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# Energy Analysis of Multiple Effect Evaporator in an Indian Pulp & Paper Industry

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***Abstract:*** ***This article represents a brief energy analysis of Multiple Effect Evaporator (MEE), used to enhance the solid concentration of the black liquor obtained from the paper industry. MEE accounts a high share of the energy consumption from the total industry's energy. Nowadays reduction of energy utilization in this MEE unit is a prime concern which may be acquired by integration of different energy reduction schemes. The energy integrated MEE model may capable of increasing the industrial self-sustainable, energy efficient and economic prosperity simultaneously. To achieve the maximized energy efficiency a newly introduced metaheuristic approach named Flow Direction Algorithm (FDA) has been applied within the constraint environment. The obtained result shows a 75.6% enhancement in the steam economy than that of the real time plant data available from the literatures.***

## Introduction:

A modern Pulp & Paper industry is self-sufficient in energy that all the steam, heat and electricity demands can be satisfied within the plant itself by using the energy of the Weak Black Liquor (WBL). For which WBL (a biomass based byproduct obtained as waste) needs to be pretreated through Multiple Effect Evaporator (MEE) to achieve higher concentration value before being used as fuel. MEE is one of the most energy intensive sub-unit of Pulp & Paper industry and is capable of consuming more than 35% of the total industry's energy [1]. Such huge amount of energy consumption necessitates incorporation of various Energy Reduction Schemes (ERSs) and operational changes in order to make it more energy efficient and economical. Some of the previously reported ERSs are Feed preheaters [2,3], Flash tanks [4,5], Thermo-Vapor Compressor [6,7], Mechanical Vapor Compressor [8], and their hybrids [9–12] and the operational changes includes steam- and feed- split operations [13,14]. Integration of these ERSs declines the rate of energy utilization that cuts operating cost up to certain extent and increases the energy efficiency which leads to improvement in the industry's socio-economic perspectives.

The energy efficiency analysis of the system is rendered through the different mathematical models [10,15,16]. Fig. 1 shows the classification of the mathematical models employed to the different energy integrated MEEs in order to numerically analyze the system. As the real time systems are generally nonlinear in practice; hence, the energy models developed for the MEE are also nonlinear in nature. The energy efficiency of the MEE is measured in terms of Steam Consumption (SC) and Steam Economy (SE) and both exhibit an inverse relationship with each other. The set of equations developed for the MEE is obtained through 1st principle of thermodynamics and the optimal SE value is achieved through formulation of a maximization problem present in the constraint environment.

As per the above discussed literatures, this study has been accounted with the solution of the developed nonlinear mathematical models for an energy integrated MEE configuration. These mathematical models are disciple into a single objective optimization problem to maximize the SE and solved in search of the optimized unknown process parameters (Li, Ti, and V0). A newly developed metaheuristic based optimization approach named Flow Direction Algorithm (FDA) has been hired to solve the optimization problem to obtain the best possible values of process parameters. Furthermore, the employment of various ERSs which includes steam, and liquor feed split operation, Thermo-Vapor Compressor (TVC) and feed pre-heater have been taken place in order to enhance the energy efficiency of the system. The SE may be further enhanced by integrating the MEE system with flash tanks that extracts heat from the waste steam as a heat source for accelerating the Kraft recovery process.

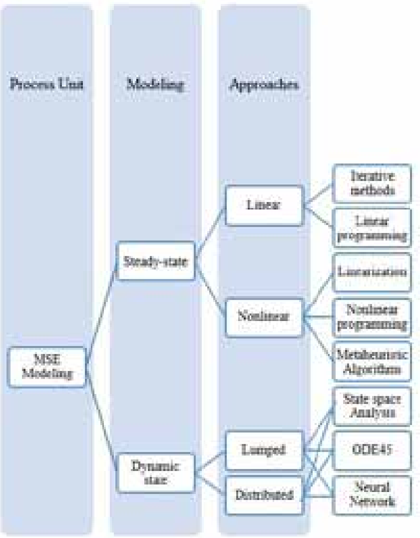

*Fig. 1 Solution approaches adopted for solving the MEE models*

### Materials and methods

The preferred MEE system is a seven stage evaporator system installed in an Indian pulp and paper mill used to concentrate the WBL. Black liquor is the waste product obtained when the Kraft recovery process proceeds towards the paper making by extracting the lignin, cellulose and other cellulose fibers from the pulpwood. It is normally concentrated about 60 – 85% by using MEE systems to produce energy and recover the cooking chemicals. Hence, the pulping industry has been using it as one of the energy sources since 1930s by extracting the water and utilizing it as a heat source to the evaporator system.

The schematic diagram of the MEE system is shown in Fig. 2. This diagram shows the backward feed flow sequence along with various ERSs such as steam split, feed split, and feed preheater. The first two stages of this MEE system are fed with the live steam by splitting it with a fraction of y and the last two effects are fed with the black liquor by splitting it with a feed spit fraction of k. The feed pre-heater is used to heat the black liquor before sending it to the evaporator system, however this pre-heater takes energy from the steam obtained from sixth effect with a steam split fraction of m and the total steam coming out from the seventh effect.

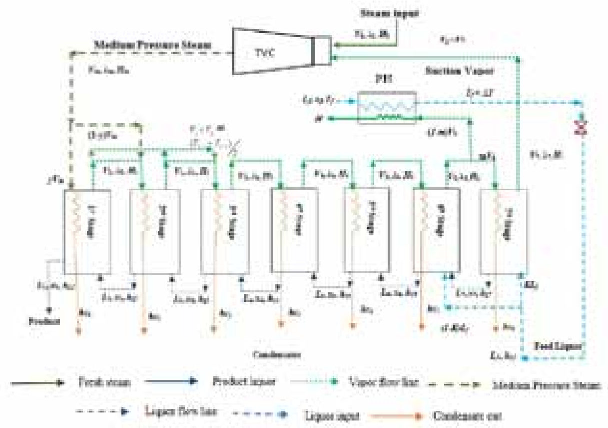

*Fig. 2 Schematic of ERSs integrated MEE model*

### Model Formulation

The energy performance of the proposed MEE model is analyzed through the nonlinear mathematical equations developed by employing the 1st principle of thermodynamics. The set of energy equations are created with some appropriate assumptions that the system operated in steady state ideal condition as no plant complexities are considered, the concentration of the solution are constant throughout the process. Due to the integration of TVC the fresh steam enter into the TVC first combined with the steam out from the 7th stage of the MEE. The intermediate steam is split with split fraction of y and (1-y) and send as heating medium for the 1st and 2nd stage respectively as illustrated in Fig. 1. Applying enthalpy balance around the 1st and 2nd stage, the obtained equations are expressed as in Eq. (1) - (4).

$$yV_m(\lambda_m - hc_m) + L_1(H_1 - h_1) + L_2(h_2 - H_1) = 0 \tag{1}$$

$$U_1A_1(T_m - T_1) - yV_m(\lambda_m - hc_m) = 0 \tag{2}$$

$$(1-y)V_m(\lambda_m - hc_m) + L_2(H_2 - h_2) + L_3(h_3 - H_2) = 0 \tag{3}$$

$$U_2A_2(T_1 - T_2) - (1-y)V_m(\lambda_m - hc_m) = 0 \tag{4}$$

The output vapor from the 1st and 2nd stage are combined with each other and fed as the heating medium for the 3rd stage of the MEE with an average temperature of Tavg and the Energy equations for this stage is represented as in Eq. (5)- (6).

$$(L_3 - L_1)(\lambda_{avg} - hc_{avg}) + L_3(H_3 - h_3) + L_4(h_4 - H_3) = 0 \tag{5}$$

$$U_3A_3(T_2 - T_3) - (L_3 - L_1)(\lambda_{avg} - hc_{avg}) = 0 \tag{6}$$

In similar way for the 4th and 5th stages of the MEE the energy equations are deduced as in Eqs. (7) - (8).

$$(L_i - L_{i-1})(\lambda_i - hc_i) + L_i(H_i - h_i) + L_{i+1}(h_{i+1} - H_i) = 0 \tag{7}$$

$$U_iA_i(T_{i-1} - T_i) - (L_i - L_{i-1})(\lambda_i - hc_i) = 0 \tag{8}$$

where, i denotes the stage number of the 4th and 5th stage. Further, employment of feed split operation to the 6th and 7th stages with a split fraction of (1-k) and k respectively. The energy balance equation get modified and rendered as in Eqs. (9) - (12).

$$(L_6 - L_5)(\lambda_5 - hc_5) + L_6(H_6 - h_6) + L_7(h_7 - H_6) + (1-k)L_f(h_f - H_6) - (1-k)L_fCp\Delta T = 0 \tag{9}$$

$$U_6A_6(T_5 - T_6) - (L_6 - L_5)(\lambda_5 - hc_5) + (1-k)L_fCp\Delta T = 0 \tag{10}$$

$$m(L_7 + (1-k)L_f - L_6)(\lambda_6 - hc_6) + L_7(H_7 - h_7) + kL_f(h_f - H_7) - kL_fCp\Delta T = 0 \tag{11}$$

$$U_7A_7(T_6 - T_7) - m(L_7 + (1-k)L_f - L_6)(\lambda_6 - hc_6) + kL_fCp\Delta T = 0 \tag{12}$$

These fourteen nonlinear equations of the MEE treated as equality constraints with fourteen number of unknown decision variables such as fresh steam supplied (V0), output temperature of each stage (Ti (i=1,2,…,6)), and output liquor flow rates (Li (i=1,2,…,7)). Eqs. (13) - (14) illustrates the side constraints of Ti and Li for the mentioned stages of the proposed MEE to maintain a continuous process with feasible bound of [0:3] (kg/s) of fresh steam (V0), required to accelerate the continuous process. The boundary values of Ti and Li that subjected to compute the optimal results are mentioned in Table 1.

$$T_i > T_{i+1},\ (i = 2,3\ldots7)\ T_7 > 52(T_8)\quad L_{i+1} > L_i, (i = 1,2\ldots7) \tag{13}$$

$$T_i > 0,\ (i = 2,3\ldots7)\ \text{and}\ \ L_i > 0,\ (i = 1,2\ldots7) \tag{14}$$

**Table 1: Boundary values of Ti and Li for ith stages of proposed ERSs integrated MEE**

| |
|---|
| $T_i(°C) \in [90:125;\ 70:120;\ 66:90;\ 60:75;\ 55:65;\ 52:63],\ (i = 1,2\ldots6)$ |
| $L_i(kg/s) \in [1.5:5;\ 3:6;\ 4:8;\ 6.5:10.5;\ 9:12;\ 6:13;\ 6:14,\ (i = 1,2\ldots7)$ |

Various approaches are reported in the literature to smoothly deal with the constraints functions, from which penalty functions is the simplest ones and considered here that the proposed objective function is penalized with respect to the violation of the constraints. In this work the fitness function is represented as in Eq. (15).

$$F = -f(z) + p_m\omega \tag{15}$$

where F is the fitness function value, negative sign indicates it is a maximization problem, f(z) is the objective function, pm is the penalty factor, and ω is the total penalty for constraints' violation.

### Objective function

In the current investigation, there are two objectives: to minimize the SC and to maximize the SE of the proposed ERSs integrated MeE. As SE is defined as the ratio of difference between the amount of feed liquor and product liquor with respect to the amount of SC by the MEE. Hence, this problem is turned in to a single objective optimization problem with several constraints. The problem for the MEE is formulated as in Eq. (16).

$$\begin{aligned} &Maximize:\ f(z) = SE = \frac{L_f - L_1}{V_0} \\ &Subjected\ to: g_i(z_1, z_2, \ldots, z_n) \geq 0 \\ &\qquad\qquad\quad h_i(z_1, z_2, \ldots, z_n) = 0 \end{aligned} \tag{16}$$

where, i, is the number of inequality/equality constraints and n number of unknown decision variables. But in this work, there is no inequality constraint is present only equality constraints are considered.

## Solution Algorithm

In this section, a newly developed a physics-based metaheuristic approach named Flow Direction Algorithm (FDA) [17] has been applied to solve the constrained optimization problem. FDA is inspired by the flow direction of the outlet point with lowest height. The performance of this algorithm has been tested only against the benchmark function and some other applications. However, it is also imperative to observe the performance of this algorithm towards such real time industrial optimization problems. Hence, FDA is adopted in this study to optimize the steam economy of the MEE unit. The pseudo code of the proposed algorithm for the proposed model are given in Table 2.

The operating parameters considered here to validate the model is a pulp and paper mill data, present in the north side of India and are available from various literature as prescribed in Table 3. The considered MEE is a seven effect evaporator operated at constant input temperature T0 (1470C).

**Table 3 Operating parameters of MEE***

| Parameters (Nomenclature) | Values (unit) |
|---|---|
| Feed liquor concentration | ($x_f$) 0.118 |
| Feed liquor flow rate | ($L_f$) 15.611 Kg/s |
| Output vapor temperature | ($T_8$) 52°C |
| Feed liquor temperature | ($T_f$) 65°C |
| Minimum temperature increment at first stage($\delta T_{\min}$) | 10°C |
| Area Evaporator units (Ai) (*i*=1,2, …,7) | 540, 540, 660<br>660, 660, 660<br>690 $m^2$ |

*Data available from Star Paper Mill, Saharanpur, U.P, India

## Result Analysis

The performance of the energy integrated MEE model has been evaluated through implication a newly developed optimization approach as mentioned above. In this study, the considered optimization problem is a single objective maximization problem solved in constraint environment to opt the SE value. Then the obtained results are compared with the previously reported results. For solving this problem, the above-mentioned algorithm, FDA is employed with 100 search agents, 1000 iterations and run for 30 times. The simulated result of the FDA converges at 600 iterations and the best optimal result is obtained at 23rd run with the execution time of 138.56 seconds.

Specifically, for this constraint grey-box optimization problem with fourteen decision variables, this FDA algorithm performs satisfactorily. The energy efficiency parameters SC and SE obtained by this approach shows a deviation of 42.21% and 75.4% respectively than that of a standalone plant operating MEE unit. Table 4 indicates the optimal unknown parameters and their dependent thermo-physic parameters of the proposed MEE by employing FDA. Fig. 3 and Fig. 4 shows the convergence curve of FDA and variation in the heat enthalpies respectively. The optimal unknown process parameter values obtained for the energy integrated MEE model have stated by a flow diagram as shown in Fig. 5. The SE obtained for the standalone MEE is 4.76 with SC 2.25 kg/s which having an error of 2.59% as compare to the plant operated MEE model [15]; whereas, due to the incorporation of different ERSs, the SE enhancement percent increased 71.1% with the implication of same algorithm. The comparative analysis of the SE and SC is demonstrated in Fig. 6.

**Table 2** Pseudo Code of FDA

```
Define objective function f(z)
Define input parameters ($L_f$, $T_1$, $A_i$, $x_i$, $\forall i$=1 to7) // Table 2
Set the initial algorithm parameters
        LB & UB // Table 1
        Number of Population (N=100)
        Search space Dimension (D=14)
        Max iteration (maxite=1000)
Initialization
        Generate the initial flows
        Evaluation of objective function value for each flow and keep the best one as the outlet
        Creation of β numbers of neighbor with Δ neighborhood radius for each individual flow
        Calculate the objective function value of each neighbor and identify the best neighbor
            if fitness of best neighbor is less than the current flow
                Update the flow velocity
                    $V = randn * S_0$ // $S_0$ slope vector between the neighbor and current position of the flow
                    $S_0(i,j,d) = \left( \frac{Flow\ fitness(i) - Neighbor\ fitness(j)}{\| Flow\,x(i,d) - Neighbor\,x(j,d) \|} \right)$ // for ith flow and jth neighbor and d dimension
                Generate the new position
                    $Flow\,newX(i) = FlowX(i) + V * \left( \frac{Flow\ fitness(i) - Neighbor\ fitness(j)}{\| Flow\,x(i) - Neighbor\,x(j) \|} \right)$
            else Generate an integer random number
                if $Flow\ fitness(r) < Flow\ fitness(i)$
                    $Flow\,newX(i) = FlowX(i) + randn * (FlowX(r) - FlowX(i))$
                else
                    $Flow\,newX(i) = FlowX(i) + 2randn * (BestX - FlowX(i))$
                end
                Update the objective function and position of the new flows
            end if
        Perform greedy selection to update population if there is better solution
Display the optimum results
```

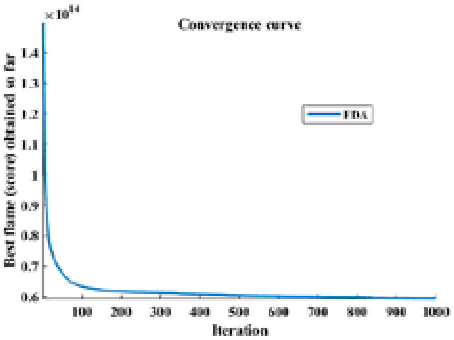

*Fig. 3 Convergence curve of FDA*

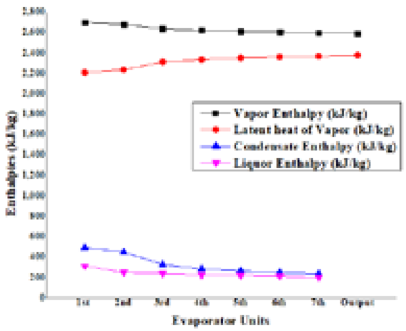

*Fig. 4 Heat Enthalpy Variation of Vapor and Liquor during MEE operation*

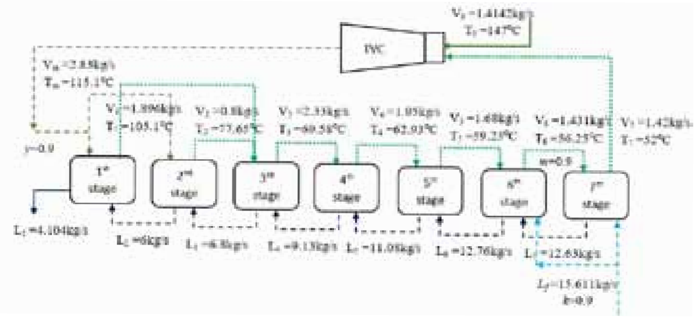

*Fig. 5 Flow sheet of the proposed MEE by employing FDA*

**Table 4 Optimal Parameters obtained by FDA for the Proposed MEE model**

| Process Parameters | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | Output |
|---|---|---|---|---|---|---|---|---|
| Vapor Enthalpy (kJ/kg) | 2697.3 | 2681 | 2636 | 2622.7 | 2611.7 | 2605.6 | 2600.7 | 2593.7 |
| Latent heat of Vapor (kJ/kg) | 2207.8 | 2236.9 | 2313.1 | 2334.1 | 2351.5 | 2360.9 | 2368.4 | 2379 |
| Condensate Enthalpy (kJ/kg) | 493.5 | 448.99 | 328.2 | 283.14 | 264.31 | 248.36 | 235.49 | NA |
| Liquor enthalpy (kJ/kg) | 314.44 | 249.25 | 239.67 | 228.41 | 221.83 | 214.83 | 201.33 | NA |
| SC (kg/sec) | 1.4142 | | | | | | | |
| SE | 8.1366 | | | | | | | |

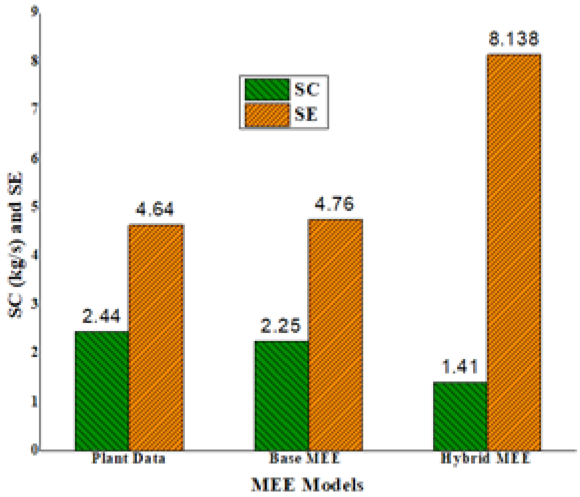

*Fig. 6 Variation in SC and SE at different operating condition*

## Conclusion

Energy integrated MEE simulated in different solution platforms provides a better energy performance than that of the standalone MEE system. The energy consumption in the paper industry can be reduced to a notable extent with integration of different ERSs. The principle of process integration and numerical optimization are the keys to reduce the energy utilization. A steady state nonlinear energy modeling of hybrid MEE based on 1st principle of thermodynamics is evolved in this work and the model is validated by comparing it with the base MEE model operated at plant with available data. The performance analysis of the proposed model is carried out with the implication of a new metaheuristic approach named FDA, and the obtained results illustrate that there is more than 70% of enhancement in the steam economy as compared to the base and plant operated MEE model with a high reduction in energy consumption which leads to reduction in economic and environmental issues.

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