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Synthesis of Triple- Effect Evaporator System

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ABSTRACT

In the present paper a new graphical technique named "Enthalpy rectangle (ER) diagram" has been developed for the analysis of complicated temperature paths of a multiple effect evaporator (MEE). The present technique provides the necessary insights for the synthesis of MEE by partitioning the feed into different segments such as concentrated liquid product stream and "n" number of condensates streams, where n is the total number of effects. The present ER diagram offers two parameters for the analysis of feed flow sequences of MEE, first, the shortest temperature path which consumes minimum hot and cold utility and second, the total amount of internal energy exchanged by different segments of feed stream. On the basis of the above parameters, the optimal feed flow sequence (OFFS) is considered to be that sequence which requires minimum hot & cold utilities and minimum amount of total internal enthalpy exchange.

To demonstrate the effectiveness of the present technique, it is applied for the synthesis of OFFS of a triple-effect evaporator (TEE). Finally, the paper suggests a few heuristics for the synthesis of OFFS, for a MEE.

Key words: multiple effect evaporator; ER diagram; optimal feed flow sequence

INTRODUCTION

Evaporators are integral and most energy intensive part of a number of process industries namely Pulp & Paper, Chlor-alkali, Sugar, Pharmaceuticals, Desalination, Dairy and Food processing, and merits special attention.

Most of the earlier literature on evaporation (Standiford, 1963) were treated from a point of view of unit operations. Textbooks written by Kern (Kern, 1950), McCabe and Smith (McCabe and Smith, 1976), King (King, 1980) and Perry's Chemical Engineer Handbook (Perry et. al., 1984) primarily address the analysis not the synthesis part of the evaporator network.

Since last few decades, modeling of MEE have been reported in literature. These models have been developed based on mass and energy balance equations and fixed heat transfer coefficients of evaporators and thus offers limited flexibility. For example, if feed sequence has to be changed or any flash stream (Product, Feed, condensate, etc.) is to be added or deleted or the streams are to be splitted or joined the whole set of equations used in the simulation need to be reframed. Stewart & Beveridge (Stewart and Beveridge, 1977) and Ayangbile, Okeke & Beveridge (Ayangbile et. al., 1984) proposed an alternate flexible method. It could easily accommodate different operating configurations. Bhargava and Mohanty (Bhargava and Mohanty, 2004) have modified the model proposed by Stewart & Beveridge and Ayangbile et. al. and improved it to accommodate different operating configurations.

These models, based on complex mathematical equations and numerical techniques provide a method to analyze MEE. However, the above model is intended primarily for analysis and not for the synthesis. From the above discussion, it appears that there is need to develop an interactive approach for the synthesis of the MEE without resorting to complex simulation, which is generally employed in above cases. Earlier synthesis work for MEE (Nishitani and Kunugita, 1981) required that one should search for all the available flow sequences and then should select the optimum one. For a eight effect MEE, which is not uncommon, the search has to be carried out for 8!=40,320 alternatives. Therefore, this search can require a substantial amount of effort.

For the synthesis of MEE, it appears that the concepts of thermodynamics and heuristic rules can be effectively utilized to cut down the search effort leading to an OFFS.

In the present work a new graphical presentation technique termed as "Enthalpy rectangle (ER) diagram" (Gulyani and Mohanty, 1998), has been developed for the analysis of complicated flow sequence of a MEE.

ENTHALPY RECTANGLE (ER) DIAGRAM

Nishida et al. (Nishida et al., 1971) presented a simple diagram called heat content diagram for the representation of heat exchanger network (HEN). The ER diagram is the marriage of modified form of Nishida's heat content diagram and the grid diagram of Linnhoff et al. (Linnhoff et al., 1982).

In the ER diagram, as shown in Fig. 1, the horizontal axis represents the relative magnitude of the heat capacity flow rate of various streams, and the vertical axis represents the temperature. On the diagram, each stream is represented by an enthalpy rectangle (ER). The area of the ER gives total enthalpy to be exchanged in order to reach its desired output temperature. It should be noted that ER diagram only deals with sensible heat of streams.

The procedure to draw ER diagram is illustrated below using the stream data of Table 1. The minimum temperature difference (ΔT_{min}) between hot and cold stream is assumed to be 10 °C.

Table 1: The stream data

Stream (s)	CP (kW/°C)	T_S (°C)	T_T (°C)
Hot	2	180	40
Cold	2.6	30	130

In Fig. 1 the enthalpy rectangles corresponding to each process stream with temperatures on T-axis and CP on CP-axis is drawn. Enthalpy of the stream is written above the ER. The enthalpy of hot stream is denoted by ΔH, while that of cold stream is denoted by ΔC. The CP of the stream is written below the ER.

On the diagram, heat exchanger between a hot and a cold stream or parts thereof is indicated by joining the two corresponding ERs or parts thereof with a line. Since the enthalpy to be exchanged between hot and cold streams must be the same, the areas of the connected hot and cold ERs or parts thereof must be same. It can be seen from Fig. 1 that cold stream, which requires 260 kW of heating, is satisfied completely by hot streams having an enthalpy of 280 kW. The residual enthalpy of hot stream must be satisfied by some other cold stream or utility.

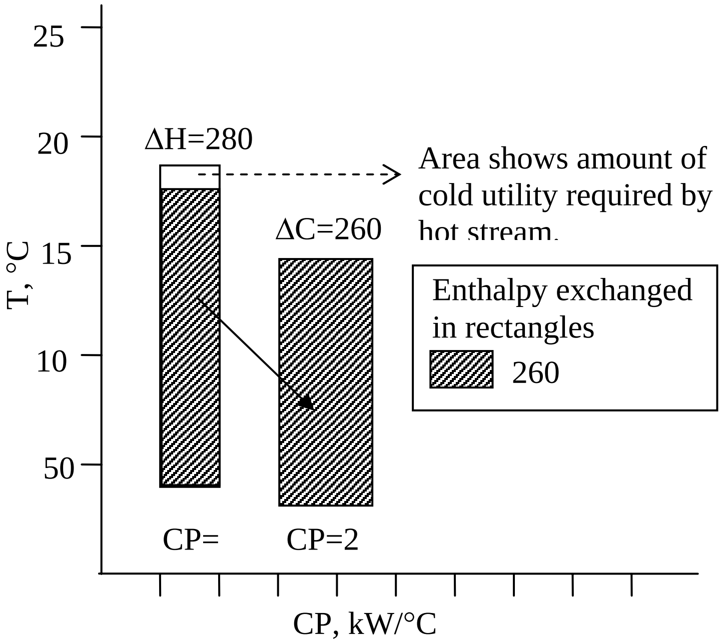


Fig. 1. The ER diagram for stream data given in Table 1

SAMPLE PROBLEM

To show the effectiveness of the present technique, the synthesis of optimal feed sequence of a triple-effect evaporator (TEE) network is carried out using the present technique. The TEE is shown in Fig. 2. The TEE network, considered for the present case, has been taken from the open literature (Westerberg and Hillenbrand, 1988). The brief description of the system is as follows: The system is employed for concentrating 10 kg/s of feed solution with 20 % by weight of salt in water to a product with 40% salt in water solution. The feed is available at 375 K while the concentrated product exits 40 K hotter at 415 K. Utility heating is to be supplied from saturated steam at 450 K and utility cooling from cold water at 300 K which must be returned no hotter than 315 K.

The heat capacities of the salt and water are taken as 1.20 kJ/kg and 4.20 kJ/kg respectively. By assuming negligible heat of mixing, the heat capacity of salt-water solution can be expressed as 4.20-3.00 x, where x is the mass fraction of salt.

In each effect, the liquid stream, which passes through an effect, is concentrated to a higher solid (salt) concentration by removing water from it by evaporation. This vapor stream is then typically condensed back to a liquid by using it as a heating medium in the next effect where it condenses at a temperature of previous effect from where is has been created. The condensed vapor’s exit temperature is generally of no concern, thus it can be treated as a free heat source.
For a TEE network, there are 6 (3!) alternative feed flow sequences (FFS). The feed can enter at any one of the three effects and can move from there into any one of two remaining effects and finally into the one remaining effect from where it exits out as a product.

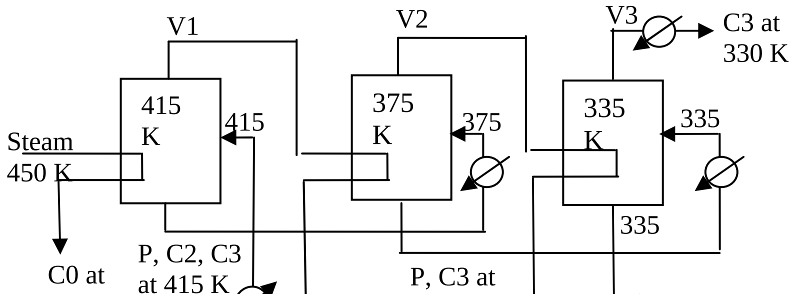
ER DIAGRAM FOR A MEE

To apply the concept of ER diagram for the analysis of MEE, a few assumptions are taken to simplify the problem as given below:

1. Boiling point elevation is zero
2. Negligible heat of mixing between different segments of feed stream
3. Specific heat of streams are not the function of temperature
4. Latent heat of vaporization is constant within the operating range of MEE.
5. Equal vaporization is considered in each effect
6. Inlet and outlet temperature and concentration of feed and product are considered to be constant.

The concept of ER diagram can be applied to a MEE by partitioning the feed stream into following segments: (1) the final concentrated liquid product stream; and (2) into n condensate streams, where n is the total number of effects. As heat of mixing is considered to be zero therefore, each of these streams can be treated as if they pass through the network physically separated from each other.

For the present TEE network, the feed is partitioned into a liquid product, P, and three condensates, C1, C2 and C3. The details of these streams, for TEE with feed flow sequence (FFS) as 123, are shown in Fig. 2. The feed sequence 123 denotes that feed enters at first effect and then flows to second effect and then to third effect. Movement of these streams in the TEE network can be visualized more clearly from Fig. 3. For the sake of computation these streams are considered as separate streams through out the TEE network while in actual practice these streams move with the feed stream which gets concentrated from its entry point to exit point. The streams, C1, C2 and C3 get separated from feed stream one by one in sequence leaving the product stream which exits at the last phase.



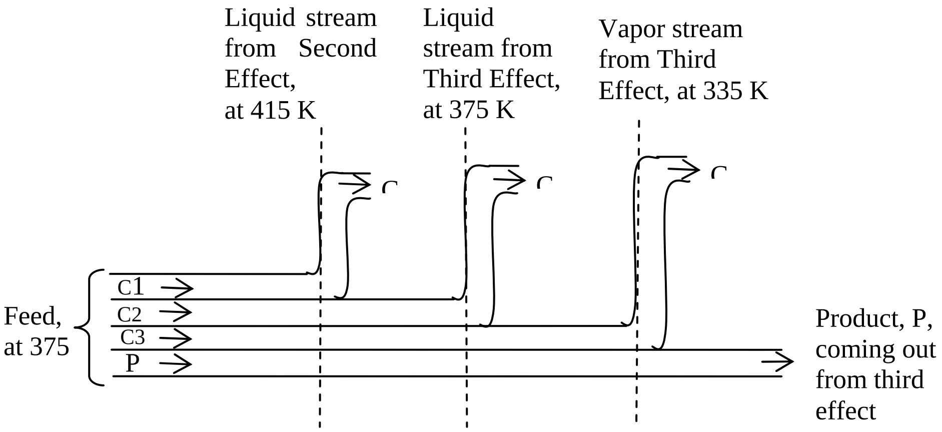


Fig. 3. Movement of product stream, P, and three condensate streams, C1, C2 and C3, through the present TEE network for the FFS-123.

Table 2: The stream data for the given TEE network with FFS-123

<table>
<tr><th>S. No.</th><th>Description of stream(s)</th><th>Name of stream(s)</th><th>CP (kW/K)</th><th>T_S (K)</th><th>T_T (K)</th></tr>
<tr><td colspan="6">The stream data for product, P</td></tr>
<tr><td>1</td><td>Product, P, enters to effect no. 1</td><td>Cold1</td><td>15</td><td>375</td><td>415</td></tr>
<tr><td>2</td><td>Product, P, exits effect no. 1 and enters to effect no. 2</td><td>Hot1</td><td>15</td><td>415</td><td>375</td></tr>
<tr><td>3</td><td>Product, P, exits effect no. 2 and enters to effect no. 3</td><td>Hot2</td><td>15</td><td>375</td><td>335</td></tr>
<tr><td>4</td><td>Product, P, exits effect no. 3</td><td>Cold2</td><td>15</td><td>335</td><td>415</td></tr>
<tr><td colspan="6">The stream data for condensate, C1</td></tr>
<tr><td>1</td><td>Condensate, C1, enters to effect no. 1</td><td>Cold1</td><td>7</td><td>375</td><td>415</td></tr>
<tr><td>2</td><td>Condensate, C1, exits effect no. 1 as vapor, V1 in Fig. 2, which enters as a heating medium to effect no. 2 and finally exits from this effect as condensate</td><td>Hot1</td><td>7</td><td>415</td><td>330</td></tr>
</table>

The stream data for condensate, C2					
1	Condensate, C2, enters effect no. 1	Cold1	7	375	415
2	Condensate, C2, exits effect no. 1 and enters effect no. 2	Hot1	7	415	375
3	Condensate, C2, exits effect no. 2 as vapor, V2 in Fig. 2, which enters to effect no. 3 as a heating medium and finally exits from effect no. 3 as condensate	Hot2	7	375	330
The stream data for condensate, C3					
1	Condensate, C3, enters effect no.1	Cold1	7	375	415
2	Condensate, C3, exits effect no. 1 and enters effect no. 2	Hot1	7	415	375
3	Condensate, C3, exits effect no. 2 and enters effect no. 3	Hot2	7	375	335
4	Condensate, C3, exits effect no.3 as vapor, V3 in Fig. 2, which enters to condenser and exits from it as condensate	Hot3	7	335	330

The heat exchangers between hot and cold streams of product, P, are placed by following the ΔT_{min} criterion which in the present case is 10 K. This criterion clearly demands that the hot streams should be at least 10 K higher in temperature than cold streams to which it is transferring heat. Due to this constraints, when product, P, passes through a series of heating and cooling cycles (as per the demand of the process), it fails to attain its target temperatures through internal heat exchange alone and in turn demands external hot and cold utilities.

As we are interested in the synthesis of OFFS for the present TEE network, it is necessary know the thermal performance for all possible FFS. One way to do it is to study the temperature paths of individual segments of feed like P, C1, C2 & C3 for different FFS and also to investigate how the temperature paths of these streams create extra utility burden on the system in question. To generate the above information the streams are treated individually as separate entity and no heat transfer amongst these are considered.

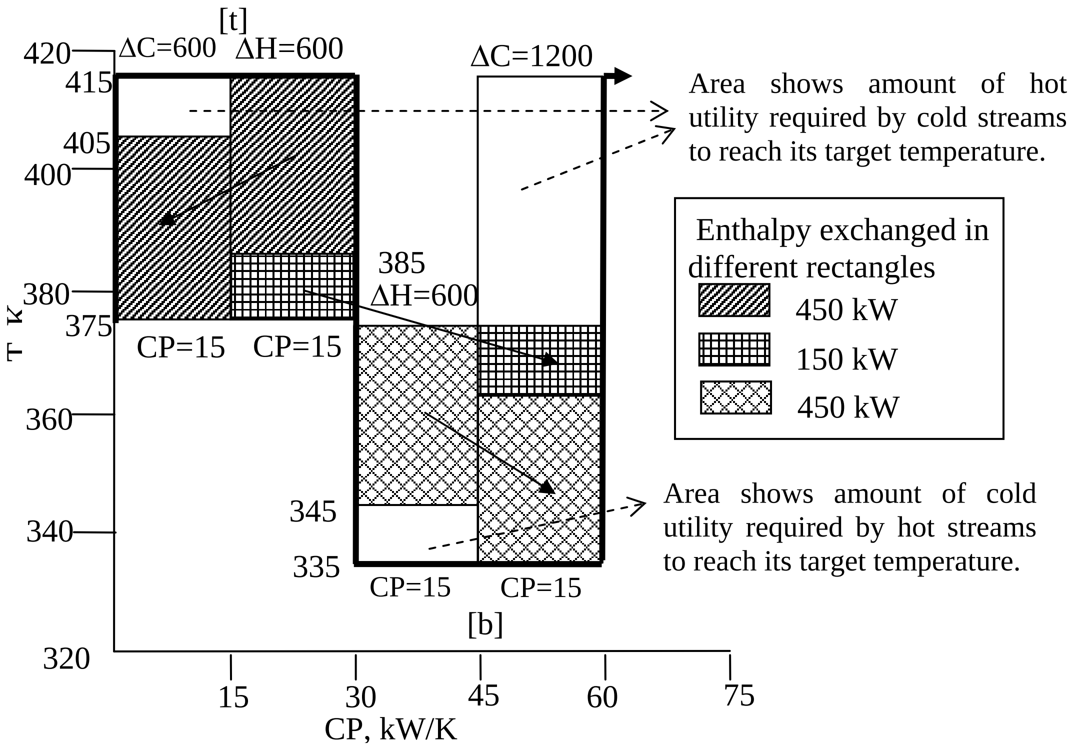


Fig. 4a. The ER diagram for product for FFS-123

It can be seen from Fig. 4a that only three heat exchangers are required for internal heat exchange between two hot and two cold streams of product, P. The first heat exchanger of duty 450 kW can be placed between Hot1 and Cold1 so that these streams attain the temperatures of 385 K and 405 K respectively. The second heat exchanger having a duty of 150 kW facilitates transfer of heat from Hot1 to Cold2 and thereby raises the temperature of Cold2 from 365 K to 375 K. Similarly, a third heat exchanger of 450 kW duty is placed between Hot2 and Cold2. From the Fig.4a it is amply clear that even if heat exchangers are used to facilitate exchange of heat amongst different hot and cold streams of the product, P, only stream, Hot1, has been able to attain its target temperature. The rest three streams, Cold1, hot2 and Cold2 require external hot and cold utilities to reach their respective target temperatures of 415K, 335 K and 415 K. This clearly demonstrates that even if the supply and target temperatures of a stream remain constant the requirement of external Hot and Cold utility by it will depend upon how its temperature is changed while it travels from its supply temperature to its target temperature. For product P, the required hot utilities to satisfy Cold1 and Cold2 are 150 kW and 600 kW, respectively where as the required cold utility for Hot2 is 150 kW. Therefore, in total, the product, P, needs 750 kW of hot utility and 150 kW of cold utility.

Similar ER diagrams for hot and cold streams of three condensates, C1, C2 and C3, are drawn, using stream data of Table 2, and shown in Fig. 4b. The possible heat exchangers between hot and cold streams of C1, C2 and C3 can be placed in a similar manner as has been carried out for product, P. It can be seen from Fig. 4b that each condensate stream C1, C2 & C3 requires 70 kW of hot utility and 385 kW of cold utility.

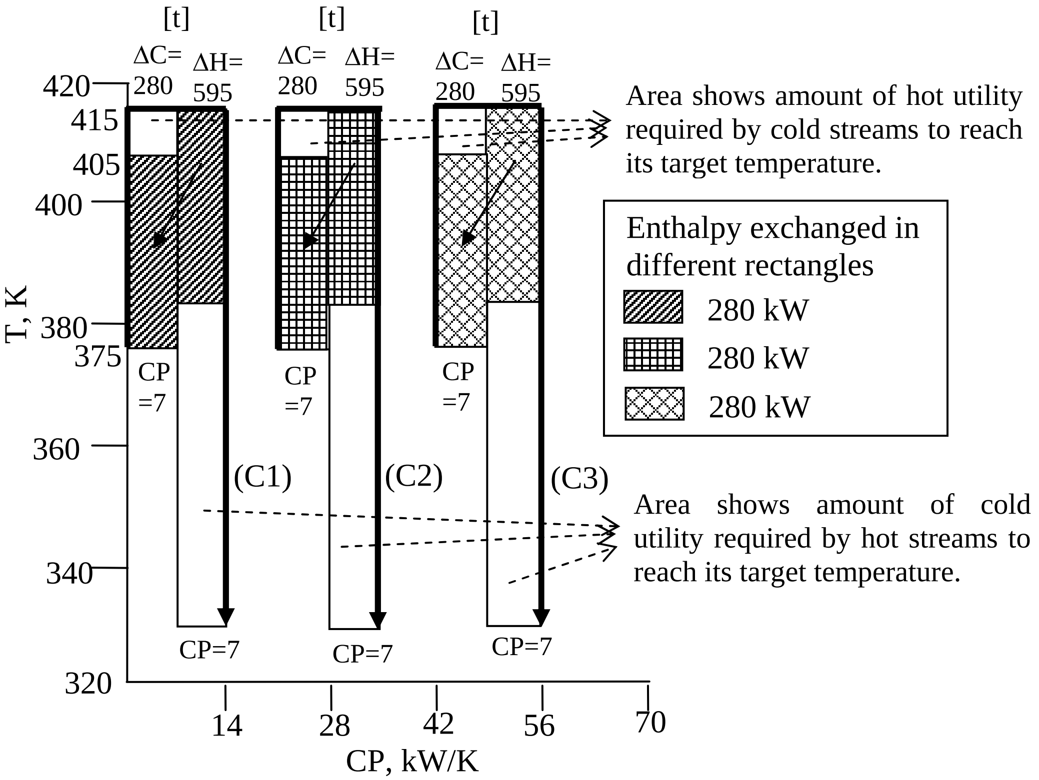


Fig. 4b. The ER diagram for three condensates for FFS-123

For the FFS-123, the total hot and cold utility required by all segments of feed, one product and three condensates, come out to be 960 kW (750 kW for P and 210 kW for three condensates) and 1305 kW (150 kW for P and 1155 kW for three condensates), respectively. Thus, the hot and cold utility requirements of a FFS appears to be an important screening tool in the selection of optimum FFS.

ANALYSIS OF FFS THROUGH ER DIAGRAM

As can be figured out from the above discussions a FFS can be easily represented by an ER diagram as shown in Fig. 4a and 4b and can provide key screening parameters like hot and cold utility requirements. The same diagram also contains another important parameter called " *temperature path* " of a stream. The temperature path of the product, P, in case of FFS-123, has been shown with the bold line on the periphery of the ER diagram. To understand the temperature path of product, P, consider again the stream data for it, given in Table 2, which contains streams, Cold1, Hot1, Hot2 and Cold2. The initial temperature of Cold1 is 375 K, which is the initial temperature of feed. First, Cold1 is heated to 405 K by Hot1 and then to 415 K by hot utility, before it enters into the first effect. Hot1 exits effect no.1 at 415 K and attains a temperature of 385 K by exchanging its heat with Cold1. Hot1 again exchanges heat with Cold2 which is flowing out from effect no. 3 and is cooled down to a temperature of 375 K before it enters to effect no. 2. The hot stream, Hot2, which exits effect no. 2 at 375 K exchanges heat with Cold2 and in turn cools down to 345 K. Finally, Hot2 cools down to a temperature of 335 K by exchanging heat with cold utility before it enters to effect no. 3. The stream, Cold 2 exits the third effect at 335 K and then picks up the heat from Hot1 and Hot2 to raise its temperature to

375 K. Finally, it is heated to 415 K, which is the target temperature of Cold2 using hot utility. Hence, the product, P, follows a temperature path as given below:

375→415→375→335→415

The above temperature path is shown in Fig. 4a with bold line around the ER. Further, this can be seen that the product is heated up and then cooled down and again heated up. While doing so it passes through one top and one bottom U-turn. A further analysis shows that such variations in temperature demands more energy from the system in terms of utilities and thus, a FFS can be said to be efficient if it passes through " *shortest temperature path* " . In fact, longer is the temperature path more hot and cold utility it will consume to follow the path.

It can be observed from Fig. 4a that the temperature path of product, P, first moves from 375 to 415 K and then from 415 to 375 K. This situation, where temperature path reverses it direction in temperature, is called U-turn. Further, if a temperature path moves upward in temperature and reverses its direction to move downward in temperature then this U-turn is called top U-turn. Similarly, if a temperature path moves downward in temperature and reverses its direction to move upward in temperature then the U-turn, created by this situation, is called a bottom U-turn. The top and bottom U-turns for product, P, are shown in Fig. 4a as [t] and [b], respectively.

The same logic can be applied to draw the temperature paths of other segments of the feed i.e. condensates C1, C2 and C3. The temperature paths and ER diagrams of C1, C2 and C3 are shown in Fig. 4b. It can be observed from Fig. 4a and 4b that the three condensate streams follow the temperature path of product, P, from their supply temperatures to the temperature of their respective effects from where these condensates are generated. The overall effectiveness of the FFS 123 will now depend on the temperature paths of the product, P, as well as three condensate streams namely C1, C2 and C3.

RESULT AND DISCUSSION

From the above analysis it appears that two parameters namely, the shortest temperature path that consumes minimum amount of hot and cold utility and the total amount of internal energy exchange by the different segments of feed streams, as can be computed through ER diagram drawn for an FFS, can be effectively used to identify an OFFS.

In fact, for an ideal case the heat transferred by the live steam to an effect cascades down through subsequent effects to the cold utility. During this process of cascading it evaporates liquid in each effect but in turn degrades it self by lowering its temperature. As we have assumed equal evaporation from each effect and almost no variation of latent heat of vaporization within the operating range of the MEE the heat required for evaporation from each effect will be equal and will not be a function of FFS. Thus it will not play a role in deciding the OFFS. In such a situation, the temperature paths, which to a large extent decide the hot and cold utility required for a FFS, will decide which FFS will consume minimum utility and will turn out to be the OFFS.

Table 3: Temperature path, hot & cold utility requirements and internal energy exchange for all six possible FFS of a TEE system

FFS	Segments	Temperature path	Utility requirement	Internal energy

	of Feed		Hot utility (kW)	Cold utility (kW)	exchange, (kW)
123	P	375→415→375→335→415	750	150	1050
	C1	375→415→330	70	385	210
	C2	375→415→375→330	70	385	210
	C3	375→415→375→335→330	70	385	210
	Total amount of		*960*	*1305*	*1890*
132	P	375→415→335→375→415	750	150	1050
	C1	375→415→330	70	385	210
	C2	375→415→335→375→330	70	385	210
	C3	375→415→335→330	70	385	280
	Total amount of		*960*	*1305*	*1750*
231	P	375→335→415	750	150	450
	C1	375→335→415→330	70	385	490
	C2	375→330	0	315	0
	C3	375→335→330	0	315	0
	Total amount of		*820*	*1165*	*940*
213	P	375→415→335→415	750	150	1050
	C1	375→415→330	70	385	210
	C2	375→330	0	315	0
	C3	375→415→335→330	70	385	210
	Total amount of		*890*	*1235*	*1470*
321	P	375→335→375→415	750	150	450
	C1	375→335→375→415→330	70	385	490
	C2	375→335→375→330	70	385	210
	C3	375→335→330	0	315	0
	Total amount of		*890*	*1235*	*1150*
312	P	375→335→415→375→415	750	150	1050
	C1	375→335→415→330	70	385	490
	C2	375→335→415→375→330	70	385	490
	C3	375→335→330	0	315	0
	Total amount of		*890*	*1235*	*2030*

To examine this hypothesis, the temperature paths and ER diagrams of all the possible FFS, such as 132, 231, 213, 321 and 312, for the present TEE network are computed and presented in Table 3. From this data it can be easily identified that which FFS will consume minimal energy to convert feed into product as well as offers minimum amount of total internal heat exchange. From Table 3, it can be evident that hot and cold utilities consumed by product, P, for six different FFSs are of the same magnitude whereas for condensates such as C1, C2 and C3, these differ significantly. Hence, for the present case, the utility consumption by condensate streams will decide the OFFS.

The OFFS for the present problem comes out to be 231. This flow sequence requires 820 kW of hot utility, 1165 kW of cold utility and 940 kW of internal energy exchange by different segments of feed, which are lowest amongst all the six FFS investigated. The hot utility, required by FFS-231, has to be indirectly supplied by the live steam.

Based on the above findings a simple heuristics can be formulated for the synthesis of an OFFS as given below:

1. In a MEE, if feed temperature coincides with an effect's temperature or is very close to it, then feed should enter in this effect first. For example, in the present TEE network, feed temperature coincides with the temperature of second effect, therefore, it should first enter into this effect.

2. Once feed has entered into an effect, it should follow one of the two possible shortest temperature paths, discussed below, so that it consumes minimum hot and cold utility:
   (a) Feed should move upward in temperature path and enters into all those effects, one by one, till it meets the hottest effect. Then it should travel downward in temperature path and enters into all the effects, one by one, till it reaches the lowest temperature effect. For the present case, feed enters in to second effect and then moves to first effect and finally to the third effect from where it should come out as a product.

   (b) The second alternate path may be as follows: Feed should move downward in temperature path and should enters into all those effects, one by one, till it encounters the coolest effect. Then it should travel in upward temperature path and should enters into all the those effects, one by one, till it reaches the hottest effect. For the present case, this means that feed should enter in to second effect and then moves to the third effect and finally to the first effect from where it should come out as a product.

3. Out of the FFS obtained from 2(a) and 2(b) the FFS which offers minimum internal enthalpy exchange in the ER diagram will be the OFFS.

CONCLUSION

Based on the present work following salient conclusions can be drawn:

1. The total internal enthalpy exchange in ER diagrams for different segments of feed for a FFS and temperature path of feed stream in an MEE are found to be two important parameters to figure out a strategy for obtaining an OFFS.
2. OFFS is that FFS which has the shortest temperature path while passing through the system and also exchanges total minimum internal enthalpy as can be identified through ER diagrams.

NOMENCLATURE

CP	Heat capacity flow rate

C (1, 2, 3)	Condensates from three effects
P	Concentrated product
T	Temperature
V (1,2,3)	Vapors from three effects
Subscript	
S	Supply temperature
T	Target temperature

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