Analysis and simulation of a multiple effect evaporator system

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ABSTRACT

The evaporator section in a paper mill consumes a large amount of energy. The reduction in energy can easily be achieved by the optimization of the process variables. In case of a multivariable problem like this, where many of the variables are dependent on one another, it is a good practice to modal the process, and then use the discrete optimization techniques for the optimization purposes. For the purpose of analysis of an evaporator system, a software has been developed which can simulate an evaporator system consisting of upto ten bodies. In the present work, a four effect evaporator system has been analyzed for the feed sequences, feed steam temperature, condenser temperature and feed and product black liquor concentrations.

Introduction :

The evaporator section in an integrated paper mill requires much attention due to high energy consumption. The function of the evaporation section is to evaporate water vapours from the black liquor coming out from the brown stock washers. The evaporation is done in two major steps - indirect contact evaporation and direct contact evaporation. The black liquor coming from the brown stock washers contains about 8%-12% solids depending upon the type and operating conditions of brown stock washers. For incineration, its concentration must be around 60%. A concentration of upto 30%-40% is achieved through indirect contact evaporation. In case of indirect contact evaporaters, it is practically impossible to use a single body for evaporation. For the same, more than one evaporators are used.

In the evaporators, the steam is supplied to the first evaporator body. The black liquor fed to this body gives flash steam, which is fed to the condenser. In a system of more than one evaporator body, we may have any of the following black liquor flow sequences—

1. Black liquor enters the first body, and moves in the direction of steam or vapor flow sequentially (Fig. 1).

2. Black liquor enters the last body, and moves against the direction of the flow of steam or vapours (Fig. 2).

3. The black liquor flow does not follow any of the above flow sequences (Fig. 3).

In most of the practical cases, the third strategy is used to concentrate the black liquor. By supplying the data for feed sequence, feed flow rate, feed liquor concentration, product concentration, feed liquor temperature and the condenser temperature, the total evaporation, amount of steam required, and steam economy can be calculated. The process is lengthy and time consuming due to a large number of equations to be solved simultaneously. Furthermore, there exists some variables which are not true constant, but vary with varying conditions, properties of the black liquor etc. If one

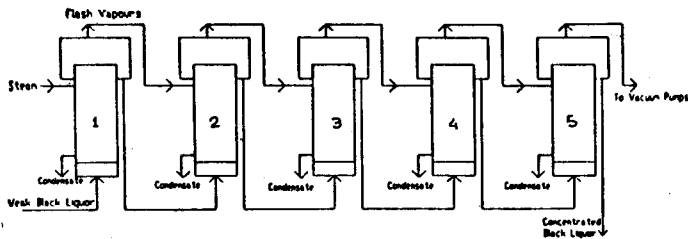*Institute of Paper Technology,
(U.O.R.), Saharanpur
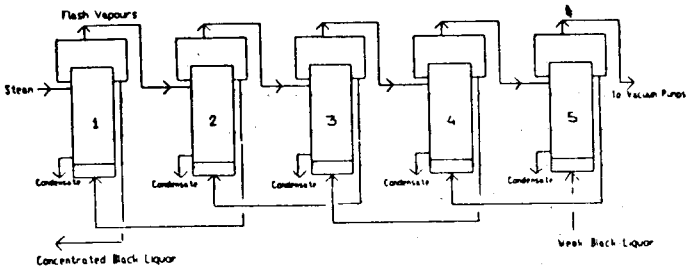
Fig 1 Five Effect Evaporator: Forward Feed

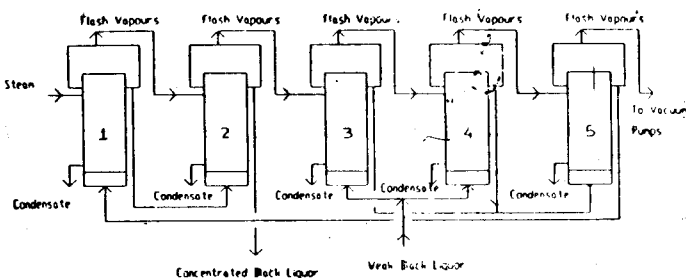Fig. 2 Five effect evaporator: Backward Feed

Fig. 3 Five Effect Evaporator Mixed Feed

tries to analyze the evaporator system for reducing the steam consumption, the only solution is to solve the equations developed through mathematical modeling.

Calculations for Evaporators :

The surface and steam requirements for multiple-effect evaporation can be computed by imposing a heat balance across each effect individually as well as a material balance over the whole system.

The heat and material balance equations for mixed feed can be written on the basis discussed in the model above. Here are the equations for a five effect evaporator system for the forward and backward feed sequences.[1]

Forward Feed :

Heat balance in first effect :
$$w_s \lambda_s + w_f c_f \ (t_f - t_1) = w_1 \lambda_1 \qquad \ldots\ldots(1)$$

Heat balance on second effect :
$$w_1 \lambda_1 + (w_f - w_1) c_1 \ (t_1 - t_2) = w_2 \lambda_2 \qquad \ldots\ldots(2)$$

Heat balance on third effect :
$$w_2 \lambda_2 + (w_f - w_1 - w_2) \ c_2 \ (t_2 - t_3) = \lambda_3 w_3 \qquad \ldots\ldots(3)$$

Heat balance on fourth effect :
$$w_3 \lambda_3 + (w_f - w_1 - w_2 - w_3) \ c_3 \ (t_3 - t_4) = w_4 \lambda_4 \ \ldots\ldots(4)$$

Heat balance on fifth effect :
$$w_4 \lambda_4 + (w_f - w_1 - w_2 - w_3 - w_4) \ c_4 \ (t_4 - t_5) = w_5 \lambda_5 \ldots\ldots(5)$$

Material balance :
$$w_{1-5} = w_1 + w_2 + w_3 + w_4 + w_5 \qquad \ldots\ldots(6)$$

The surface requirements will be :

$$A_1 = \frac{Q}{U_D \ \delta \ t} = \frac{w_s \lambda_s}{U_1 \ (T_s - t_1)} \qquad \ldots\ldots(7)$$

$$A_2 = \frac{w_1 \lambda_1}{U_2 \ (t_1 - t_2)} \qquad \ldots\ldots(8)$$

$$A_3 = \frac{w_2 \lambda_2}{U_3 \ (t_2 - t_3)} \qquad \ldots\ldots(9)$$

$$A_4 = \frac{w_3 \lambda_3}{U_4 \ (t_3 - t_4)} \qquad \ldots\ldots(10)$$

$$A_5 = \frac{w_4 \lambda_4}{U_5 \ (t_4 - t_5)} \qquad \ldots\ldots(11)$$

Let $A_1 = A_2 = A_3 = A_4 = A_5 \qquad \ldots\ldots(12)$

Where U_D, U_1, U_2, U_3, U_4 and U_5, are the design overall heat transfer coefficients in the respective effects. From the material balance and heat balance there are six equations and six unknowns : w_s, w_1, w_2, w_3, w_4 and w_5 These may be solved simultaneously.

Backward Feed :

Heat balance on fifth effect :

$$w_4\lambda_4 + w_f c_f (t_f - t_5) = w_5\lambda_5 \qquad \text{......(13)}$$

Heat balance on fourth effect :

$$w_3\lambda_3 + (w_f - w_5) c_5 (t_5 - t_4) = w_4\lambda_4 \qquad \text{......(14)}$$

Heat balance on third effect :

$$w_2\lambda_2 + (w_f - w_5 - w_4) c_4 (t_4 - t_3) = w_3\lambda_3 \qquad \text{......(15)}$$

Heat balance on second effect :

$$w_1\lambda_1 + (w_f - w_5 - w_4 - w_3) c_3 (t_3 - t_2) = w_2\lambda_2 \quad \text{...(16)}$$

Heat balance on the first effect :

$$w_s\lambda_s + (w_f - w_5 - w_4 - w_3 - w_2) c_2 (t_2 - t_1) = w_1\lambda_1 \quad \text{...(17)}$$

Material balance :

$$w_{1-5} = w_1 + w_2 + w_3 + w_4 + w_5 \qquad \text{......(18)}$$

The surface areas can be calculated as in the case of forward feed. In the above equations, the values of the heat transfer areas will be same for all of the effects, since it is a normal practice to have all of the evaporator bodies similar to each other. The heat and material balance equations for mixed feed can also be written on the same basis. Normally to start with, the areas and overall heat transfer coefficients are not known for a given evaporation load. An assumption may be made for area, boiling point rise, and the overall heat transfer coefficients, and the values for delta t (δT), the amount of heat transferred, evaporation in each effect. The physical properties can be estimated with the help of known correlations or available data for the existing operating conditions.

Model for the Evaporator Section :

The following steps have been used for the simulation and development of a computer program for the evaporator section —

1. The latent heat of steam (2) is a function of temperature.

    $$\lambda = 267.10411 \times (647.2 - t)^{0.38}$$

2. The boiling point rise (3, 4) for the black liquor is a function of the black liquor concentration.

    $$BPR = 84 \times C^2 - 107.5 \times C^3 - 3.55 \times C$$

3. The viscosity of the black liquor (5) is a function of its concentration and temperature as per the following relation —

    $$Ln \mu = a + b.S + c.S^2 + d.S^3$$

    Where,

    $$a = 0.4717 - (0.02472 \times t) + (0.7059 \times 10^{-5} \times t^2)$$

    $$b = 0.06973 - (0.5452 \times 10^{-3} \times t) + (0.1656 \times 10^{-5})^2$$

    $$c = 0.002046 + (0.3183 \times 10^{-4} \times t) - (0.976 \times 10^{-7} \times t^2)$$

    $$d = 0.5793 \times 10^{-4} - (0.6129 \times 10^{-6} \times t) + (0.1837 \times 10^{-8} \times t^2)$$

4. The heat transfer coefficient of the evaporator body is a function of the evaporator tube material, steam pressure, and the viscosity of black liquor. In the program, this has been taken according to the following equation —

    $$U = A/(B + (\mu^{0.4}))$$

    Where, A and B are constants depending upon evaporator design variables, steam pressure and purity, and properties of black liquor. In the actual system, the heat transfer coefficient varies due to variation of phases along the length of the tube, but for the ease of calculations single overall heat transfer coefficient has been taken.

5. The amount of heat transferred in any effect is the product of heat transfer coefficient, heat transfer area, and the temperature difference between the liquor and steam/vapour-

    $$Q = U \times A \times \delta T$$

6. The amount of heat transferred in an effect is also the product of latent heat of the steam and the amount of steam fed.

    $$Q = S \times \lambda$$

7. The heat transferred is used to evaporate a fraction of the liquor and to heat up the rest of the liquor.

8. For the practical purposes, the heat losses may be assumed to be fixed for each evaporator body. For the present case 5.0% heat loss has been assumed.

The calculated values of Q, U and δt are then used in the above equations to estimate area. With the help of these calculated areas, it is possible to make fresh assumptions, and more iterations till the conditions inside the evaporators, flow rates and areas match closely with the desired values. For such iterations computers can easily be used with help of appropriate software.

In case of a mixed feed multiple effect evaporator, it can be shown easily that the temperature difference in each effect is inversely proportional to the heat transfer coefficient, provided that the heat transfer areas are equal for each effect, and there are no heat losses. Of course, the heat transfer coefficients are not exactly known, and also the heat losses are not equal to zero, but the application of this concept along with the assumption that the all heat transfer coefficients are the same gives a good starting point for the iterative calculations. For the present case 150 iterations have been used, which take nearly 15 seconds for the total calculation on a PC/XT system.

With the help of these calculated areas, boiling point rise and heat transfer coefficients, the calculations are repeated again for the determination of physical properties of black liquor, and the temperature distribution etc. These calculations are repeated till the results obtained converge to a suitable degree, or for a sufficiently large number of times in order to get the results of the desired accuracy. Now-a-days, since computers are being extensively used for such calculations, it is relatively easier to make a sufficiently large, but fixed number of iterations to give the desired results.

In industry, different raw materials are used for the paper-making; and unfortunately, the physical properties of different black liquors are different from each other. For the present simulation, the properties of black liquor for the agricultural residues have been used. In case the properties of black liquor are different than the properties used in this work, the expressions in the program can be modified as per requirements.

During operation the heat transfer coefficient may not stay constant as calculated in the formula used above. This will occur if there is undue scaling in one of the effects, if the black liquor contains large amounts of silica, or if liquor levels are not properly maintained. Another factor may be the withdrawal of large quantities of steam from one of the effects as a source of low pressure heating steam. Any deviation from the calculated values does not mean that the entire multiple effect assembly will fail to operate but instead the unit will assume a new temperature distribution and operate with a reduced capacity and steam economy.

Computer Algorithm Used For Simulation :

For the simulation of evaporation section, the following algorithm was used —

1. Read input data for the number of stages, feed sequence, feed steam condition, condenser temperature, concentration of week black liquor, concentration of strong black liquor, plant capacity in terms of black liquor solids per day, and feed liquor temperature.

2. Assumption of heat transfer area, boiling point rise, heat transfer coefficienis etc, for starting calculations in the program.

3. Determination of the flow rate of black liquor from the inlet and outlet concentrations and the solids flow rate.

4. Computation of δT values.

5. Liquor and vapour temperature determination from δT using the given data.

6. Determination of the latent heat of steam.

7. Determination of the liquor temperature rise.

8. Determination of the feed quantity for the different effects of the evaporator.

9. Determination of the heat transferred, and evaporation. In this case a part of the total heat has to be deducted from the amount of heat transfered, considering that a known fraction of it is lost to the surroundings.

10. Determination of the evaporation from different stages of evaporation.

11. Determination of the total evaporation desired, and from this getting a new value for the feed steam quantity for the next iteration.

12. Determination of the boiling point rise of the liquor.

13. Determination of the black liquor viscosity and the heat transfer coefficients for the different stages.

14. Determination of the heat transfer area of the different stages.

15. Taking the average value of the heat transfer area.

16. Repetition of the steps 4 through 15 for a fixed number of times, to get a suitable convergence of the results.

17. Determination of the steam economy of the system.

18. Writing the results in the output data file.

Results and Discussions :

The calculations have been carried out for different combinations, for a four effect system to analyze the effect of various operating variables.

1. Effect of feed sequence

2. Effect of feed steam temperature

3. Effect of condenser vapour temperature

4. Effect of black liquor solids content of the feed and product, for the same percentage rise in concentration.

Effect of Feed Sequence

GENERAL CONDITIONS :

Feed Steam Temperature	141.9 °C
Condenser Temperature	61.9 °C
Feed B/L Concentration	15.0 %
Product Concentration	35.0 %
Black Liquor Solids	256.0 TPD
Feed Temperature	126.9 °C

Flow Sequence	Area m²	Steam Economy	Flow Sequence	Area m²	Steam Economy
1,2,3,4	959,45	3.294	1,2,4,3	957.37	3,296
1,3,2,4	954.52	3 310	1,3,4,2	957.83	3.300
1,4,2,3	957.88	3.284	1,4,3,2	952,71	3.322
2,1.3,4	957.76	3 305	2,1,4,3	954.62	3.311
2,3,1,4	954.98	3.287	2,3,4,1	962 48	3.254
2,4,1,3	964.09	3.225	2,4,3,1	960.69	3.237
3,1,2,4	962.36	3.261	**3,1,4,2**	**97 2,35**	**3 204**
3,2,1,4	951.58	3.317	3,2,4,1	961.94	3.279
3,4,1,2	946.09	3.333	**3,4,2,1**	**949.07**	**3.320**
4,1,2,3	959.04	3.251	4,1,3,2	965.35	3.208
4,2,1,3	952,74	3.311	**4,2,3,1**	**950 58**	**3.344**
4,3,1,2	954.02	3.279	4,3,2,1	950.77	3.325

From the above results, it seems that the mixed feed is the best option in terms of steam economy as well as of heat transfer area required for the system. The highlighted data are for the maximum and minimum values of steam economy and the area, and the flow sequence 4, 2, 3, 1, gives an optimum solution. It is also interesting to note that the maximum steam economy of the system also gives the minimum area requirement. Thus, selection of a feed sequence for the maximum steam economy also results in increased productivity of the system. For a four effect system, as is clear from the above results, a steam consumption of even upto 4% can be reduced.

Effect of Feed Steam Temperature

The effect of feed steam temperature can easily be obtained by making experiments on the simulator (the computer program) for the different operating conditions. As the possible combinations with a four stage system are high (24), the effect of feed steam temperature has been considered for two cases of the maximum and minimum steam economy only. The results are as under.

GENERAL CONDITIONS—

Condenser Temperature	61.9 °C
Feed B/L Concentration	15.0%
Product Concentration	35.0%
Black Liquor Solids	256.0 TPD
Feed Temperature	126.9 °C

Feed steam Temp. °C	Area m²	Steam Economy	Area m²	Steam Economy
Feed Sequence......3-1-4-2.........			......4-2-3-1......	
116.9	1122.30	3.237	1099.47	3.369
121.9	1042.06	3.222	1019.94	3.357
126.9	0972.36	3.204	0950.58	3.344
131.9	0911.17	3.188	0888.36	3.333
136.9	0856.77	3.173	834.57	3.319

Here, we can see that the required area is decreasing with an increase in feed steam temperature. This is because the available temperature differential is more. The steam economy of the system reduces with the rise in steam temperature. These results provide another way for the process optimization. By this we can analyze the system, and if the black liquor flow rate is lower than the desired value due to some changes in the pulping section, the steam pressure can be reduced, in order to get a higher steam economy. Another point of interest is that the steam economy 'gain' is more in case of 4,2,3,1 flow sequence, or in other words, the steam economy sensitivity of the system is more for the case where the steam economy is still higher.

Effect of Condensate Temperature

GENERAL CONDITIONS :

Feed Steam Temperature	141.9 °C
Feed B/L Concentration	15.0 %
Product Concentration	35.0 %
Black Liquor Solids	256.0 TPD
Feed Temperature	126.9 °C

Condenser Temp. °C	Area m²	Steam Economy	Area m²	Steam Economy
Feed Sequence ......3-1-4-2......			......4-2-3-1.........	
31.9	0882 83	3.169	0861.29	3.328
41.9	0972 36	3.204	0950.58	3.344
51.9	1089 28	3.243	1067.48	3 361
61.9	1251 57	3.282	1229 75	3.380
71.9	1484 53	3.326	1463.57	3 402

The increase in condenser temperature results in higher heat output to the condenser, thus a reduction in heat utilization. Also the overall working temperature of the system increases, with a lower temperature difference available for the heat transfer. This results in an increased area requirement for the system. In this case, against the previous one, we can see that the steam economy is more sensitive to condenser temperature for the case of lower steam economy.

Effect of black liquor solids content of the feed and product, for the same percentage rice in concentration

GENERAL CONDITIONS :

Feed Steam Temperature	141.9 °C
Condenser Temperature	61.9 °C
Black Liquor Solids	256.0 TPD
Feed Temperature	126 9 °C

Feed & Product Concentration, %	Area m²	Steam Economy	Area m²	Steam Economy
Feed Sequence	————3—1—4—2————		—·—·—4—2—3—1————	
08.0% — 32.0%	972.36	3.204	950.58	3.344
09.0% — 33.0%	859.39	3.203	583.82	3.343
12.0% — 36 0%	658.87	3.204	647.46	3.347
13 0% — 37.0%	622.78	3.205	631.34	3.352
14.0% — 38.0%	598.99	3.207	591.09	3.358

At lower black liquor concentrations, the total evaporation load in terms of water evaporation is high, resulting in a higher area requirement for the heat transfer. Later, with increase in solid contents of black liquor, the evaporation load decreases, and hence, the area requirement goes down. Here again the sensitivity of steam economy, is more for the flow sequence giving a higher steam economy, but it is much lower than the previous cases.

Conclusion :

The results indicate clearly that the simulation can easily and effectively be used for the analysis of an evaporation system. The application of computer program allows to get the results within a very short time span of around 15 seconds on a simple PC/XT machine, with 150 iterations in the computer program. The steam economy improvement can be achieved, with the strategy obtained by the application of this simulation, and thus steam consumption can be reduced. This also allows us to analyze the performance of an existing system, and suggestions can be made to improve the productivity of the system and conserve energy.

Nomenclature :

c_{1-5} = specific heat of feed, Kcal/(Kg) (°C)

t = temperature of feed, °C

w = feed, kg/hr

T_s = saturation temperature of steam to the first effect, °C

w_s = Steam to the first effect, kg/hr

w_{1-5} = total water removed by evaporation, kg/hr

t_1, t_2, t_3, t_4, t_5 = boiling points of liquor in effects 1 to 5, °C

w_1, w_2, w_3, w_4, w_5 = water removed in effects 1 to 5, kg/hr

$U_1, U_2, U_3, U_4, U_5, U_D$ = design overall heat transfer coefficients, Kcal/hr. m^2 °C

λ = latent heat of steam, Kcal/kg

$BPR_1 - BPR_5$ = Boiling point rise in effects, °C

μ = viscosity of the black liquor, Cp

Q = Total amount of heat transferred in effects 1 to 5, Kcal/hr.

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