Published in Applied Energy – Article in Press
DOI: http://dx.doi.org/ 10.1016/j.apenergy.2009.05.003

Energy reduction schemes for multiple effect evaporator systems

Shabina Khanam[1,*], Bikash Mohanty[2]

[1] Department of Chemical Engineering, National Institute of Technology Rourkela, Rourkela-769008, India

[2] Department of Chemical Engineering, Indian Institute of Technology Roorkee, Roorkee-247667, India

Abstract

In the present work different energy reduction schemes (ERSs), used to reduce the consumption of steam for a multiple effect evaporator (MEE) system, are developed. These ERSs are condensate-, feed- and product- flashing and vapor bleeding. Further, a new scheme is proposed where condensate of vapor chest of an effect is used to preheat the liquor, which is entering into that effect using a counter current heat exchanger. This work also presents a comparative study between existing ERSs and selects the best ERS amongst these based on steam consumption as well as number of units involved. Further, in the present paper a simple graphical approach named "Modified Temperature Path (MTP)" is developed for the analysis of different feed flow sequences of a MEE system to screen best possible feed flow sequence. To study the effect of different ERSs on steam consumption and MTP analysis an example of septuple effect flat falling film evaporator (SEFFFE) system, employed for concentrating weak black liquor in an Indian Kraft Paper Mill, is considered. The results show that ERSs reduce the steam consumption up to 24.6%.

Keywords: Energy reduction scheme; Flashing; Vapor bleeding; Screening tool; Multiple effect evaporator system; Steam consumption

1. Introduction

An energy audit shows that Evaporator House of a Pulp and Paper industry consumes about 24-30% of its total energy and thus designates multiple effect evaporator (MEE) as an energy intensive process [1]. This has posed a serious challenge to the investigators. Thus, since last few decades researchers tried to develop different energy reduction schemes (ERSs) for the MEE system, which could cut down the energy bills and provide maximum steam economy. Generally, the ERSs used in the MEE systems are condensate-, feed- and product- flashing and vapor bleeding.

Since last seven decades many investigators analyzed the MEE system using mathematical models with the induction of condensate flashing [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13]. Many researchers [3, 5, 12, 13, 14, 15] also incorporated vapor bleeding to pre-heat the feed in the MEE system. These investigators have developed the model for MEE system with condensate flashing and vapor bleeding, however, they did not present an analysis for selecting best ERS based on minimum steam consumption (SC) to optimize the performance of MEE system. Moreover, they used these ERS but nonetheless analyze variation in SC with different configuration of these schemes.

Thus, this work presents a comparative study between existing ERS and selects the best ERSs amongst these based on SC. Further, a new scheme is proposed where condensate of vapor chest of an effect is used to preheat the liquor which is entering into that effect using a counter current heat exchanger.

* Corresponding author:
E-mail address: shabinahai@gmail.com, skhanam@nitrkl.ac.in
Tel. No. +91-661-2462267; Fax No. +91-661-2462999

The induction of ERS in MEE system forces one to change the existing design of MEE system which is time and resource consuming. This further calls to develop a method which is able to reduce the value of SC only by changing the flow sequence. It is to select and operate MEE system with optimal feed flow sequence (OFFS) that provides highest steam economy.

To screen the OFFS of a MEE system, Kern [16] and Harper & Tsao [17] developed different models for the optimization of evaporation process for some typical feed flow sequences (FFS) such as forward and backward. Nishitani and Kunugita [18] extended the work of Harpor and Tsao [17] to propose an algorithm for generating non-inferior FFS amongst all possible FFSs of a MEE system. The non-inferior FFSs were based on minimum heat transfer area and live SC. They suggested that if an OFFS is required, one has to only examine the set of non-inferior FFSs. Further, Bhargava [12], Bhargava et al. [13] proposed a modified generalized cascade algorithm based on the model proposed by Stewart & Beveridge [19] and Ayangbile et al. [20]. This model could screen the OFFS when different operating configurations like feed-, product- and condensate- flashing and steam splitting were included in the MEE system.

These models were based on complex mathematical equations. Though these models help in screening OFFS these make the approach complicated and time consuming. To facilitate this screening process, Westerberg and Hillenbrand [21] proposed a method based on concepts of Process Integration. For this purpose, they developed concepts of temperature paths and heat shunt to provide insights to the analysis, which is based on constant boiling point rise (BPR), negligible heat of mixing, constant physical properties of steam/condensate and equal vaporization from each effect. Based on these concepts they suggested some heuristic rules to screen OFFS. However, they did not show the reliability of these rules using a case study. Thus, in the present work a modified temperature path (MTP) is developed which is used to select the OFFS amongst different FFS and thus called as a screening tool.

2. The MEE system and mathematical model

To show the effect of different ERSs on total SC the septuple effect flat falling film evaporator (SEFFFE) system, being operated in a nearby Indian paper mill for concentrating weak black liquor, is taken and shown in Fig. 1. The operating data for it are directly obtained from the plant and shown in Table 1. Here the measured value for steam consumption is provided for SEFFFE system with condensate, feed and product flashing, shown in Fig. 3, as it is not available for SEFFFE system shown in Fig. 1. This system, Fig.1, is considered as base case. It uses steam in first two effects and thus these effects are operated at almost equal temperature. The steam going into first effect is 7 °C colder than that into second effect. This is an actual scenario and thus it has been taken as it is during simulation. The plausible explanation is unequal distribution of steam from the header to these effects leading to two different pressures in the steam side of these effects.

While developing model it is assumed that the feed is composed of a number of individual streams such as condensate streams, which subsequently come out from different effects (except first as it utilizes live steam), and a product stream. For the SEFFFE system feed, in virtual sense, is composed of eight streams namely: one product stream, P, and seven condensate streams designated as, C_1 to C_7. These streams can be treated as separate (individual) streams and their temperature paths can be studied separately. Following assumptions are made to cut down the complexity of the model such as equal driving force in each effect, boiling point rise, heat loss and heat of mixing between different streams are negligible. In fact, the assumption of negligible BRP is relaxed and its constant value is considered by Mohanty and Khanam [22] to develop a modified model.

A stream of feed, while traversing from entry effect to exit effect, passes through different levels of temperatures. This fact is demonstrated using the concept of temperature path defined as a “Path followed by the temperatures of a stream when it passes through an effect or a network of it” [21]. It plays a vital role in the development of model equations. The temperature paths of all eight streams of feed are shown in Fig. 2 in which T_1 to T_7 are vapor body temperatures of 1^{st} to 7^{th} effects. The temperature paths are plotted to demonstrate another important concept called internal heat exchange. It allows different streams or their parts to exchange heat with each other in order to facilitate maximum amount of heat to be exchanged through internal exchange and thus provides a mean to minimize the amount of live steam required by the system.

To demonstrate the concept of internal heat exchange the temperature path of P, shown in Fig. 2, is considered. It first moves downward in temperature from point “a” to “c” through point “b” and thus behaves as a hot stream from point “a” to “c”. However, the same stream from point “d” to “g” through “e” & “f” works as a cold stream as its temperature rises in this section of temperature path. The hot stream part of P can exchange heat with its cold stream part subjected to the driving force constraint, which is in this case ΔT_{min}. Thus, the hot stream part of product “P” first cools down from point “a” to “b” and the cold stream part rises from point “d” to “e” under this exchange only. Thus, stream “P” enters 7^{th} effect at point “b” and is cooled down to T_7 by flashing inside the effect. For the product stream, P, maximum feasible internal heat exchange is equal to [$PC_{PL}(T_F-T_7-\Delta T_{min})$] kW. Further, the cold part of product stream “P” enters the 6th effect at point “e” (which is T_6) and also exits it at same temperature corresponding to point “e”. The stream “P” then enters effect no. 5 at the “e”. In this effect, it is heated up to point “f” through sensible heat exchange inside the effect provided by vapor V_4. Similarly, the heating of stream “P” from “f” to “g” also takes place.

For the SEFFFE system, the temperature of each effect, T_1 to T_7, are known based on assumption of equal driving force (ΔT) in each effect, which is calculated as:

$$[(T_s-T_{Le})/n]=[(140-52)/6]=14.6\ ^\circ C \tag{1}$$

It is to be noted here that total number of effects are seven amongst these effect no. 1 & 2 are operated at same temperature. Therefore, driving force is computed based on only six effects. Moreover, ΔT in effect 2 is 7◦ larger than other effect. Thus, for this particular effect, the assumption of equal ΔT in each effect violates. This is the actual scenario of the paper mill and thus considered as it is.

For the SEFFFE system the mathematical model is developed based on a method shown in the work of Khanam and Mohanty [23]. To develop the model equation of an effect the temperatures at which a stream enters (supply temperature, T_s) into it and exits (target temperature, T_t) from it should be known. These temperatures can be obtained from the temperature paths shown in Fig. 2. For example, to develop equation for the first effect $T_{1,s}$ and $T_{1,t}$ of streams, P and C_1 are taken as T_2 and T_1 respectively. The governing equations for this system are shown below:

The energy balance around first effect at steady state provides following equations:

Latent heat supplied by live steam at T_{01} (Term 1)	+	Sensible heat of entering streams, P & C_1 at $T_{1,s}$ (Term 2)	=	Latent heat available with the vapor steam, V_1 at $T_{1,t}$ (Term 3)	+	Sensible heat of exiting streams, P & V_1 at $T_{1,t}$ (Term 4)	(2)

where,

Term 1 = $(fs \times Ws) \times \lambda_{01}$ (3)

If $Ws1 = fs \times Ws$

In the present case the steam, Ws, is divided equally in effect no. 1 & 2. Thus, the value of fs is 0.5.

Then, Term 1 = $Ws1 \times \lambda_{01}$ (4)

Where, λ is latent heat of vaporization, which is computed using following equation:

$\lambda = 2500.7 - 2.3173 \times T - 0.0004 \times T^2 - 5 \times 10^{-6} \times T^3$ kJ/kg

Term 2 = $P\, C_{PL}\, (T_{1,s} - T_r) + C_1\, [T_{1,s}\, C_{PW}(T_{1,s}) - T_r\, C_{PW}(T_r)]$ (5)

Where, T_r is the reference temperature.

The expressions of C_{PW} and C_{PL} are given by following equations:

$C_{PW} = 4.1586 + 0.0006\, T - 6 \times 10^{-06}\, T^2 + 4 \times 10^{-08}\, T^3$ kJ/kg°C

$C_{PL} = 4.187 \times (1 - 0.54\, x)$ kJ/kg°C (6)

Term 3 = $V_1 \times \lambda_1$ where, $V_1 = C_1$ thus,

Term 3 = $C_1 \times \lambda_1$ (7)

Term 4 = $P\, C_{PP}\, (T_{1,t} - T_r) + V_1\, [T_{1,t}\, C_{PW}(T_{1,t}) - T_r\, C_{PW}(T_r)]$ (8)

Now, Eqs. 4 to 8 are substituted in Eq. 2 considering $T_{1,s}=T_{1,t}$ as the first two effects are operated at same temperatures. Consequently, following equation for first effect is obtained:

$$Ws1\left[\frac{\lambda_{01}}{\lambda_1}\right]-C_1=0 \tag{9}$$

In the similar manner, equations for effects 2 and 3 are derived. The developed equations for these effects are given as:

Second effect:

$$Ws2\left[\frac{\lambda_{02}}{\lambda_2}\right]+C_1\left[\frac{b_1}{\lambda_2}\right]+C_2\left[\frac{b_1}{\lambda_2}-1\right]+\frac{P\,C_{PP}\,(T_3-T_2)}{\lambda_2}=0 \tag{10}$$

where, $Ws2=(1-fs)\times Ws$ and $b_1=[\mathrm{T_3\,C_{PW}\,(T_3)\,-T_2\,C_{PW}(T_2)}]$

Third effect:

$$C_1\left[\frac{\lambda_2+b_2}{\lambda_3}\right]+C_2\left[\frac{\lambda_2+b_2}{\lambda_3}\right]+C_3\left[\frac{b_2}{\lambda_3}-1\right]+\frac{PC_{PP}(T_4-T_3)}{\lambda_3}=0 \tag{11}$$

where, $b_2=[\mathrm{T_4\,C_{PW}\,(T_4)\,-T_3\,C_{PW}(T_3)}]$

Similarly, for the k^{th} effect following equation is developed:

$$C_{k-1}\left[\frac{\lambda_{k-1}+b_k}{\lambda_k}\right]+C_k\left[\frac{b_k}{\lambda_k}-1\right]+\frac{P\,C_{PP}\,(T_{k,s}-T_{k,t})}{\lambda_k}=0 \tag{12}$$

where, k = 4, 5, …..7 and $b_k=T_{k,s}\,C_{PW}(T_{k,s})-T_{k,t}\,C_{PW}(T_{k,t})$

Overall mass balance around the SEFFFE system provides:

$$\sum_{i=1}^{7}C_i=F-P \tag{13}$$

Where, P is obtained by overall component balance as: $P = (F\,x_F)/x_P$ (14)

A set of eight linear algebraic equations is obtained for the present model. It is not out of place to mention that for the similar MEE system the published models contain at least 23 equations. In fact, the present model is simplified by assuming equal driving force in each effect and thus it eliminates the necessity of values of U as well as heat transfer area. The input variables are F, P, T_F, T_0 & T_i (i=1 to 7) whereas, output variables are Ws & C_i (i=1 to 7). The set of linear equations is solved simultaneously using Gaussian Elimination Method with partial pivoting (GEMPP). For the solution of the present model a computer program has been developed. This program plots the *temperature paths* of different streams of feed and also automatically generates the set of governing equations of the model, once the input data are provided. The details of solution procedure are given in the work of Khanam and Mohanty [23].

The solution of this model gives values of SC (=Ws), and SE for the base case SEFFFE system, shown in Fig. 1, as 10467 kg/h and 4.2, respectively. The SE is calculated as total water evaporated (F-P) divided by SC. The present model is validated using four case studies [23]. The results show that the average error of 5.2 % was found in the prediction of value of SC.

3. Energy reduction schemes (ERSs)

The SC for the MEE system can be reduced by incorporating different ERSs. These ERSs are induction of flashing, vapor bleeding, heating up liquor using condensate, etc. in the MEE system.

3.1. Induction of flashing

Generally, for the MEE system three types of flashing such as condensate, feed and product flashing are incorporated. Normally, the condensate from all the effects except first remains unused. Since, being at low temperature, it cannot be used in any other process and being contaminated by the entrained liquor it cannot be sent to the boiler feed tank. The condensate, which exits from steam/vapor chest of an effect, contains sufficient amount of sensible heat, which can be put to use. Its sensible heat can be extracted by means of flashing, which produces low pressure vapor. This vapor can be used as a heating medium in vapor chests of other effects to improve steam economy of the whole system.

Further, provisions of feed and product flashing in the MEE system are used for two purposes: first, it helps water to be evaporated from feed and product without using steam/vapor and the second, vapor generated from flashing of feed and product, are used as a heating medium at appropriate effects. Thus, these provisions enhance the steam economy of the system.

The SEFFFE system with the induction of three primary, four secondary condensate, one feed and one product flash tanks are shown in Fig. 3. In the present work, condensate of live steam is denoted as primary condensate whereas; condensate of other vapor streams that exit from vapor chests of effects 2 to 7 etc., is referred to as secondary condensate. Moreover, the model of a condensate flash tank, PF1, shown in Fig. 4, is obtained by material and energy balance.

In Fig. 4, condensate stream "CS_1" enters in to PF1 at temperature, T_{01}, and is flashed at T_3. As a result of it, vapor stream, CS_V, and liquid stream, CS_L, are generated. Then the vapor, CS_V, is mixed with V3 and vapor generated through flashing in SF1. These vapors are further used as a heating medium in effect 4. The mathematical expressions of CS_V and CS_L are derived as:

Overall mass balance around PF1

$$CS_1 = CS_V + CS_L \quad (15)$$

Energy balance around PF1

$$CS_1\, h_s = CS_V\, H_3 + CS_L\, h_3 \quad (16)$$

Following expressions can be obtained by putting CS_L from Eq. 15 into Eq. 16,

$$CS_V = \frac{CS_1\,(h_s - h_3)}{(H_3 - h_3)} = \frac{Ws1(h_s - h_3)}{(H_3 - h_3)} \quad (17)$$

Eqs. 15 and 17 are used to obtain the expression of CS_L as:

$$CS_L = (CS_1 - CS_V) = Ws1\left[1 - \frac{(h_s - h_3)}{(H_3 - h_3)}\right] \quad (18)$$

This model gives the amount of vapor generated by flashing at the temperature of flash tank, which is decided by the temperature of effect. Thus, it does not require the information about the pressures of effects.

The complete model for SEFFFE system shown in Fig. 3 is developed in the work of Khanam [24]. It also includes eight linear equations which are solved using GEMPP. The SC and SE for SEFFFE system with condensate flashing are computed as 8878 kg/h and 4.95, respectively. However, with the induction of feed and product flashing in the above system, the SC and SE are found to be 8705 kg/h and 5.04, respectively. The measured value of SC of the SEFFFE system, used in Indian paper mill and shown in Fig. 3, is 8800kg/h as indicated in Table 1. It is 1.09 % more than that predicted using present model. Moreover, for the same SEFFFE system Bhargava et al. [14] developed a rigorous mathematical model by taking in to account the variation in physical property, boiling point rise, heat losses from effects, heat transfer area and an empirical model for U, obtained from plant operating data of a falling film evaporator as functions of ΔT, composition and feed flow rate. Further, the validity of this model was tested against the data obtained from a nearby paper mill. The results showed that U match within an maximum error limit of 10% for the operating data, shown in Table 1, liquor concentration and vapor temperatures of different effects match within error limits of -0.2 to +0.4% and –0.26 to +1.76%, respectively. This model predicts the value of SC as 8802kg/h which is 1.1% more than the present simplified model.

3.2. Induction of vapor bleeding

Another scheme to reduce overall SC is to use liquor re-heaters positioned outside the effect to increase the temperature of liquor. These re-heaters use bled vapor streams from suitable effects to preheat the liquor. For the SEFFFE system four re-heaters are used between 2^{nd} & 3^{rd}, 3^{rd} & 4^{th}, 4^{th} & 5^{th} and 5^{th} & 6^{th} effects and hence the required vapor can be bled from V_2, V_3, V_4 and V_5, respectively. Therefore, vapor streams, V_2 to V_5, need to be split into two vapor streams each out of which one is used in the vapor chest of appropriate effect for heating whereas, the other vapor stream is employed in the re-heater to preheat the liquor. The condensate of bled vapor is flashed and the vapor generated from it is also used as heating medium in the appropriate effects.

The block diagram of a re-heater is shown in Fig. 5 in which exit liquor of $(k+1)^{th}$ effect at temperature T_{k+1} enters into re-heater (Rh). Where, liquor is heated up to the target temperature, T_t, using bled vapor of amount, V_k. This vapor stream is a part of vapor generated in k^{th} effect.

The target temperature, T_t, to which liquor is preheated before being fed to k^{th} effect is defined as:

$$T_t = T_{k+1} + 0.5(T_k - T_{k+1}) \quad (19)$$

This expression has been taken from Bhargava et al. [14]. The complete model for SEFFFE system with re-heaters is proposed by Khanam [24] that consists of twelve linear equations: eight are similar to Eqs. 9 to 14 and four are for re-heaters. The total amount of SC and SE for SEFFFE system with condensate flashing and vapor bleeding are obtained as 8542 kg/h and 5.14, respectively. Further, the model of SEFFFE system with four re-heaters is validated with the work of Bhargava et al. [12] and found that for above system the later model predicts 8473 kg/h of SC.

The reason for the decrease in the values of SC when re-heaters are used in comparison to a situation when they are not used can be explained as follows: When liquor moves in backward sequence, it enters into seventh effect and moves successively to first effect from where it comes out as a product. In this process its temperature gradually increases from the lowest value (seventh effect has lowest temperature) to the highest value available at first effect. To explain the above fact, let us take an example when liquor flows from Effect No.3 (having a temperature T_3) to Effect No.2 (having a temperature T_2). Obviously, $T_2>T_3$. In such a situation, sensible heat required to raise the temperature of liquor from T_3 to T_2 as well as latent heat for evaporation required at effect no. 2, are supplied by live steam. However, when re-heater is introduced between 2nd and 3rd effect then liquor first heated up to a temperature, T_t, [where, $T_t = T_3+\{(T_2-T_3)/2\}$] by the re-heater using a part of bled vapor from 2nd effect i.e. V_2. By this arrangement liquor enters into 2nd effect at T_T. The above referred sensible heating is done by vapor at a lower pressure (higher latent heat) than the live steam. As a consequence of it, the amount of sensible heat required to heat up the liquor (from T_T to T_2) inside the effect decreases in comparison to a case when re-heater is not used. As a result, the amount of live steam required in 2nd effect is decreased. Thus, SC decreases and SE increases when re-heaters are incorporated or placed in the system. It appears that this is due to the appropriate utilization of driving force (ΔT) for sensible heating by low pressure vapor (with high latent heat) which improves the value of SE and decreases the value of SC.

3.3. Induction of liquor heating with condensate

In this paper a new scheme is proposed in which feed (liquor) is preheated as has been carried out for the case of reheater. However, here condensate is used as a heating medium instead of bled vapor. The modified SEFFFE system is shown in Fig. 6 in which four heat exchangers (HX) are used to preheat the liquor. For this situation the same model is used as developed for SEFFFE system shown in Fig. 1. The only difference is in this model liquor enters into the effect at effect's temperature. The model solved to obtain values of SC and SE for this system as 8390 kg/h and 5.23, respectively. This reduction in SC is due to a fact that after preheating liquor is entering at temperature of effect and thus steam/vapor is used only for evaporation instead of sensible heating.

Further, Fig. 6 shows that condensates of live steams, CS_1 and CS_2 are not utilized in the process. Thus, the SEFFFE system, shown in Fig. 6, is modified to incorporate three primary flash tanks, PF1 to PF3, as has been shown in Fig. 3. In these tanks condensates, CS_1 and CS_2, are being flashed. The modified SEFFFE system consumes 8064 kg/h of steam. Further, the SC of the above system can be reduced by incorporating feed and product flashing, up to a level of 7895 kg/h.

3.4. Comparison between different ERSs

In the present paper different ERSs, used in a MEE system to reduce overall SC, are discussed and then these are compared, based on SC and total annual cost, to select the best ERS. For this purpose Table 2 is created which shows that different ERSs reduce the SC in a range of 15.2% to 24.6%. Thus, a significant amount of steam can be saved by incorporating these ERSs in MEE system. Based on value of SC, ERS6 is selected as best as it consumes minimum steam.

The analysis is further refined by plotting Fig. 7 which indicates the capital-, operating- and total annual- cost of ERS0 to ERS6. The capital cost is computed for flash tanks, pumps and heat exchangers ERS [25, 26] but not for an evaporator. This is because all the ERS include 7 evaporators, however, other units than this may vary. As costs of these evaporators are same for all ERS thus, it is not playing any role in selecting the best ERS. Hence, these costs are excluded from the calculation of total annual cost which on the other hand eliminates the necessity for area of an evaporator. However, operating cost is computed based on steam cost and operation time of the system equal to 122.7 Rs/ton and 300 days/year, respectively. The plant life is assumed as 5 years.

Further, based on total annual cost ERS6 is found as the best. In fact, ERS4 consumes 3.9% more cost then ERS6 and consequently provides a considerably less complex SEFFFE system in comparison to ERS6. Thus, if the designer can tolerate to expend 3.9% more cost then ERS4 may be selected for final design.

4. Selection of OFFS

The ERSs discussed above can be used by changing the design of the existing MEE system using units such as flash tanks, heat exchangers, etc. However, in the present paper a simplified technique is also proposed that can reduce value of SC without modifying the MEE system and hence it is different from ERSs. The present technique is to select the optimal feed flow sequence (OFFS), amongst the feasible flow sequences, for which MEE system can be operated to give best steam economy.

4.1. Modified temperature paths

Based on the discussion of different energy reduction schemes, ERS4 is selected for final design as it is less complex, easy to operate and consumes 19.8% less steam than base case. Further, it is considered for the development of a graphical approach to show the possible improvements in SE without modifying the SEFFFE system. For this purpose, the feasible FFSs shown in Table 3, are studied to obtain the OFFS, which yields highest possible steam economy. These FFSs are selected based on the flow sequences of SEFFFE systems reported in the literature [13] as well as that have been employed in industry. Table 3 includes one backward and five mixed FFS.

In Fig. 6, feed follows in backward flow sequence, S1. Schematically, this is represented as "Feed→7→6→5→4→3→2→1→ product". For this system the feed is hypothetically considered to be composed of eight different streams: P, C_1, C_2, C_3, C_4, C_5, C_6 and C_7.

To draw the temperature path of a stream, the concept of modified temperature path (MTP) is used, which is the revised form of temperature path proposed by Westerberg and Hillenbrand [21] as MTP does not include internal heat exchange. For the present case, MTPs for different constituent streams of feed are shown in Fig. 8. The MTP followed by stream, P, for FFS, S1, can be demonstrated schematically as: $T_F \rightarrow T_7 \rightarrow T_6 \rightarrow T_5 \rightarrow T_4 \rightarrow T_3 \rightarrow T_2 \rightarrow T_1 \rightarrow T_P$. In the present work, these are plotted for different FFS using a computer program, which is developed based on equal driving force in each effect and temperature of feed. Other parameters such as feed and product flow rate and concentration, U and heat transfer area are not accounted for drawing MTP. This approach is used as screening tool to select OFFS amongst the several possible FFS before a complete study of any MEE system is carried out.

The MTP of stream, P, presented in Fig. 8, shows that the temperature of the stream drops from point a to a' and then rises from point a'' to a''' (here a' = a''). When MTP of any stream reverses its direction an *U-turn* is generated. For this case it is a *bottom U-turn* denoted by [b]. Further, if temperature rises first and then falls and there by reverses its direction then the *U-turn* so created is called *top U-turn* and is denoted by [t].

4.2. Results of MTP and discussions

For the SEFFFE system, shown in Fig. 6, the vapor body temperatures of each effect can be predicted by assuming constant ΔT, discussed in Section 2, between the steam/vapor chest of an effect and liquor inside the effect. The MTPs of eight streams of feed for FFS, S1, are shown in Fig. 8.

It can be seen from this figure that MTPs for a flow sequence mainly contain two characteristic elements: (1) length of path (in terms of temperature) traversed by different streams, and (2) total number of U-turns encountered in the path. More are the number of U-turns more is the length of temperature path.

The number of U-turns in a MTP means that the stream is undergoing through heating and cooling phases, which may not be desirable. In other words the internal heat exchange of the streams becomes less efficient due to minimum temperature drop criterion. In a MEE system when a stream moves downward, i.e. from higher temperature effect to a lower temperature effect, it produces vapor inside the effect due to flashing. These vapors contribute in evaporation in subsequent effect where it is used as a heating medium and generate more amount of vapor there, which subsequently enters into vapor chest of the next effect. This process continues up to the last effect. The exit vapor from last effect goes into the condenser thereby increases its load i.e. increases the requirement of cold water in the condenser. Thus, if more flashing takes place inside the effect, more amount of cold water will be needed.

On the other hand if a stream moves upward, from lower temperature effect to a higher temperature effect, it takes heat from the vapor of previous effect to raise its temperature. So in this case the amount of vapor required from previous effect will be more. This effect travels upto the first effect and consequently increases the requirement of live steam as it is the only source of heat in a MEE system.

Thus, more is the number of U-turns in the path of temperatures followed by a stream more will be the requirement of amount of cold water and live steam. So, the main criteria for the selection of an OFFS with the help of temperature path are as follows:

1. For an OFFS, different streams of feed follow the shortest temperature paths
2. The temperature paths for an OFFS of a MEE system contain least number of U-turns.

As can be seen from Fig. 8 that for flow sequence, S1, the temperature path followed by stream, P, is $T_F \rightarrow T_7 \rightarrow T_6 \rightarrow T_5 \rightarrow T_4 \rightarrow T_3 \rightarrow T_2 \rightarrow T_1$ which contains only one U-turn as can be seen in row 2 of Table 4. Similarly, the temperature path for C_1 can be given as

$T_F \rightarrow T_7 \rightarrow T_6 \rightarrow T_5 \rightarrow T_4 \rightarrow T_3 \rightarrow T_2 \rightarrow T_1$ with one U-turn. In the same way temperature path along with U-turns for streams C_i where i = 2 to 7 can be drawn as shown in row 2 to row 5 of Table 4. Likewise, the MTPs of different streams of feed for flow sequences, S2 to S6, in terms of the length of temperature path as well as U-turns are shown in Table 4. Further, this table includes the quantitative information for consumption of steam and cold water. The cold water consumption is directly related to the amount of vapor, V_7, which is entering into condenser where cold water is used. Hence, V_7 is reported in Table 4 instead of cold water consumption.

In fact, for constant feed flow rate and concentration when the values of V_7 vary for different flow sequences it do not affect the product concentration as total vapor flow rate, V_1 to V_7, are constant for each sequence. It may be explained as: for all flow sequences feed and product concentrations are fixed which are clearly shown in Table 1. Therefore, for different MTP when V_7 varies any other vapor flow rates amongst V_1 to V_6 acquire such flow rates which provides total vapor produced constant. Thus, when V_7 vary it will not affect the product concentration.

It is observed from Table 4 that different streams of feed for flow sequence, S1, follow the shortest temperature path and contain least number of U-turns which comes out to be eight whereas, streams for flow sequences, S2 to S6, follow longer paths than that of S1 and contain more number of U-turns. On the other hand sequence, S1, consumes lesser steam and cold water than other FFS. So, for the present case, flow sequence, S1, can be selected as an OFFS.

4.2.1. Comparison of Predictions of Present Graphical Approach with published Models

To test the reliability of the present MTP approach its predictions have been compared with the predictions of other models, which were based on rigorous simulation. These models were developed by Kern [16], Nishitani and Kunugita [18] and Bhargava et al. [13]. These investigators have used different approaches to select OFFS. The results of comparisons are shown in Table 5.

Kern [16] considered a triple effect evaporator (TEE) system for the concentration of chemical solution and predicted the OFFS. The model was based on mass and enthalpy balance, negligible BPR, constant physical properties of solution and different U for different effects. The author used forward and backward FFSs and selected the OFFS, based on minimum live steam consumption, as backward flow sequence. The MTPs and U-turns of streams for different flow sequences, shown in Table A.1, clearly indicates that backward FFS follows shortest temperature paths and consist of zero U-turns. However, in the case of forward feed flow sequence the temperature paths are longer, w.r.t. backward FFS, and it contain 3 U-turns. Moreover, it also consumes less steam. Thus, the present graphical approach and model proposed by Kern [16] predict the same OFFS for the above system.

Nishitani and Kunugita [18] have used a TEE system employed for concentrating milk. Based on mass and energy balance equations and operating constraints such as viscosity of liquid and formation of scale, they have developed a model for screening of OFFS. Their criteria for selection of a set of non-inferior (This is a set of flow sequences which includes OFFS as well as near OFFSs in order of decreasing total annual cost (TAC)) flow sequences is based on minimum heat transfer area and live steam consumption. The authors predicted FFS-213 as non-inferior flow sequence based on the value of TAC for the given operating parameters shown in Row 4 of Table 5. The MTPs of different streams of feed for six possible flow sequences are shown in Table A.2. From this table it is observed that for above system FFS-213 comes out to be optimum as temperature paths of this flow sequence are shorter, number of U-turns is lowest and value of SC is minimum. Thus, the approach of Nishitani and Kunugita [18] and that of present predict similar results for the TEE system.

Bhargava et al. [13] based on the SEFFFE system shown in Fig.1 developed a rigorous non-linear mathematical model for the simulation of above system by taking in to account the variation in physical property, BPR, heat losses from effects and an empirical model for U, obtained from plant operating data of a falling film evaporator as functions of ΔT, composition and feed flow rate. The author selected the optimal sequence based on value of live steam consumption. For above system the present approach and model due to Bhargava et al. [13] select S1 as OFFS as can be evident from Table 4 & 5.

From the above discussion it can be observed that as far as the selection of OFFS is concerned there is no difference in the predictions of present approach and that of other models. The above facts amply prove that though the present graphical approach is based on simplified assumptions it can work effectively as a pre-screening tool for the selection of OFFS for a MEE system.

5. Conclusions

The present paper consists of two different parts. In the first part a new energy reduction scheme (ERS) is proposed where condensate of an evaporator is used to preheat the liquor using a counter current heat exchanger. It helps in reducing the steam consumption for a multiple effect evaporator (MEE) system. Further, a comparative study between different ERSs such as condensate-, feed- and product- flashing, vapor bleeding and new scheme is carried out. These ERSs are employed by changing the design of the existing MEE system using units such as flash tanks, heat exchangers, etc. Based on the comparative study an optimum ERS is chosen for final design which is further considered in the second part of the paper for developing a simplified technique called modified temperature path (MTP) to reduce steam consumption without modifying the MEE system. This technique is used to select the optimal feed flow sequence (OFFS) amongst the feasible flow sequences. The salient features of the complete work are as follows:

1. Different ERSs save steam up to 24.6%. The best ERS is selected based on steam consumption as well as number of units involved in ERS.
2. Liquor heating with condensate contributes considerably to reduce steam consumption. Moreover, it also produces less complex MEE network in comparison to other ERSs.
3. MTPs indicate the optimal flow sequence of an MEE system based on shortest temperature path and U-turns. This approach is easy and needs comparatively less computation in comparison to other techniques based on complex simulation, which is generally used for screening of OFFS. However, MTP is used as a pre-selection tool.

Appendix A

The MTPs for different flow sequences for models, proposed by Kern [10] and Nishitani & Kunugita [12], are shown in Table A.1 and A.2, respectively.

References

[1] Rao NJ, Kumar R. Energy Conservation Approaches in a Paper Mill with Special Reference to the Evaporator Plant. Proceeding of IPPTA Int. seminar on energy conservation in pulp and paper industry, New Delhi, India, 1985.

[2] Mondkar SM. Condensate flashing in multiple effect evaporation plant. Chem Age Ind 1972; 23:659-664.

[3] Radovic LR, Tasic AZ, Grozanic DK, Djordjevic BD, Valent VJ. Computer design and analysis of operation of a multiple effect evaporator system in the sugar industry. Ind Eng Chem Proc Des Dev 1979; 18:318-323.

[4] Miyatake O. Comparative study of flash evaporation rates. Desalination 1994; 96:163-171.

[5] Bremford DJ, Muller-Steinhagen H. Multiple effect evaporator performance for black liquor-I Simulation of steady state operation for different evaporator arrangements. APPITA J 1994; 47:320-326.

[6] El-Dessouky HT, Ettouney HM. Multiple-effect evaporation desalination systems: thermal analysis. Desalination 1999; 125:259-276.

[7] E1-Dessouky HT, Shaban HI, A1-Ramadan H. Steady-state analysis of multi-stage flash desalination process. Desalination 1995; 103:271-287.

[8] El-Dessouky HT, Ettouney HM. Al-Juwayhel F. Multiple effect evaporation-vapor compression desalination processes. Trans IchemE Part A 2000 ; 78 : 662-676.

[9] Jernqvist A, Jernqvist M, Aly G. Simulation of thermal desalination processes. Desalination 2001; 134:187-193.

[10] Ray AK, Singh P. Simulation of Multiple Effect Evaporator for Black Liquor

Concentration, IPPTA J 2000; 12:53-63.

[11] Ray AK, Sharma NK, Singh P. Estimation of energy gains through modeling and simulation of multiple effect evaporator system in a paper mill. IPPTA J 2004; 16:35-45.

[12] Bhargava R. Simulation of flat falling film evaporator network. PhD thesis, Indian Institute of Technology Roorkee, India, 2004.

[13] Bhargava R, Khanam S, Mohanty B, Ray AK. Selection of optimal feed flow sequence for a multiple effect evaporator system. Comp Chem Eng 2008; 32: 2203-2216.

[14] Bhargava R, Khanam S, Mohanty B, Ray AK. Simulation of flat falling film evaporator system for concentration of black liquor. Comp Chem Eng 2008; 32: 3213–3223.

[15] Kaya D, Sarac HI. Mathematical modeling of multiple-effect evaporators and energy economy. Energy 2007; 32, 8:1536-1542.

[16] Kern DQ, Process heat transfer, McGraw Hill; 1950.

[17] Harper JM, Tsao TF, Evaporator strategy and optimization. In: Jelinek R, editors. Computer programs for chemical engineering education VI Design, Austin, Texas: Aztec Publishing; 1972, p. 117-145.

[18] Nishitani H, Kunugita E. The optimal flow pattern of multiple effect evaporator systems. Comp Chem Eng 1979; 3: 261-268.

[19] Stewart G, Beveridge GSG. Steady state cascade simulation in multiple effect evaporation. Comp Chem Eng 1977; 1, 1:3-9.

[20] Ayangbile WO, Okeke EO, Beveridge GSG. Generalized steady state cascade simulation algorithm in multiple effect evaporation. Comp Chem Eng 1984; 8:235-242.

[21] Westerberg AW, Hillenbrand Jr JB. The synthesis of multiple effect evaporator systems using minimum utility insights-II liquid flow pattern selection. Comp Chem Eng 1988; 12: 625-636.

[22] Mohanty B, Khanam S. Development of an efficient linear model for the analysis of multiple effect evaporator system, Proceeding of Int. conference on advances in energy research, IIT Bombay, Mumbai, Maharastra; 2007; 724-730.

[23] Khanam S, Mohanty B. A Process Integration based Approach for the Analysis of Evaporator System. Chem Eng Tech 2007; 30:1659-1665.

[24] Khanam S. Synthesis of multiple effect evaporator system. PhD thesis, Indian Institute of Technology Roorkee, India, 2006.

[25] http://www.epa.gov/gasstar/documents/workshops/gillette-2006/dehydration.pdf

[26] Shenoy UV, Heat Exchange Network Synthesis: Process Optimization by Energy and Resource Analysis, Gulf Publishing Company Tokyo; 1995, 43-44.

Nomenclature

BPR	Boiling point rise
C	Condensate flow rate of vapor, kg/h
C_P	Specific heat capacity, J/kg °C
CS	Condensate flow rate of steam, kg/h
ERS	Energy reduction scheme

F	Feed flow rate, kg/h
FFS	Feed flow sequence
fs	Fraction of steam
GEMPP	Gaussian elimination method with partial pivoting
HX	Heat exchanger
MEE	Multiple effect evaporator
MTP	Modified temperature path
n	Number of effects
OFFS	Optimal feed flow sequence
P	Flow rate of product stream, kg/h
S1 to S6	Feed flow sequences
SE	Steam economy
SEFFFE	Septuple effect flat falling film evaporator
T	Temperature, °C
TEE	Triple effect evaporator
U	Overall heat transfer coefficient, W/m^2K
V	Vapor flow rate, kg/h
SC, Ws	Steam consumption, kg/h
x	Concentration of solids in liquor, dimensionless

Subscripts

1 to 7, k	Effect number
F	Feed

0	Live steam entering into first effect
L	Liquor
Le	Last effect
P	Product
r	Reference
s	Supply
t	Target
V	Vapor
W	Water

Greek letters

λ	Heat of vaporization, kJ/kg

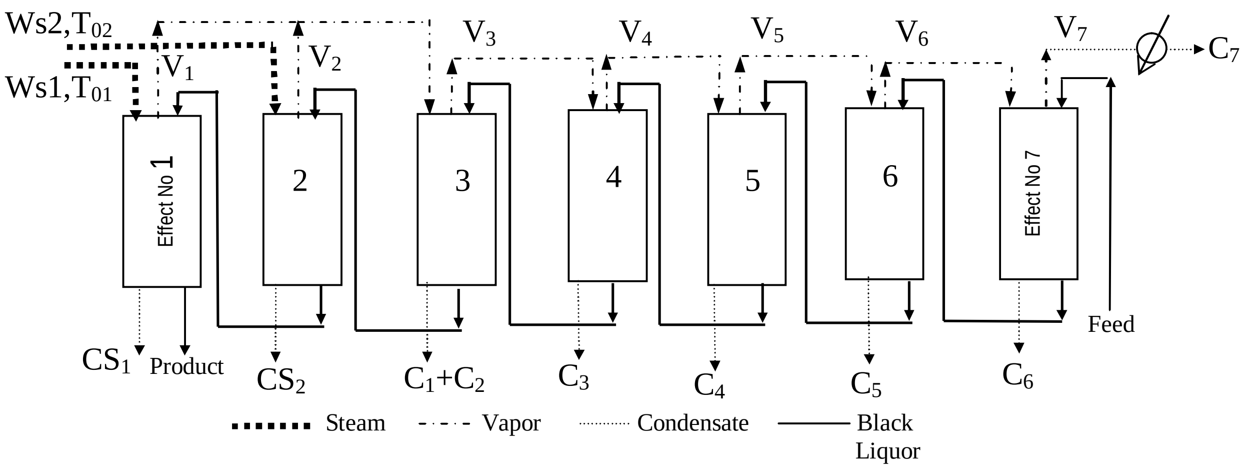


Fig. 1. The schematic diagram of a SEFFFE system

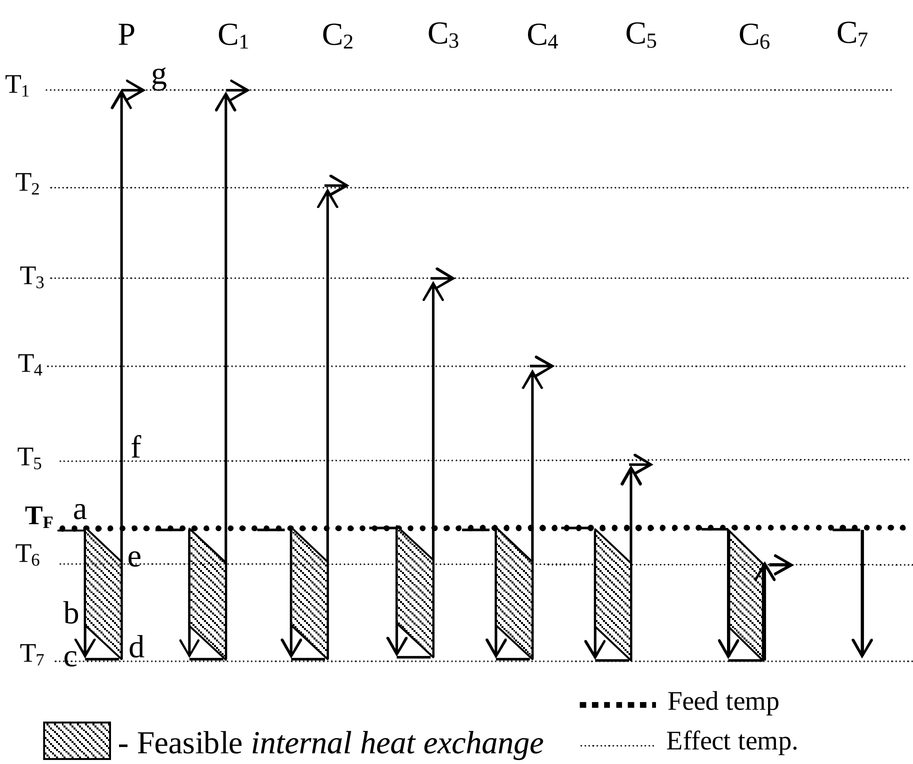


Fig. 2. Temperature paths of different streams for SEFFFE system

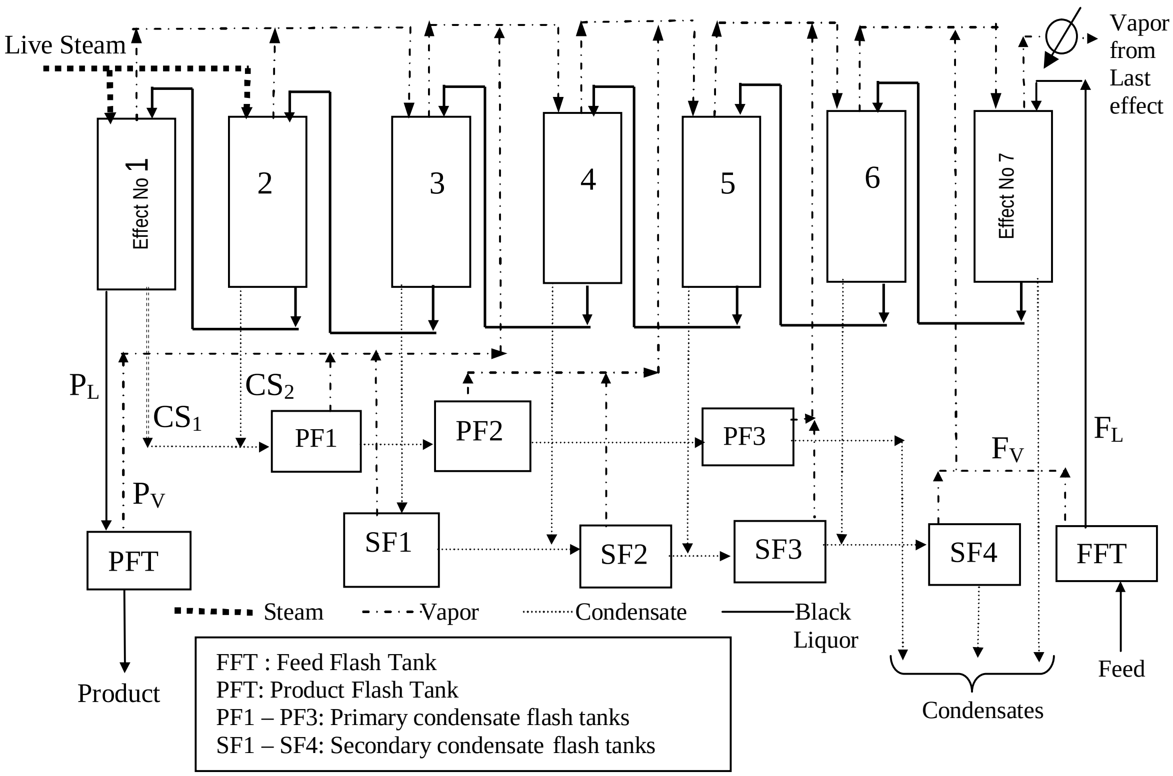


Fig. 3. Schematic diagram of a SEFFFE system with flashing

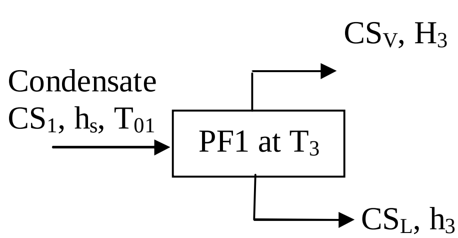
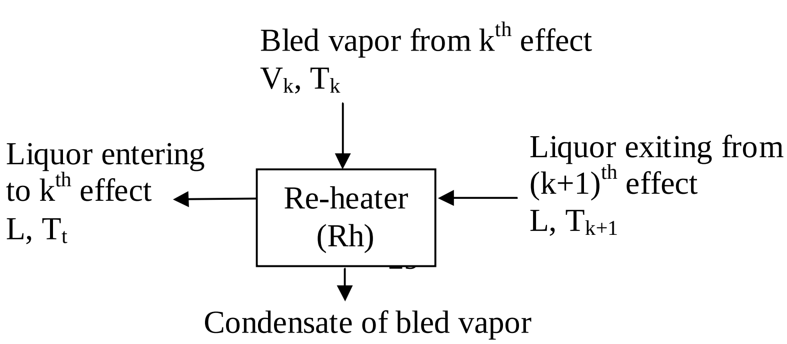


Fig. 4. Block diagram of a condensate flash tank, PF1



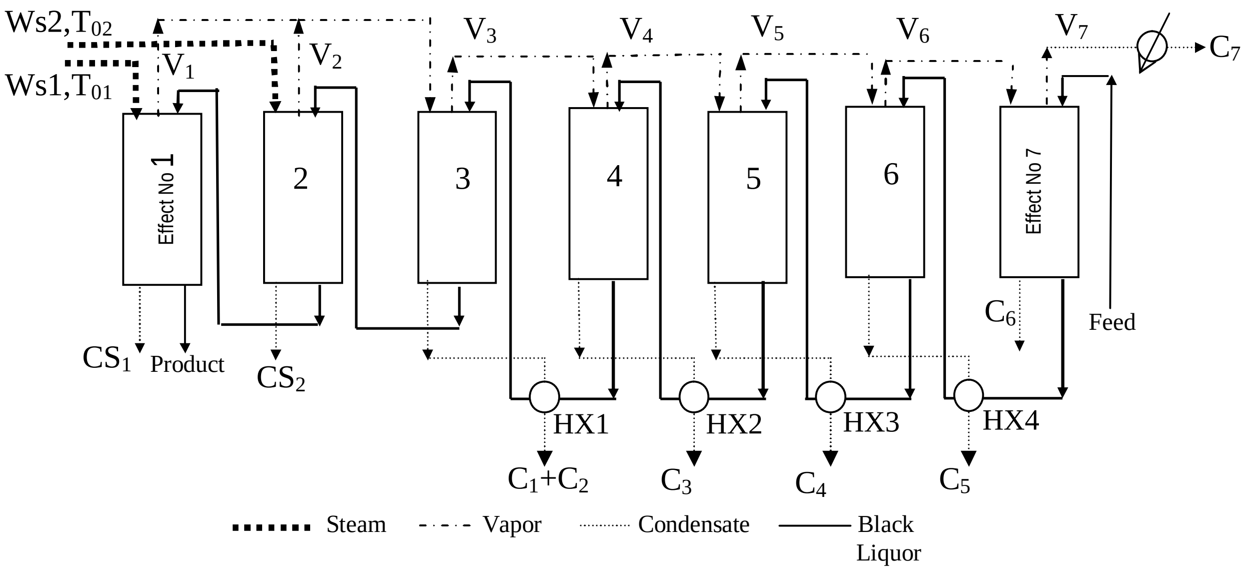


Fig. 6. The schematic diagram of a SEFFFE system with four heat exchangers

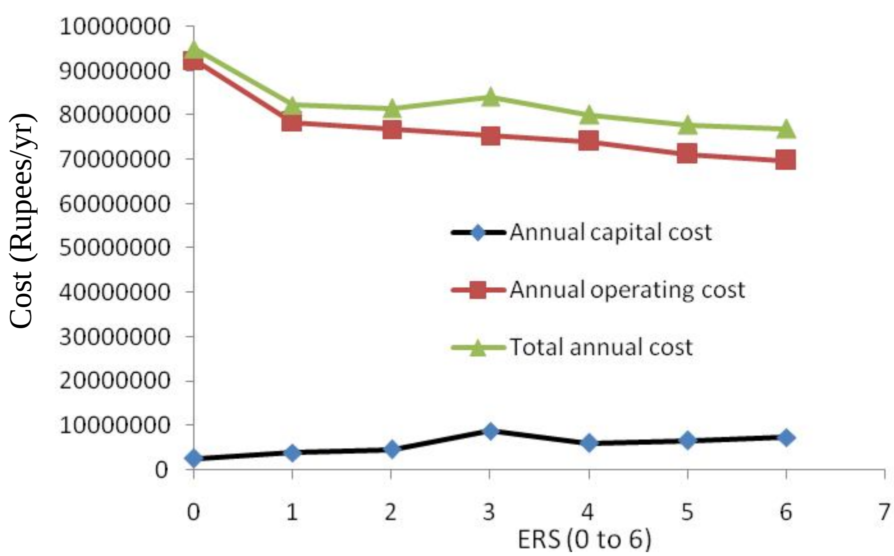


Fig. 7. Capital, operating and total costs for ERS (0 to 6)

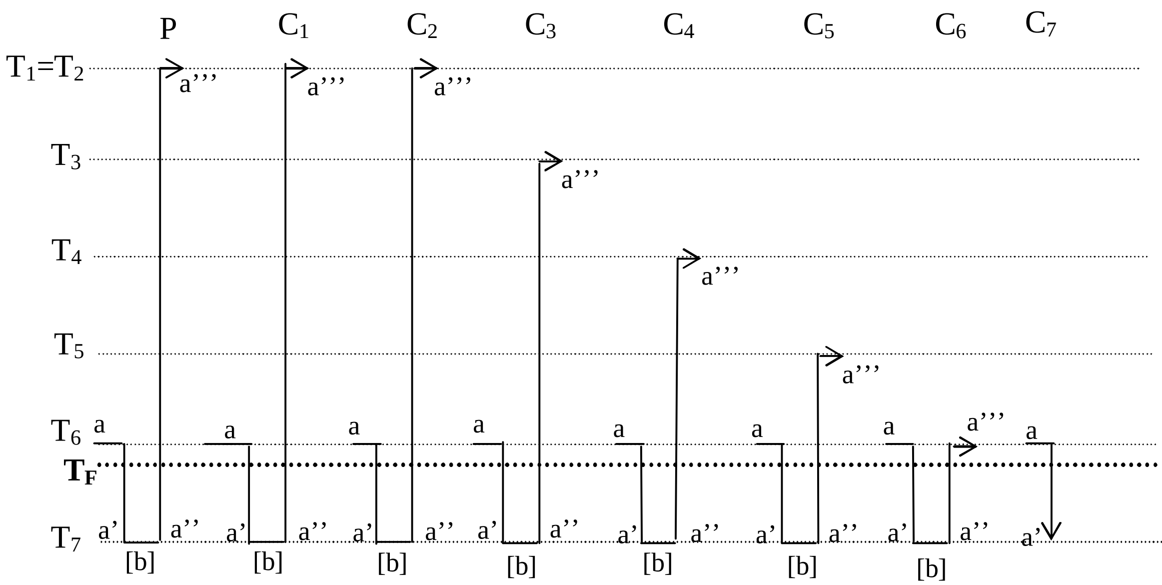


Fig. 8. MTPs of different streams of feed for FFS, S1

Table 1

The operating parameters for the SEFFFE system

Parameter(s)		Value(s)
Total number of effects		7
Number of effects being supplied live steam		2
Live steam temperature	Effect 1	140 °C
	Effect 2	147 °C
Black liquor inlet concentration		0.118
Black liquor outlet concentration		0.54
Liquor inlet temperature		64.7°C
Black liquor feed flow rate		56200 kg/h
Last effect vapor temperature		52 °C
Feed flow sequence		Backward
Steam consumption for SEFFFE system shown in Fig. 3.		8800 kg/h

Table 2

Value of SC and % reduction in SC from base case for different ERSs

ERS	Units used for ERS	SC, kg/h	SE	% reduction in SC from the base case
Base case (ERS0)	Nil, 7 pumps	10467	4.2	0
Induction condensate flashing (ERS1)	PF1,PF2,PF3,SF1,SF2, SF3,SF4, 7 pumps	8878	4.95	15.2
Induction of feed, product and condensate flashing (ERS2)	PF1,PF2,PF3,SF1,SF2, SF3,SF4,FFT,PFT, 8 pumps	8705	5.04	16.8
Induction of vapor bleeding (ERS3)	PF1,PF2,PF3,SF1,SF2, SF3,SF4,FFT,PFT & 4 re-heaters, 12 pumps	8542	5.14	18.4
Induction of liquor heating with condensate (ERS4)	HX1,HX2,HX3,HX4, 9 pumps	8390	5.23	19.8
Induction of liquor heating and condensate flashing (ERS5)	HX1,HX2,HX3,HX4,PF1,PF2,PF3, 9 pumps	8064	5.45	23
Induction of liquor heating, feed, product and condensate flashing (ERS6)	HX1,HX2,HX3,HX4, PF1, PF2, PF3, FFT, PFT, 10 pumps	7895	5.56	24.6

Table 3

Feasible FFSs in a SEFFFE system

Sequence No.	FFS	Sequence No.	FFS
S1	7→6→5→4→3→2→1	S4	4→5→6→7→3→2→1
S2	6→7→5→4→3→2→1	S5	3→4→5→6→7→2→1
S3	5→6→7→4→3→2→1	S6	4→5→6→7→1→2→3

Table 4

MTPs and U-turns for different flow sequences

Flow Seq.	Stream	MTPs of different streams	No. of U turns	Stream	MTPs of different streams	No. of U turns
S1	P	$T_F \to T_7 \to T_6 \to T_5 \to T_4 \to T_3 \to T_2 \to T_1$	1	C_4	$T_F \to T_7 \to T_6 \to T_5 \to T_4$	1
	C_1	$T_F \to T_7 \to T_6 \to T_5 \to T_4 \to T_3 \to T_2 \to T_1$	1	C_5	$T_F \to T_7 \to T_6 \to T_5$	1
	C_2	$T_F \to T_7 \to T_6 \to T_5 \to T_4 \to T_3 \to T_2$	1	C_6	$T_F \to T_7 \to T_6$	1
	C_3	$T_F \to T_7 \to T_6 \to T_5 \to T_4 \to T_3$	1	C_7	$T_F \to T_7$	0
		Total number of U-turns = 7		SC=8390 kg/h, V_7=8116 kg/h		
S2	P	$T_F \to T_6 \to T_7 \to T_5 \to T_4 \to T_3 \to T_2 \to T_1$	2	C_4	$T_F \to T_6 \to T_7 \to T_5 \to T_4$	2
	C_1	$T_F \to T_6 \to T_7 \to T_5 \to T_4 \to T_3 \to T_2 \to T_1$	2	C_5	$T_F \to T_6 \to T_7 \to T_5$	2
	C_2	$T_F \to T_6 \to T_7 \to T_5 \to T_4 \to T_3 \to T_2$	2	C_6	$T_F \to T_6$	0
	C_3	$T_F \to T_6 \to T_7 \to T_5 \to T_4 \to T_3$	2	C_7	$T_F \to T_6 \to T_7$	1
		Total number of U-turns = 13		SC=8492 kg/h, V_7=8221.62 kg/h		
S3	P	$T_F \to T_5 \to T_6 \to T_7 \to T_4 \to T_3 \to T_2 \to T_1$	2	C_4	$T_F \to T_5 \to T_6 \to T_7 \to T_4$	2
	C_1	$T_F \to T_5 \to T_6 \to T_7 \to T_4 \to T_3 \to T_2 \to T_1$	2	C_5	$T_F \to T_5$	0
	C_2	$T_F \to T_5 \to T_6 \to T_7 \to T_4 \to T_3 \to T_2$	2	C_6	$T_F \to T_5 \to T_6$	1
	C_3	$T_F \to T_5 \to T_6 \to T_7 \to T_4 \to T_3$	2	C_7	$T_F \to T_5 \to T_6 \to T_7$	1
		Total number of U-turns = 12		SC=8628 kg/h, V_7=8344 kg/h		
S4	P	$T_F \to T_4 \to T_5 \to T_6 \to T_7 \to T_3 \to T_2 \to T_1$	2	C_4	$T_F \to T_4$	0
	C_1	$T_F \to T_4 \to T_5 \to T_6 \to T_7 \to T_3 \to T_2 \to T_1$	2	C_5	$T_F \to T_4 \to T_5$	1
	C_2	$T_F \to T_4 \to T_5 \to T_6 \to T_7 \to T_3 \to T_2$	2	C_6	$T_F \to T_4 \to T_5 \to T_6$	1
	C_3	$T_F \to T_4 \to T_5 \to T_6 \to T_7 \to T_3$	2	C_7	$T_F \to T_4 \to T_5 \to T_6 \to T_7$	1
		Total number of U-turns = 11		SC=9055 kg/h, V_7= 8762 kg/h		
S5	P	$T_F \to T_3 \to T_4 \to T_5 \to T_6 \to T_7 \to T_2 \to T_1$	2	C_4	$T_F \to T_3 \to T_4$	1
	C_1	$T_F \to T_3 \to T_4 \to T_5 \to T_6 \to T_7 \to T_2 \to T_1$	2	C_5	$T_F \to T_3 \to T_4 \to T_5$	1
	C_2	$T_F \to T_3 \to T_4 \to T_5 \to T_6 \to T_7 \to T_2$	2	C_6	$T_F \to T_3 \to T_4 \to T_5 \to T_6$	1
	C_3	$T_F \to T_3$	2	C_7	$T_F \to T_3 \to T_4 \to T_5 \to T_6 \to T_7$	1
		Total number of U-turns=12		SC=9490 kg/h, V_7=9100 kg/h		
S6	P	$T_F \to T_4 \to T_5 \to T_6 \to T_7 \to T_1 \to T_2 \to T_3$	3	C_4	$T_F \to T_4$	0
	C_1	$T_F \to T_4 \to T_5 \to T_6 \to T_7 \to T_1$	3	C_5	$T_F \to T_4 \to T_5$	1

	C_2	$T_F \to T_4 \to T_5 \to T_6 \to T_7 \to T_1 \to T_2$	2	C_6	$T_F \to T_4 \to T_5 \to T_6$	1
	C_3	$T_F \to T_4 \to T_5 \to T_6 \to T_7 \to T_1 \to T_2 \to T_3$	2	C_7	$T_F \to T_4 \to T_5 \to T_6 \to T_7$	1
		Total number of U-turns = 13		SC=9424 kg/h, V_7=9019 kg/h		

Table 5

Comparison of results of present approach with that of other models

Description of model			Results		Remarks
N	liquor	Problem	MTP Approach	Model-X	
3	Chemical solution	F=22679.65 kg/h, x_F=0.1, x_P=0.50, T_F=37.7 °C, T_L=51.7 °C, T_0=163 °C, flow sequences: 123, 321	OFFS: 321	OFFS: 321	X: Kern (1950)
3	Milk	F=6803.9 kg/h, x_F=0.1, x_P=0.4, T_F=60 °C, T_L=41.7°C, T_0=121.3°C, flow sequences*: 123, 132, 213, 231, 321, 312	OFFS: 213	NFS: 213	X: Nishitani and Kunugita (1979) NFS: Noninferior flow sequence
7	Black liquor	MEE system and its operating parameters are shown in Fig. 2 and Table 1 and feasible FFSs are given in Table 3.	OFFS : Backward (S1 in present case)	OFFS: Backward	X: Bhargava (2007)

Table A.1

MTPs and U-turns for different flow sequences for model of Kern [16]

Flow sequence	Stream(s)	Temperature path(s)	No. of U turns	Remarks
123	P	$T_F \rightarrow T_1 \rightarrow T_2 \rightarrow T_3$	1	Total number of U-turns = 3 SC=7907 kg/hr
	C_1	$T_F \rightarrow T_1$	0	
	C_2	$T_F \rightarrow T_1 \rightarrow T_2$	1	
	C_3	$T_F \rightarrow T_1 \rightarrow T_2 \rightarrow T_3$	1	
321	P	$T_F \rightarrow T_3 \rightarrow T_2 \rightarrow T_1$	0	Total number of U-turns = 0 SC=7237 kg/hr
	C_1	$T_F \rightarrow T_3 \rightarrow T_2 \rightarrow T_1$	0	
	C_2	$T_F \rightarrow T_3 \rightarrow T_2$	0	
	C_3	$T_F \rightarrow T_3$	0	

Table A.2

MTPs and U-turns for different flow sequences model of Nishitani & Kunugita [18]

Flow sequence	Stream(s)	Temperature path(s)	No. of U turns	Remarks
123	P	$T_F \rightarrow T_1 \rightarrow T_2 \rightarrow T_3$	1	Total number of U-turns = 3 SC=1890 kg/h
	C_1	$T_F \rightarrow T_1$	0	
	C_2	$T_F \rightarrow T_1 \rightarrow T_2$	1	
	C_3	$T_F \rightarrow T_1 \rightarrow T_2 \rightarrow T_3$	1	
132	P	$T_F \rightarrow T_1 \rightarrow T_3 \rightarrow T_2$	2	Total number of U-turns = 5 SC=1917 kg/h
	C_1	$T_F \rightarrow T_1$	0	
	C_2	$T_F \rightarrow T_1 \rightarrow T_3 \rightarrow T_2$	2	
	C_3	$T_F \rightarrow T_1 \rightarrow T_3$	1	
213	P	$T_F \rightarrow T_2 \rightarrow T_1 \rightarrow T_3$	1	Total number of U-turns = 2 SC=1875 kg/h
	C_1	$T_F \rightarrow T_2 \rightarrow T_1$	0	
	C_2	$T_F \rightarrow T_2$	0	
	C_3	$T_F \rightarrow T_2 \rightarrow T_1 \rightarrow T_3$	1	
231	P	$T_F \rightarrow T_2 \rightarrow T_3 \rightarrow T_1$	2	Total number of U-turns = 5 SC=1932 kg/h
	C_1	$T_F \rightarrow T_2 \rightarrow T_3 \rightarrow T_1$	2	
	C_2	$T_F \rightarrow T_2$	0	
	C_3	$T_F \rightarrow T_2 \rightarrow T_3$	1	
321	P	$T_F \rightarrow T_3 \rightarrow T_2 \rightarrow T_1$	1	Total number of U-turns = 3 SC=1920 kg/h
	C_1	$T_F \rightarrow T_3 \rightarrow T_2 \rightarrow T_1$	1	
	C_2	$T_F \rightarrow T_3 \rightarrow T_2$	1	
	C_3	$T_F \rightarrow T_3$	0	
312	P	$T_F \rightarrow T_3 \rightarrow T_1 \rightarrow T_2$	2	Total number of U-turns = 5
	C_1	$T_F \rightarrow T_3 \rightarrow T_1$	1	

	C_2	$T_F \rightarrow T_3 \rightarrow T_1 \rightarrow T_2$	2	SC=1927 kg/h
	C_3	$T_F \rightarrow T_3$	0	