Design of Black Liquor Multiple Effect Evaporator System - Effect of Splitting of Feed and Flash Utilization

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ABSTRACT

In earlier communication (1) a generalised algorithm is developed for design and simulation of black liquor multiple effect evaporator system (MEE) with a typical backward feed sequence. In the present investigation the above algorithm is extended for backward feed sequence involving splitting of feed and distributing equally the same to the last two bodies of the set and the results of the two sequences are compared. Further comparison is made if flash from condensate and product are used for additional advantages of energy gains and higher steam economy in a typical backward feed sequence with no splitting of feed. Significant saving in steam consumption with enhanced steam economy has been achieved but with slight increase of heating surface demand for the evaporator system. This is however tested with a sextuple effect multiple effect evaporator system which is found to be optimum based on curent operating and equipment cost. The procedurefor the latter is designed by developing mathematical models based on the set of 17 non-linear simultaneous equations unlike the former two where 12 equations are needed for steady state mass and energy balance , enthalpy balance heat transfer rate equations coupled with models for overall heat transfer coefficients and physico thermal properties of black liquor including boiling point rise calculations. A number of iterative schemes is developed for each parameter with the help of Fortran 77 computer program, interlinked with each other and solved for the desired objective The systems of non linear equations are solved by Newton-Raphson method with Jacobian matrix and method of Gauss elimination with partial pivoting with the aid of Hilbert norms. The benefits accrued in terms of reduced steam consumption and enhancement of steam economy are quantified for a set of typical operating parameters normally used in a paper mill. This procedure appears to be newer for rapidity of convergence and estimates the energy consumption more accurately and efficiently.

INRODUCTION:

Mathematical model is a powerful tool for accruing more economic benefits in terms of energy saving in any process industry including pulp and paper. There are many areas where mathematical models are used in pulp and paper industry, Multiple Effect Evaporator (MEE) simulation and optimization

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is one of them. In fact the MEE is a device to concentrate black liquor for delivering it to the recovery furnace for steam and power generation with recovery of spent chemicals present in the black liquor. It is well known that MEE operation is a bottleneck in terms of major energy consuming operation in a paper mill. Some investigator (1-7) developed steady state Mathematical models of MEE with usual mass and energy balance equations, heat transfer rate equation, equilibrium relationship and solved by linear and non-linear techniques iteratively. The equations for MEE for soda black liquor & sugar juice has also been discussed by Kern (7). The overall heat transfer coefficient based on temperature & heat flux values have been developed and them empirically fitted with 450 sets of industry data by Gudmundson (8). Ray etal. (9) reviewed the correlations of all physico-thermal properties of black liquor and discussed the suitability of each equations. Parametric influence on steam consumption, (SC), steam economy (SE) and area requirements (A) w as mainly studied. Singh and Ray have studied in d e tail the backward feed sequence (1), and split feed sequence (10) with more realistic operational parameters and further investigated the impact of condensate flash and product flash on energy factors for backward feed sequence (11). In all these investigatons instead of using equations for equilibrium relationship for boiling point rise, correlations of latter has been coupled in the main program. As a result the 4 N equations needed for sextuple effect evaporator have been reduced to smaller number of equations. The system is designed with an aim to make the system most energy efficient and cost effective. In this present investigation firstly a comparison has been made between backward feed sequence and the same with the feed splitted and distributed euqally to the last two bodies, and then subsequently with addition of condensate flash and product flash in some of these sequences. The present work therefore extends the work previously communicated (1,10,11) for a backward feed MEE system to backward feed flow sequence with feed splitting and to backward feed flow sequence with utilization of flash vapour from condensate and product. It is not out of place to mention that these designs, especially the splitted flow sequence are very popular in North American paper mills. To the best of author's knowledge this type of systematic analysis is scarce.

MATHEMATICAL MODELS:

In previous communication (1) it has been shown that the minimum annual cost based on prevaling market prices corresponds to six number of bodies (1) Six body or sextuple effect evaporator is thus the most feasible MEE set for the present investigation as a basis for modelling and simulation of black liquor concentratin system for paper industry.

It is wellknown that the modelling of sextuple effect evaporator system will start with 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. The steady state modelling of backward feed sequence has been discussed in earlier communications with detailed derivation for the first effect (1). In the present modelling the additional complexities arise due to feed splitting favoured by North American mills and also accomodating the terms related toboth condensate and product flash utilization in the constitutive equations of a backward feed sequence. Hence remodellling of the systems incorporating both condensate and flash utilization should be attempted a fresh. When the feed is splitted and euqally distributed between two bodies, 5th and 6th of as sextuple effect evaporator system, the equations for 4 5 and 6 effect of the sextuple effect black liquor evaporator system will different and hence can be derived accordingly with suitable modifications of the equations. Based on the approach of Holland (5) for sextuple effect evaporator system for the evaporation of black liquor, without detailing of the derivation the general mass and energy balance equations for flow sequence due to backward feed, splitted fed and backward feed with condensate and product flash for any body of an N body set are presented here. However, all the equations presented here are scaled form of the functions. The effect of scale deposition is not included in the modelling.

2.1 Case I: Mathematical model for a sextuple effect evaporator system with backward feed: ($6 \rightarrow 5 \rightarrow 4 \rightarrow 3 \rightarrow 2 \rightarrow 1$)

For the design procedure of a sextuple effect evaporator system for backward feed sequence the model gives rise to a set of 12 independent nonlinear algebraic equations in scaled form in 12 unknowns.

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

$$g_{i+1} = U_n T_s a_n/50.\ \lambda_s\{u_{n-1} - (u_n + BPR_n/T_s)\} - (l_n - l_{n-1})/\lambda_s(\lambda_{n-1} + CPvBPR_{n-1})$$
$$(i=1,3....11;\ n = 1,2......6) \quad ...(2)$$

2.2 Case II: Mathematical model for a sextuple effect evaporator system with split feed:

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

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

$$g_i = l_{n+1}T_s/\lambda_s\{CP_{n+1}(u_{n+1} + BPR_{n+1}/T_s) - CP_n(u_n + BPR_n/T_s)\} + (l_n - l_{n-1})/\lambda_s (\lambda_{n-1} + CPvBPR_{n-1}) - (l_{n+1} - l_n)/\lambda_s\{(\lambda_n + CPvBPR_n) - CP_n T_s((u_n + BPR_n/T_s)\} - (l_{n+1} - l_n)/\lambda_s(\alpha u_n + \beta/T_s)T_s \quad ...(3)$$

$$g_{i+1} = U_n T_s a_n/50.\ \lambda_s\{u_{n-1} - (u_n + BPR_n/T_s)\} - (l_n - l_{n-1})/\lambda_s(\lambda_{n-1} + CPvBPR_{n-1})$$
$$(i=1,3....11;\ n = 1,2......6) \quad ...(4)$$

2.3 Mathematical model for a sextuple effect evaporator system with backward feed andwith condensate and product flash: (6 →5 → 4 →3 → 2 → 1)

For the design procedure of a sextuple effect evaporator system with the above design, the model gives rise to a set of 17 independent nonlinear algebraic equations in scaled form in 17 unknowns.

(a) Case III:Backward feed with condensate flash tank:

$$g_i = l_{n+1}T_s/\lambda_s\{CP_{n+1}(u_{n+1} + BPR_{n+1}/T_s) - CP_n(u_n + BPR_n/T_s)\} + (l_n - l_{n-1} + m_{n-1})/\lambda_s(\lambda_{n-1} + CPvBPR_{n-1}) - (l_{n+1} - l_n)/\lambda_s\{(\lambda_n + CPvBPR_n) - CP_n T_s((u_n + BPR_n/T_s)\} + m_{n-1}\lambda_{n-1}/\lambda_s - (l_{n+1} - l_n)/\lambda_s(\alpha u_n + \beta/T_s)T_s \quad ...(5)$$

$$g_{i+1} = U_n T_s a_n/50.\ \lambda_s\{u_{n-1} - (u_n + BPR_n/T_s)\} - (l_n - l_{n-1} + m_{n-1})/\lambda_s(\lambda_{n-1} + CPvBPR_{n-1}) - m_{n-1}\lambda_{n-1}/\lambda_s$$
$$(i=1,3....11;\ n = 1,2......6) \quad ...(6)$$

The general equation for I[st] to 5[th] condensate flash tank:

$$g_i = ((l_n - l_1 + m_1)AT_s/\lambda_s)(u_{n-1} - u_n) - m_n T_s/\lambda_s(Yu_n + Z/T_s)$$
$$(i=13,14,...17;\ n=1,2,...5) \quad ...(7)$$

(b) Case IV:Backward feed with condensate flash and additional flash tank:

For addition of flash vapour utilization in the system with condensate flash in the preceeding models only fourth to sixth body will be affected.

The equations for backward feed with condensate and product flash with suitable modifications can also be derived in the similar way as under:

EFFECT NO. 4

$$g_7 = l_5 T_s/\lambda_s\{CP_5(u_5 + BPR_5/T_s) - CP_4(u_4 + BPR_4/T_s)\} + l_6 T_s/\lambda_s\{CP_6(u_6 + BPR_6/T_s) - CP_4(u_4 + BPR_4/T_s)\} + (l_4 - l_3 + m_3 + m_p)/\lambda_s(\lambda_3 + CPvBPR_3) - (l_5 - l_4)/\lambda_s\{(\lambda_4 + CPvBPR_4) - (l_5 - l_4)/\lambda_s(\alpha u_4 + \beta/T_s)T_s \quad ...(8)$$

$$g_8 = U_4 T_s a_4/50.\lambda_s\{u_3 - (u_4 + BPR_4/T_s)\} - (l_4 - l_3 + m_3 + m_p)/\lambda_s(\lambda_3 + CPvBPR_3) \quad ...(9)$$

EFFECT NO. 5

$$g_9 = l_6 T_s/\lambda_s\{CP_6(u_6 + BPR_6/T_s) - CP_5(u_5 + BPR_5/T_s)\} + (l_5 - l_4 + m_4)/\lambda_s(\lambda_4 + CPvBPR_4) - (0.5 - l_5)/\lambda_s\{(\lambda_5 + CPvBPR_5) - CP_5 T_s((u_5 + BPR_5/T_s)\} - (l_6 - l_5)/\lambda_s(\alpha u_5 + \beta/T_s)T_s \quad ...(10)$$

$$g_{10} = U_5 T_s a_5/50.\lambda_s\{u_4 - (u_5 + BPR_5/T_s)\} - (l_5 - l_4 + m_4)/\lambda_s(\lambda_4 + CPvBPR_4) \quad ...(11)$$

EFFECT NO.6

$$g_{11} = T_s/\lambda_s\{CP_f(u_f + BPR_f/T_s) - CP_6(u_6 + BPR_6/T_s)\} + (l_6 - l_5 + m_5)/\lambda_s(\lambda_5 + CPvBPR_5) - (1.0 - l_6)/\lambda_s\{(\lambda_6 + CPvBPR_6) - CP_6 T_s((u_6 + BPR_6/T_s)\} - (1.0 - l_6)/\lambda_s(\alpha u_6 + \beta/T_s)T_s \quad ...(12)$$

$$g_{12} = U_6 T_s a_6/50.\lambda_s\{u_5 - (u_6 + BPR_6/T_s)\} - (l_6 - l_5 + m_5)/\lambda_s(\lambda_5 + CPvBPR_5) \quad ...(13)$$

Where $Y = \gamma - \alpha$ and $Z = \delta - \beta$ and where the constants α, β, γ and δ have the values 4.1832, 0.127011, 1.75228 and 2503.35 respectively.

The diagrammatic skektches of the above design alternatives are depicted in Appendix-A.

SOLUTION OF MODELS:

SELECTION OF MATHEMATICAL METHODS:

The mathematical models invelves nonlinear algebraic equations which are difficult to solve. Many investigators (1,4-6,10,11) developed algorithms which reduce the systems of non linear algebraic equations that govern the evaporator system to a linear form by any means and solve them iteratively by a linear technique, e.g. Gaussian Elimination etc. Holland (5)has reported that the Newton Raphson Jacobian matrix method followed by method of Gauss elimination is the best to solve the system of non-linear equation. Newtons algorithm is widely used because it more rapidly convergent than other methods. An algorithm based on Gudmundson model (8) is developed as shown in appendix-B and used as a subprogram. A separate subroutine/suprogram is also developed for estimating physico thermal properties of black liquor (1) All the subroutines/subprograms are interlinked with the main program for mass, energy and heat transfer rate equations.

In the present investigation Newton-Raphson Method with Jacobian matrix and method of Gauss Elimination have been used with partial pivoting and Hilbert Norms to solve the system of non linear equations thus generated. The set of a non linear equations governing the system in matrix form can be written as:

$$J_k \Delta X_k = - g_k \quad ....(15)$$

Where J is the square Jacobian matrix of order 12,12 and 17 for present sequences: i.e., backward feed split feed and backward feed with condensate and product sequence respectively. ΔX_k and g_k are conformable vectors.

On the basis of an assumed set of values for the elements of the column matrix X the corresponding values of the elements of J_k and g_k are computed.

COMPUTER SIMULATION AND MODEL VALIDATION:

Computer programs based on FORTRAN-77 have been developed for all the three cases separately with the following initial approximation. Initially the evaporation rates and areas are considered equal as: $v_j = v;\ a_j = a\ (1 \le j \le 6)$ ... (20)

Case - I and II :

The knowns variables are: F, T_f, X_f, T_s, T_n, x_p (x_1) U_1, U_2, ... U_6, and BPR_1, BPR_2,.. BPR_6. The unknowns variables are: v_0, l_2, l_3, ... l_6, u_1, u_2, ...u_5, a, and x_1, x_3, ... x_6.

Case-III and IV:

The knowns variables are: F, T_f, X_f, T_s, T_n, x_p (x_1) U_1, U_2, U_6, and BPR_1, BPR_2,.. BPR_6. The unknowns variables Are v_0, l_2, l_3, ... l_6, u_1, u_2, ...u_5, m_1, m_2, ...m_1, m_5, a and x_2, x_3, ... x_6, The term x can be calculated by mass balance for solid : $F_{xf} = L_i x_i$ (i = 1, 2 ...6). The specified variables are latent heat of vaporisation boiling point rise (BPR) and specific heat (CP) etc. which can be calculated by different correlations for all the three cases.

Kern's (7)data for six effect evaporator body with backward feed sequence(without considering scale deposition) is used for model validation. As explained the oveall heat transfer coefficient from Gudmundson' model (8) and physico chemical and thermal properties of kraft black liquor such as density, viscosity, specific heat and thermal conductivity etc from Ray etal. (1,9) are also employed. The model predicted data matches well with Kern's data indicating the accuracy of the model developed in this present investigation

RESULTS AND DISCUSSION:

Earlier works (1,3,4) have shown that the out put parameter SC, SE and A, are quite sensitive to variation in the steam temperature, T_s, liquor feed temperature, T, feed concentration, X_f, feed temperature, T_f and feed flow rate, F. The values of above input parameters are selected in such a way that they must lie within the normal mill's operating conditions. How ever the effect of scale deposition is not considered. The variations of steam temperature, T_s, on SC, SE and A at various values of T_n, T_f, X and F are displayed with the same trend for split feed also as for truly backward feed flow sequence as shown earlier (1). There are marginal difference of the value observed. The split feed sequence gives better result. These are shown in figs. 1-15. From the figures it is evident that with the increase of T_s, SC increases, SE decreases and A drops; with the increase of T_f, SC and A drops but SE increases; with the increase of X, SC, SE and decrease; raising the value of T_n, SC decreases but SE and A increase; increasing F the increase of SC and A are observed with SE remaining almost constant.

The most advantageous point is to increase the feed temperature. Therefore comparison between two sequences are made on T only.

With the increase of T by 10°C (70°C to 80°C) the SC decreases by 3.4-3.5% with split feed in comparison to 2.2-2.3% saving for normal backward feed The requirement of A is increased to approx 3.0% incase of split feed as 2.55% in the case of truly backward feed flow sequence. However these values are estimated on different operating conditions. If same operational conditions are used the split feed will always be superior compared to backward feed sequence. This is clearly evident in Table 1. As the split feed needs splitting of the feed through valves and various connections and requires pipe lines. In India the use of split feed is apparently limited though it is always better than backward feed sequence in all respects.

The gain by using condensate and product flash from a truly backward feed will now required to be quantitatively evaluated as given in the following paragraphs.

COMPARISON OF SC SE AND A AMONG VARIOUS PROPOSED OPTIONS FOR BACKWARD FEED SEQUENCE EXCEPT SPLIT FEED:

In this Section the SC SE and A values are compared if a six body truly backward feed sequence (A') is extended for additional heat economy measures viz, condensate flash utilization (B) and with further addition of product flash (C).

The effects of T_s T_f X_f T_n and F, on SCl SE and A for the above three cases follow the usual trend as expected. The variations are shown in fig. 16-30. These are quite self explanatory. With the rise of feed temperature, decrease of SC, increase of SE, and rapid decrease of A are noticed. This is valid for all the cases, namely A,B,C.

The variations of other parameters are examined through graphical correlations and the following observations are made at 80°C of feed temperature:

a. The SE values are enhanced with utilization of condensate flash and further enhanced with addition of product flash. The gain in steam economy has been found to be on the order of 5.7 and 5.6 for the design C at st eam temperature, 130°C and 140°C respectively.

TABLE 1

Comparison among various options of evporator designs (Kern's Data)

($F = 18.144$ kg/s, $x_f = 0.152$, $T_f = 76.67^0C$, $T_s = 137.78^0C$, $T_n = 51.67^0C$, $x_p = 0.405$)

Parameter	Backward Feed flow sequence (BFFS) A	Split feed flow sequence (No flash) D	BFFS with condensate flash B	BFFS combined condensate flash and product flash C	% gain, C-A'/D-A'
SC, kg/s	2.6119	2.5671	2.120	1.9894	23.83/1.72
SE, kg/kg	4.340	4.417	5.346	5.697	31.20/1.77
A, m^2	295.566	292.46	303.539	306.619	03.74/0.71

Note : (Value from chosen sequence - value from BFFS) x 100/Value from BFFS

The steam saving of 18.8% (A to B) can be accomplished if condensate flash is utilized. The use of product flash decreases the steam consumption further on the order of 6.0-6.2% (B to C).

b. The SE values at steam temperature of 137.78°C and feed temperature of 70°C found are 4.269, 5.257 and 5.569 respectively for without flash, with condensate flash and with combined condensate and product flash, indicating economy gain on the order of 23% and 29.6% respectively.

The advantage in terms of reduction of SC, enhancement of SE, and disadvantage of extra heating surface are found to be 23.85% 31.2% & 4.2% respectively if one shifts from the design A to the design C at 80°C as feed temperature at fixed set of other input parameters as mentioned in the figures.

c. Nearly 2.6% more area is to be provided in the case of system with condensate flash in comparison to the system without flash. The system with combined product and condensate flash demands extra area on the order of only 1% thus, becoming total 3.6% over and above the system without any flash.

On closer scrutiny of the results of simulation on computer the following inferences can be made:

It is established that in the Back ward feed sequence C is better than B and B is better than split feed D and the latter is better A considering all the aspects of steam consumption, steam economy and particularly area compensation effects on total cost. This is also verified from the data given in Table 1 which is obtained from Kern (7). The values are onthe same level as indicated in above. Thus confirms the accuracy of estimation of benefits.

CONCLUSIONS

For a given number of stages the mathematical procedure computes design variables such as area (or area ratio between effects), externally supplied steam flow rate, stage temperature and flows, etc. For a multiple effect evaporator (scaling is not considered). Significant improvement has been found in terms of benefits in energy consumption though slight increase of heating surface requirements is observed.

- The most advantageous point is to increase the feed temperature. Around 3.4-3.5% steam saving is possible if one uses split feed flow sequence in comparison to truely backward feed sequence (2.2-2.3%) steam saving normal working conditions if one increases the feed temperature by 10°C.
- The split feed sequence is always better in terms of reduction in steam consumption, gain in steam economy and reduction in area demand though marginally.
- The advantage in terms of reduction of SC, enhancement of SE, and disadvantage of extra heating surface are found to be 23.85%, 31.2% & 4.2% respectively if one shifts from the design A to the design C at 80 C as feed temperature at fixed set of other input parameters. The steam saving of 18.8% can be accomplished if

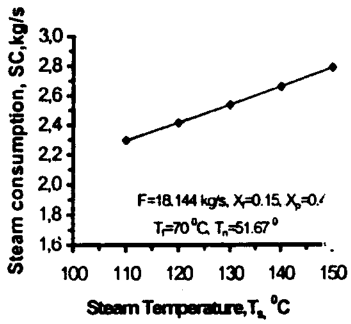


Fig-1 Influence of Steam Temperature on Steam Consumption

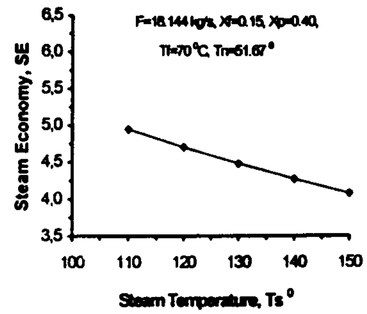


Fig-2 Influence of Steam Temperature on Steam Economy

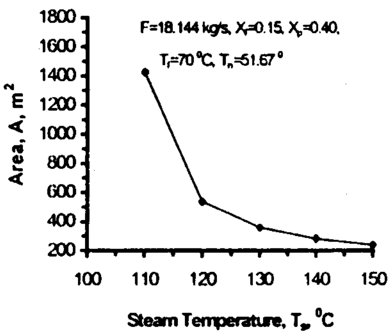


Fig- 3 Influence of Steam Temperature on Area

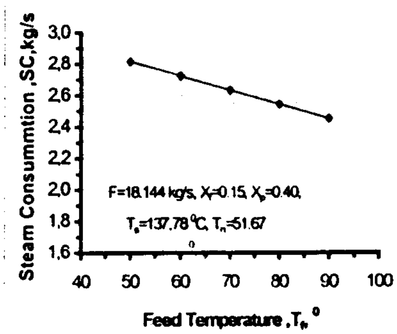


Fig- 4 Effect of Feed Temperature on Steam Consumption

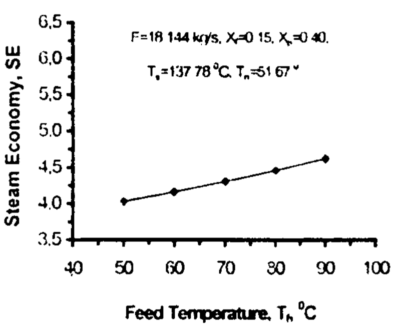


Fig-5 Effect of Feed Temperature on Steam Economy

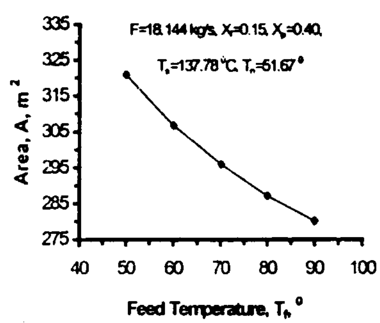


Fig- 6 Effect of Feed Temperature on Area

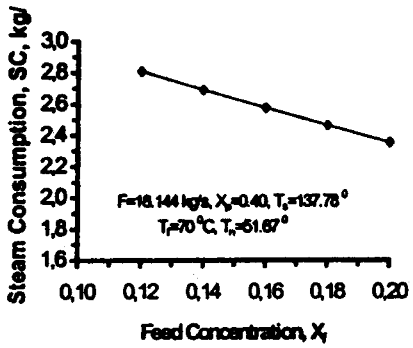


Fig-7 Influence of Feed Concentration on Steam Consumption

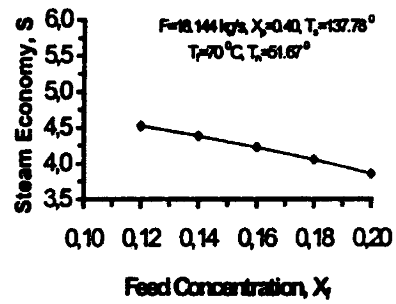


Fig-8 Influence of Feed Concentration on Steam Economy

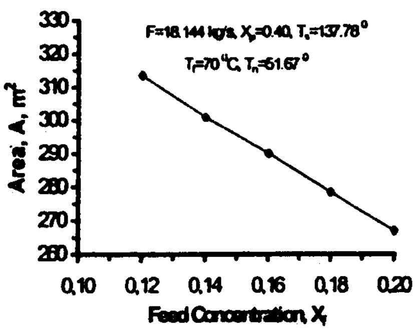


Fig- 9 Influence of Feed Concentration on Area

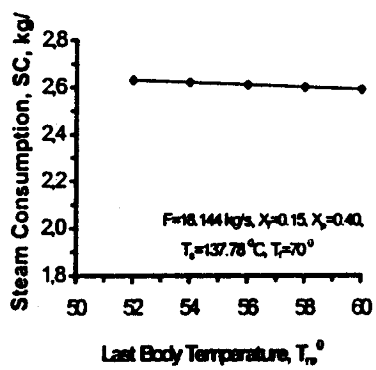


Fig- 10 Effect of Last Body Temperature on Steam Consumption

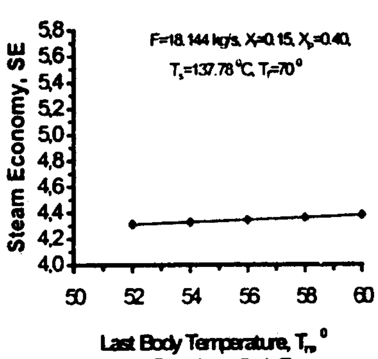


Fig- 11 Effect of Last Body Temperatur on Steam Economy

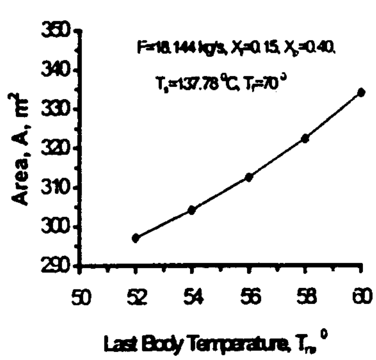


Fig-12 Effect of Last Body Temperature on Area

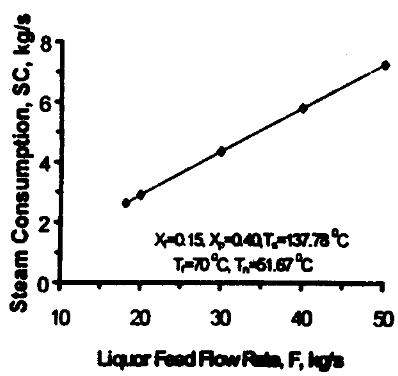


Fig- 13 Effect of Liquor Flow Rate on Steam Consumption

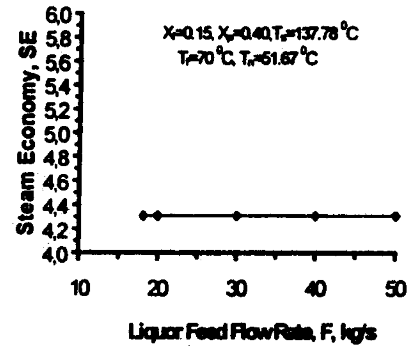


Fig-14 Effect of Liquor Flow Rate on Steam Economy

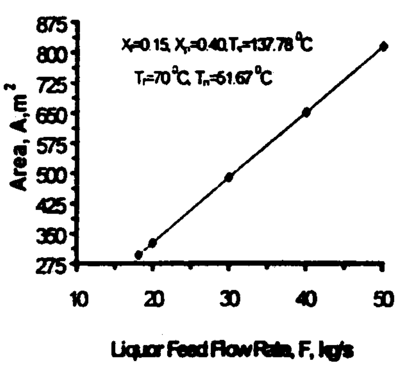


Fig-15 Effect of Liquor Flow Rate on Area

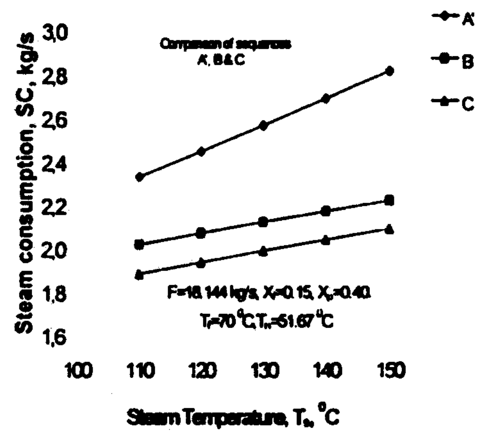


Fig- 16 Effect of Steam Temperature on Steam Consumption

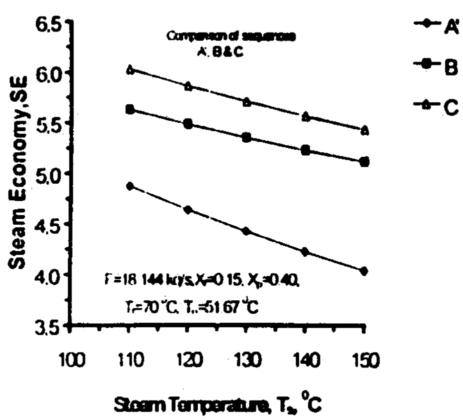


Fig- 17 Effect of Steam Temperature On Steam Economy

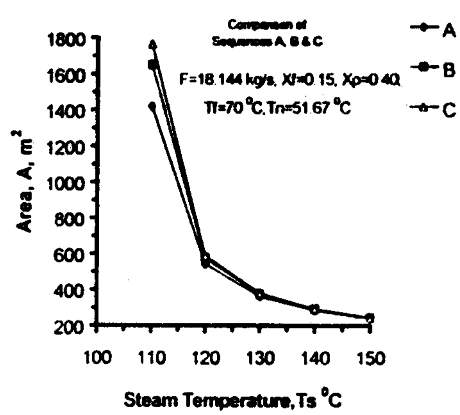


Fig- 18 Influence of Steam Temperature on Area

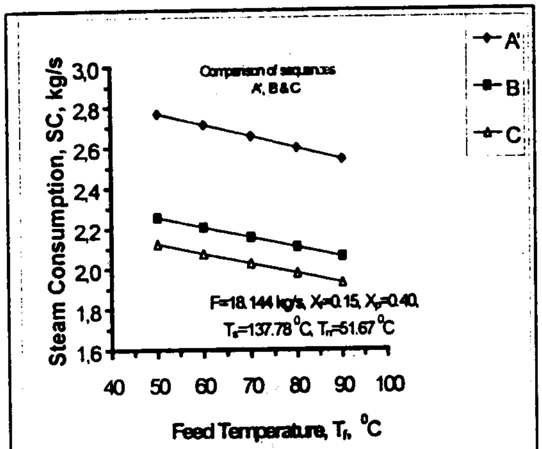


Fig- 19 Effect of Feed Temperature on Steam Consumption

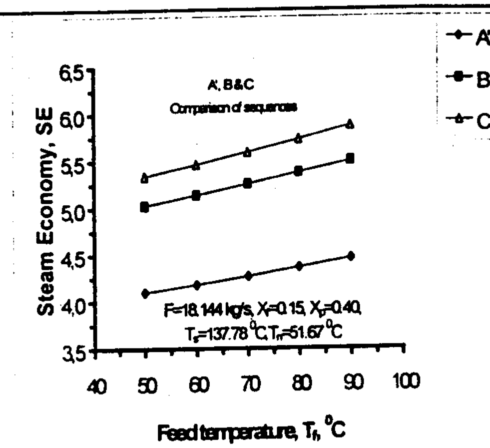


Fig-20 Effect of Feed Temperature on Steam Economy

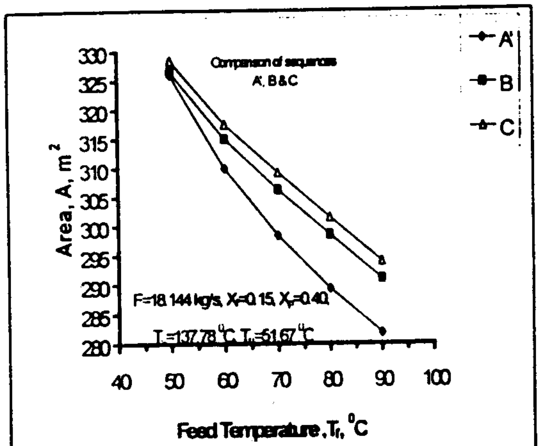


Fig-21 Effect of Feed Temperature on Area

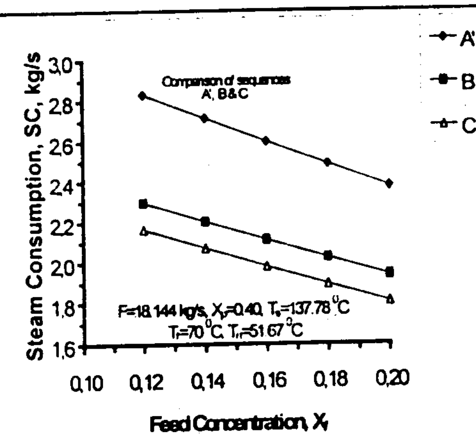


Fig- 22 Influence of Feed Concentration on Steam Consumption

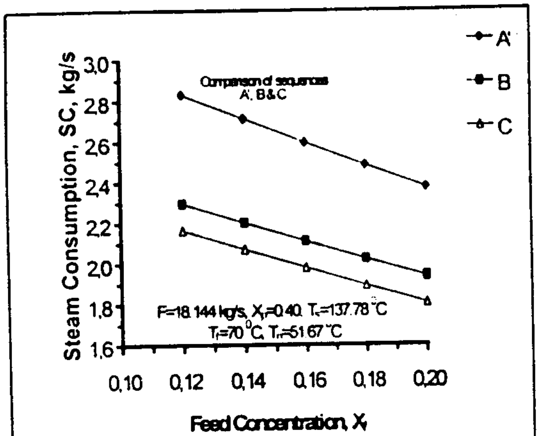


Fig- 22 Influence of Feed Concentration on Steam Consumption

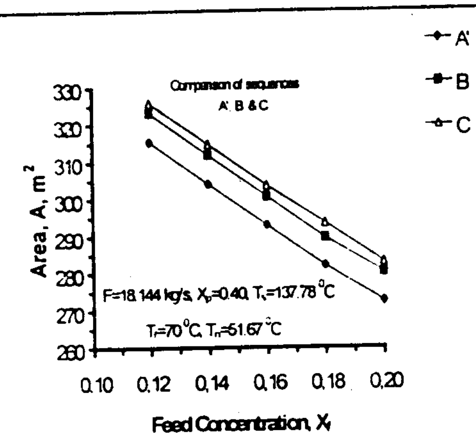


Fig- 24 Influence of Feed Concentration on Area

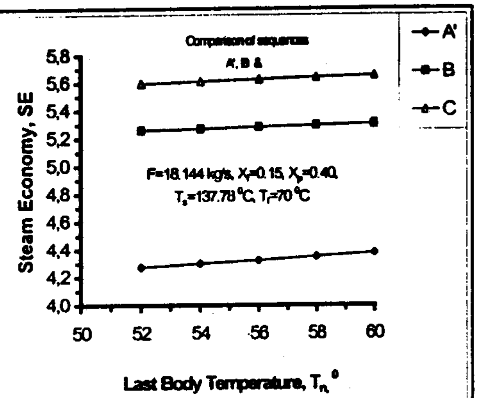


Fig- 25 Influence of Last Body Temperature on Steam Economy

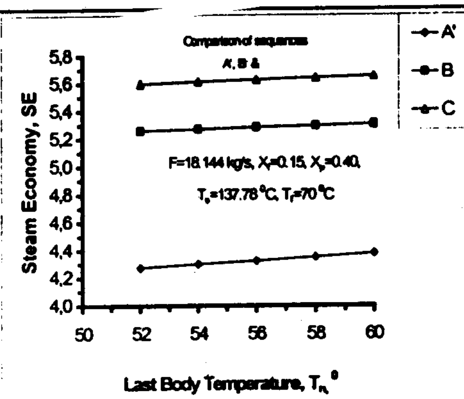


Fig- 26 Influence of Last Body Temperature on Steam Economy

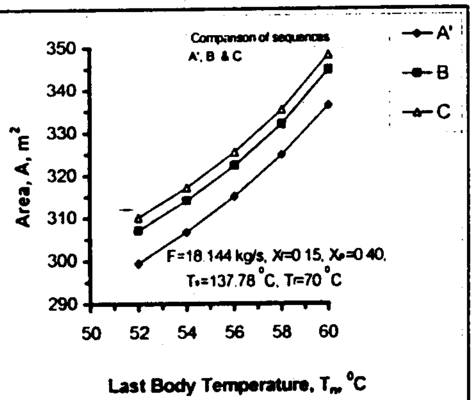


Fig- 27 Influence of Last Body Temperature on Area

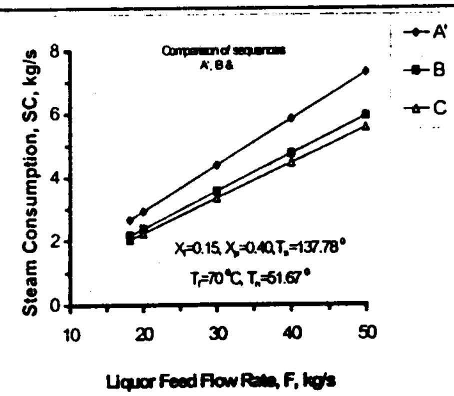


Fig- 28 Steam Consumption as a Function of Liquor flow Rate

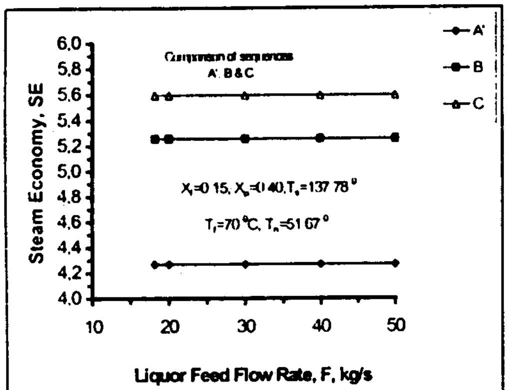


Fig- 29 Steam Economy as a Functionof Liquor Flow Rate

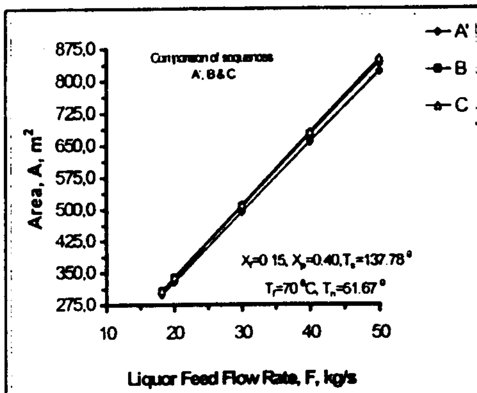
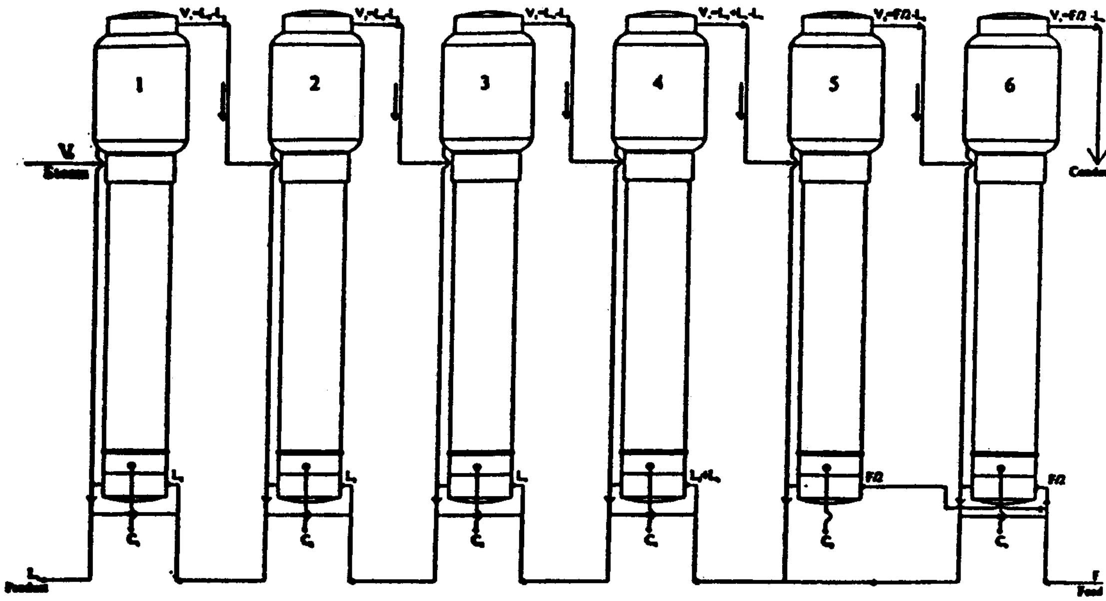


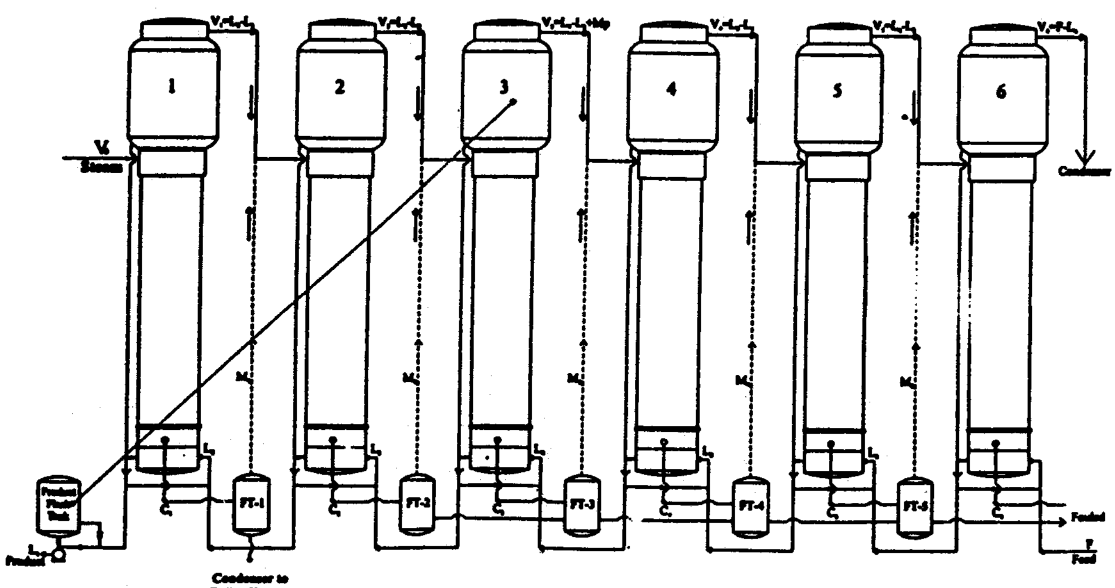
Fig- 30 Area as a function of Liquor Flow Rate

APPENDIX -A



Sextuple Effect Evaporator System With Split Feed (D)

5
(> 4 → 3 → 2→ 1)
6



Sextuple Effect Evaporator System With Backward Feed and With Condensate and Product Flash Tank
(6→5→4→3→2→1)

condensate flash is utilized. On use of product flash decreases the steam consumption further on the order of 6-6.1%.

- The SE values found are 4.269, 5.257 and 5.596 respectively for without flash, with condensate flash and with combined condensate and product flash, indicating economy gain on the order of 23% and 29.6% respectively.

APPENDIX-B

ALGORITHM FOR CALCULATIONS OF HEAT TRANSFER COEFFICIENT BASED ON GDMUNDSON'S MODEL (8)

The overall heat transfer coefficient, U is a function of q,i.e. U=f(q) which in turn is a function of various physico-thermal properties. In adition one has to know its boiling temperature, temperature of subcooling, superheating, maximum t emperature and flow rate . The procedure is depicted as under:

- Estimate $\rho(C,T)$, $\mu_m(C,T)$, $C_p(C,T)$, $k(C,T)$ for black liquor from respective equations(1)
- Calculate F,liquor feed flow rate per unit cross sectional area,kg/m^2s.
- Estimate the approximate value of heat flux q, W/m^2
- Estimate T_{boil} as suggested by Gudmundson(8)
- Estimate Z
- Calculate the limiting value of Bound1
  $Bound1 = 19500+2000 \text{ Log}\mu_m - 95 (T_{boil})$
  If $\mu_m < 1.0$ then put $\mu_m = 1.0$ in equation of Bound1.
- Estimate T_{max}
  $T_{max} = 15.0 + [0.12 - 0.001 (T_{boil}) F + [3.0 - 0.025 (T_{boil})] \log\mu_m - 0.12 (Tboil)$
- Estimate T_{sub}
  $T_{sub} = T_{max} - T_{in}$
- Estimate the values of correlation factor C
  $C = C_\mu * C_T * C_F$
  $C_\mu = 1.0-0.07858 \mu_m + 0.002735 \mu_m^2 - 0.1092 \times 10^{-4} \mu_m^3 ; (0<\mu_m<15)$
  $C_\mu = 1.576- 0.095 \log \mu_m;(\mu_m>15)$
  $C_T = -1.02 + 0.0476 (T_{boil}) - 0.364 \times 10^{-3}(T_{boil})^2 + 0.946 \times 10^{-6} (Tboil)^3$
  $C_F = Z + [-0.0515 + 0.0505 Z) F$
  $Z = 1.0 + 0.01 \times \text{Tanh} [(q - Bound1)/21800] T_{sub}^{0.4}$
  If $T_{sub}<0.0$ then put $T_{sub}=0.0$ in Z.
- Calculate the limiting values of Bound2
  $T_{sup} = T_{in} - T_{max}$
  A heat balance on the tube gives the increment of heat flux as
- $\Delta q = T_{sup} \times C_p \times F \times 0.00181 \times 0.61/1.321$
- At extremely low heat flux, when q<Bound2,
  $Bound2 = 4300+100 \text{ Log}\mu_m - 14.0 (T_{boil})$
  If $\mu_m < 1.0$ then put $\mu_m = 1.0$ in equation of Bound2.
  For bound 2 $\leq q \leq 20000 W/m^2$ calculate
  $U = 0.981 C^{1.0}[0.2334 q - 0.1006 \times 10^{-4} q^2 + 0.1362 \times 10^{-9} q^3]$
  For Bound 2 $q>20000 W/m^2$.U=U at $q=20000 W/m^2$
- $C_{sub} = 1.0 + 0.04 \times T_{sub} [(Bound 2- q)/Bound 2]^2$
  If $T_{sub}<0$, put $T_{sub}=0$ in the later equation.
- Calculate the overall heat transfer coefficient as under
  $U = [h+ (U_{bound} - h) \times q /Bound2] \times C_{sub}$; when q<Bound2,
  $h=0.023. Re^{0.8}. Pr^{0.4} k/D$

NOTE:

Cf is directly proportional to the liquid feed rate and decreases with increasing feed rate for q>Bound1. When q>Bound 1, Cf may increase with increasing feed rate especially with greatly subcooled liquid feed.

The function Tanh (tangent-hyberbolicus), was chosen due to its limiting values which are given as:- 1>Tanh(x)>1

The superheating liquid feed contribtes an increase inheat flux. If the liquid feed is superheated then extra vapour is flashed off in the tube which will be equivalent to a certain increase in the heat flux.

The correction factior for subcooling considers the varourable effect of the subcooling of the liquid feed on the over all heat transfer coefficient.

The values of h and U are to be adjusted are adjusted from mill data are correction factors due to liquor viscosity, boiling point, liquid feed rate. and subcooling respectively.

- **Nearly 2.6%more area is to be provided in the case of system with condensate flash in comparison to the system without flash. The system with combined product and condensate flash demands extra area on the order of only 1% thus, becoming total 3.6% over and above the system without any flash.**

On closer scrutiny of detailed results of simulation on computer the following inferences can be drawn :

The gain in economy and reduced steam usage in terms money scores over the penalty in capital cost of extra heating surface of evaporator. Enormous financial benefits can be accrued if considered on annual basis.

- It is established that in the Bacward feed sequence C is better than B and B is better than split feed and the latter is better A'.
- The algorithm developed can be extended to many other process industries which use backward feed multiple effect evaporator.

NOMENCLATURE

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

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

BPR Boiling point rise, ^0C,k

C Condensate from steam chest

CP Specific heat of liquor; kJ/kg ^0C

F Liquor feed rate , kg/s

g A function defined by as g =f/f

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 the set

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

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

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

I,m,u and v are scaled liquor flow rate, flash vapour flow rate, temperature and vapour flow rate defined by $l_j = L_j = /F$, $m_j / = M_j/F$, $u_j = T_j / T_s$ and $v_j = V_j / F$ respectively.

SUBSCRIPTS AND GREEK LETTERS

f- feed; p-output product; s- steam, saturation v-vapour

γ - Latent heat of vaprozation, kJ /kg

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