steam Economy

For an increase of F by 8kg/s, the area demand increases on an average of 40% at 140°C of Ts. As both SC and evaporation rate increase, the steam economy (ratio of evaporation and steam consumption) remains virtually constant. The variations are observed to be very much insignificant (Figure 12). The observations can be briefed as follows:

The value of SC increases slowly with the increase of T_s but rises very rapidly with the increase of F. Approximately 40% increase of SC is expected with the increase of F by 8 kg/s at T_s equal to 140°C.

From Figure 12 it is interestingly noted that the straight lines corresponding to the feed flow rates, F, merge each other, showing that SE remains almost constant for all the values of F investigated.

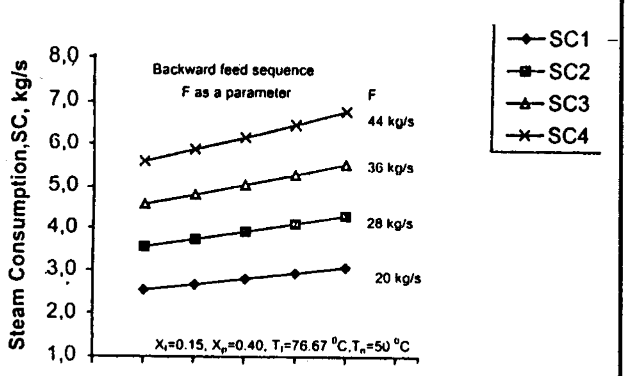

Fig-11 Effect of SteamTemperature on Steam Consumption

Figure 13 brings out the fact that heating surface area is an important function of Ts and F.

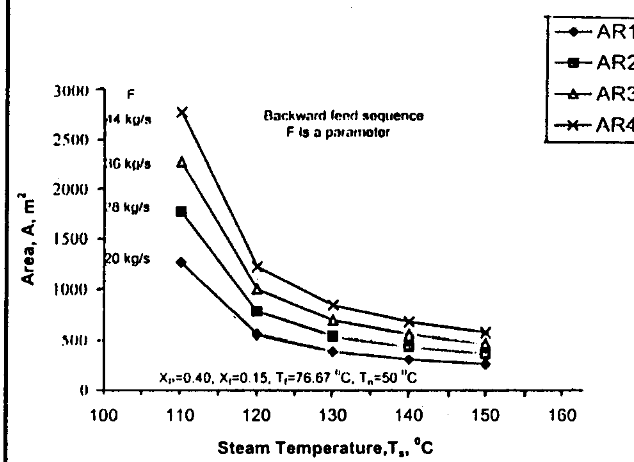

Fig-13 Effect of Steam Temperature on Area

CONCLUSIONS

From the computer program developed on the models and the detailed analysis of computed results the following conclusions can be drawn. However the results are shown by varying two parameters out of five (viz, steam temperature, feed temperature, feed concentration, feed flow rate, and last body temperature) examined at a time while the rest three parameters are kept constant.

- With the increase of steam temperature for a fixed set of other operating conditions steam consumption increases, both steam economy and area decrease with last body temperature as a parameter. Same trends are observed if feed temperature, feed concentration, and feed flow rate are also varied individually while the other parameters are kept constant (except the varying one).

- With the increase of feed temperature, steam consumption and are decrease while the steam economy increases.
- With the increase of feed concentration steam consumption, steam economy and area decrease.
- With the increase of feed flow rate both steam consumption and area decrease but steam economy remains almost constant.
- Rising the last body temperature steam consumption decrease but both steam economy and area increase.

The most advantageous point is to increase the feed temperature. Around 2.2 -2.3% steam saving is possible at normal working conditions if one increases the feed temperature by 10 C . The mathematical models developed and the solution technique employed in this present investigation can precisely evaluate data for any sequences of any MEE set up. The computational procedure developed helps to generate large body of data and can handle many variables and their interactions and interdependence with each other. In today's context it is extremely essential to use this software for the benefit of Industry, paper mill in particular. The design procedure developed can bring accuracy in assessing the performance of an existing evaporator system or can help in designing a new system for a Greenfield pulp and paper mill.

NOMENCLATURE

A. Area of evaporator body, Heat transfer area of effect, m^2 in evaporator set: air, input per unit feed in equation-2.

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

BPR Boiling point rise, ^0C or K

B An exponent, Eq.(2)

Cp Specific heat of liquor; v. vapour; w, water, kJ/kg

C Condensate from steam chest; Cost; pi, water injection seprated handling : pc, spray cooling water. Rs/kg of water

Cw Cost of replacement water, Rs/kg

D Number of working days per year exclusive of cleaning days

e_i Evaporation coefficients, kg/hr m^2

E_t Total amount of water evaporated per day in the evaporator, kg/ day

F1 Fraction of capital cost of evaporator for repair and maintenance cost; functional notation in Eqs. (5.7) & (5.8)

F Liquor feed rate, kg/s; fixed charges as fraction of the capital cost of evaporator

g_j A function defined as gj =fj/Fλ_0

H Specific enthalpy of the vapor, k_j/kg

h Specific enthalpy of liquor kJ/kg; heat transfer coefficient, W/m^2 K

K_i Relative cost factor of cleaning;i, for any body

k thermal Conductivity, W/m^2K

L Liquor flow rate from the effect. kg/s

I Fractional liquor flow rate defined by I_j=L/F

M Flash vapor flow rate from flash tank, kg/s

m Fractional flash vapor flow rate from flash tank defined by M_j=M_j/F, A constant

n Number of effects in an evaporator; exponent in Eq. (2), last effect

P Pressure, N/m^2

$(Pa)_{std}$ First cost of air handling equipment of some basic capacity (a_{std}) taken as standard.

Q Rate of heat transfer across the tube from the steam/water vapor to the liquor, W

q Heat flux, W/m^2

R Time between successive cleaning (for first the two bodies), days r A factor for replacement cum make up water

SC Steam consumption, kg/s

SE Steam economy, kg/kg.

T Saturation temperature of water at pressure P, ^{0}C

Ts Temperature of steam interning the first effect,^{0}C

TS Total soiled content of liquor, %

$(\Delta T)_{eff}$ Effective Temperature, ^{0}C

t_f Tempreature, ^{0}F

U Overall heat transfer coefficient, W/m^{2}k

u Fractional temperature defined by $uj = T_j/T_0$

V Vapor flow rate from the effect, kg/s

v Fractional vapor flow rate from the effect defined by vj = Vj /F

w Amount of water required per kg of vapor condensed

X Mass fraction of solute in the liquor

GREEK SYMBOLS

ρ Density of liquor, kg/m^3

μ Viscosity of liquor, cp, m Pas

λ_0 Latent heat of vaporization of primary vapor in the first effect, kJ/kg

λ_j Latent heat of vaporization of water at its saturation temperature T_j and Pressure, P_j, kJ/kg

SUBSCRIPTS (EXCEPT AS ABOVE)

a Air

c-c Condensing and cooling

f Feed, feed concentration

j input; effect number (j = 1, 2, 3,......, n)

m Average

Std Standard

REFERENCES

1. Holland, C.D., "Fundamentals and Modelling of Separation Processes", Prentice-Hall, Englewood Cliffs, N.J., (1975).
2. Kern, D. Q., "Process Heat Transfer", International Edition, McGraw Hill Book Co. Inc. N.Y. (1950).
3. Gudmundson, C., "Heat Transfer in Industrial Black Liquor Evaporator Plants", Part-II, Sevensk. Paperstinnding, Vol. 75, No. 22, PP 901-908 (Dec. 1972).
4. Mathur, T.N.S., Ph.D. Thesis "Energy Conservation Studies for the Multiple Effect Evaporator House of Pulp and Paper Mills" University of Roorkee, Roorkee (1992).
5. Ray, A.K. "Studies in Short Tube Multiple Effect Sugar Cane Juice Evaporator", Ph.D. Thesis, University of Roorkee, Roorkee, (1989).
6. Singh, P. "Optimization Techniques and Their Applications in Paper Industry" Ph.D. Thesis, C.C.S. University Meerut, (1999).