Synthesis of Mass Exchange Networks for Batch Processes. Part 2: Batch Network Design

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Abstract

The first part of this series of papers (see [1]) presented a methodology for identifying the minimum utility targets for a mass exchange network (MEN) for a batch process. This paper describes a procedure for designing a minimum utility network. The time-grid diagram (TGD) and the overall time-grid diagram (OTGD) that include the time dimension in network design have been introduced to provide a better representation of the mass exchange network for a batch process. It is desired to design a maximum mass recovery (MMR) network that will achieve the minimum utility targets set during the targeting stage of the synthesis problem [1].

Keywords:

Mass exchange networks design, pinch analysis, batch process systems, time-grid diagram, overall time-grid diagram.

Introduction

The majority of research on mass exchange network synthesis (MENS) have focused on continuous processes [2, 3, 4 and 5]. The only work on mass exchange network (MEN) design for batch process that was based on Pinch Analysis was reported by Wang and Smith [6] for the special case of water minimisation. Clearly, more work needed to be done in this area, and, in particular, for the general case of MENS for batch process systems involving mass separating agent (MSA) other than water.

The batch MEN research described in this paper is based on the same framework that was developed for heat exchange network synthesis (HENS) for batch processes developed by Kemp and Macdonald [7]. They first represented the batch heat exchange network (HEN) using the conventional grid diagram that was developed for continuous processes. To achieve maximum energy recovery (MER), they carried out the HEN design separately for each time interval. Established pinch design rules for HEN design were used to obtain a completed network [7].

Kemp and Deakin [8] later formulated a procedure for the network design with heat storage. The heat storage system may function either as a hot stream (heat source) or a cold stream (heat sink), depending on which stream that the storage system is finally integrated with. The storage system may act as a hot source if it is to be matched with a colder stream. Similarly, the storage system may act as a hot sink if it is to be matched with a hotter stream.

Kemp and Macdonald [7] also pointed out that network design using the conventional grid diagram [9] could not completely represent the heat recovery network for a batch process. The main drawback of this representation is the absence of the time variable to indicate how the various processes are interlinked. Hence, a better representation is needed.

In this paper, we will first a detailed procedure for designing a minimum utility batch MEN by introducing two new graphical tools, i.e. the time-grid diagram (TGD) and overall time-grid diagram (OTGD). These grid diagrams include time as another dimension in network design to enable designers to have a better understanding of the batch system during the design stage. The above methodologies are illustrated using the case study of coke

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oven gas (COG) sweetening process presented in the first part of this series of papers [1].

Case study – the COG sweetening process

A batch COG sweetening process [10] has two process rich streams, i.e. COG stream (denoted by R_1) and Claus tail gas (denoted by R_2) as well as one process lean stream, which is a process MSA (aqueous ammonia, denoted by S_1). The transfer of only one component – hydrogen sulphide (H_2S) is considered. The synthesis task is to maximise the mass exchange between the process rich and lean streams, leaving the excess mass load for external MSA (in this case, a chilled methanol stream, denoted by S_2). The minimum concentration difference, ε is fixed at 0.0001.

Data for the case study in the batch mode is shown in Table 1 [1]. The equilibrium solubility data for H_2S in aqueous ammonia and methanol respectively is given by,

$$y = 1.45\,x_1 \qquad (1)$$

and

$$y = 0.26\,x_2 \qquad (2)$$

Table 1 - Stream Data For COG Batch Process

Rich stream	y^s_i	y^t_i	Start time, t^f (hr)	Finish time, t^g (hr)	G_i (kg/hr)
R_1	0.0700	0.0003	0.0	0.5	6480
R_2	0.0510	0.0001	0.4	1.0	600
Lean stream	x^s_j	x^t_j	t^f (hr)	t^g (hr)	L^c_j (kg/hr)
S_1	0.0006	0.0310	0.3	0.7	20700
S_2	0.0002	0.0035		∞	∞

Minimum flowrate for process MSA and external MSA are respectively given by:

$$L_1 = L_1^c - \frac{m_{H_2S,P}}{\left(x_1^t - x_1^s\right)} \qquad (3)$$

and

$$L_2 = \frac{m_{H_2S,ext}}{\left(x_2^t - x_2^s\right)} \qquad (4)$$

Utility targets for this problem is reported as 3237.6316 kg mass for aqueous ammonia (process MSA, S_1) and 44160.0000 kg for chilled methanol (external MSA, S_2) [1]. The synthesis task now is to design a batch MEN to achieve the minimum utility targets for the problem. This technique will be demonstrated in the coming sections of this paper.

Grid diagram for batch MEN design

Generally, the overall development of HEN design for heat integration of batch processes has received far less attention as compared to the utility targeting. The conventional grid diagram [9] is used in most of the works related to batch heat integration [7, 8, 11]. The greatest drawback of this approach is that the designer hardly visualise the actual existence of the heat exchanger in each time interval. Examples of batch network representation on conventional grid diagram are shown in Figure 1. This conventional grid diagrams do not represent heat recovery network in batch processes satisfactory. No time indications were found where designer could visualise the allocation of heat exchangers in each time interval. This drawback will be resolved with the graphical tools presented in this paper.

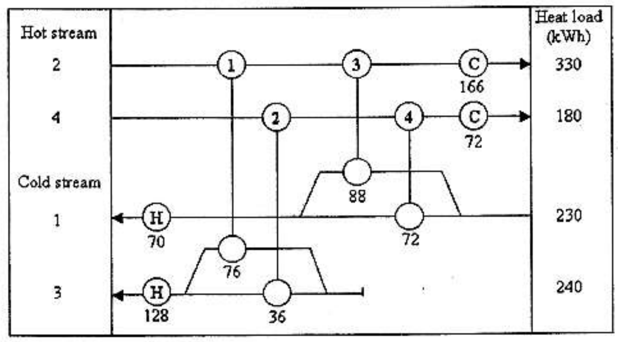

Figure 1 - Batch networks shown on the conventional grid diagram

The approach developed for the design of batch MEN in this work is based on the work of Kemp and Macdonald [7] as well as that of El-Halwagi and Manousiouthakis [10]. As in the case of batch HEN, the desired mass transfer in MEN cannot be achieved by mass exchange alone. They are limited by the instantaneous mass flowrate of each stream and by the periods when both streams actually exist.

In designing a MEN for a batch system, it would be advantageous to represent the composition change in the grid diagram during the time interval of interest. In order to achieve this, we have introduced the *time-grid diagram* (TGD). The TGD is a modification of the conventional grid diagram for HENS [9] as well as for MENS [10]. Consideration of the composition and time interval will allow us to clearly represent the network in terms of the streams driving force and the duration in which they exist.

Figure 2 shows that the TGD comprises of two axes. The vertical axis represents the composition driving force for the rich and lean streams. The horizontal axis represents the period when the streams exist in the process. A rich stream is drawn from the top to the bottom of the composition interval while a lean stream is drawn in the opposite direction. The streams are shown in the time slice in which they exist. A mass exchanger is represented by a pair of linked circles. The amount of mass being transferred is shown in a box. The pinch compositions are indicated by the dashed line which divides the network into the regions above and below the pinch.

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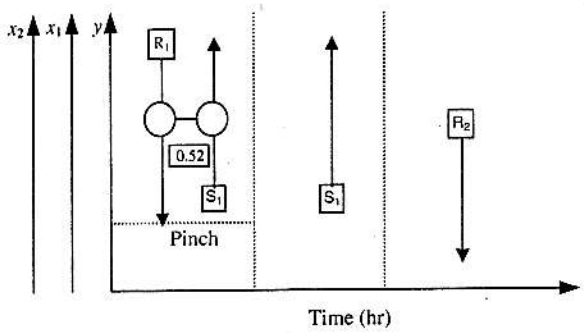

Figure 2 - The new TGD shows the driving force of the system and the actual period of time when the streams exist in the system

In order to achieve the minimum utility targets established, batch network design are conducted independently for each time interval [7]. Besides, two feasibility criteria for stream matching at the pinch, similar to the ones used for the HENS problem are to be followed [10]. These are:

1. Stream population

Immediately above the pinch, all rich streams are to be matched with the lean streams in order to bring down the rich streams to the pinch composition. Therefore, the number of rich streams (N_R) should be less than the number of lean streams (N_S) above the pinch, i.e.:

$$N_{R,above} \leq N_{S,above} \tag{5}$$

Below the pinch, lean streams are to be brought to the pinch composition through mass exchange with the rich streams. Thus, below the pinch, the number of lean streams should be less than the number of rich streams, i.e.:

$$N_{R,below} \geq N_{S,below} \tag{6}$$

In order for this principle to be observed, stream splitting may be required at the pinch.

2. Operating versus equilibrium line

This criteria is analogous to that of the *FCP* (heat capacity flowrate) inequality in HENS problem. However, it does incorporate the mass transfer equilibrium.

A feasible match above the pinch shall have a minimum driving force of ε at the pinch side. Thus the slope of the operating line should be greater than that of the equilibrium line, i.e.

$$\left(\frac{L_j}{m_j}\right)_{above\ pinch} \geq G_{i,above\ pinch} \tag{7}$$

Immediately below the pinch, the opposite must be true:

$$\left(\frac{L_j}{m_j}\right)_{below\ pinch} \leq G_{i,below\ pinch} \tag{8}$$

In order for these criteria to be met, stream splitting may be required.

Even though the TGD in

Figure 2 is essential in indicating the streams' timing and composition levels, it may not provide a clear picture of the entire MEN for the batch system. A non-expert user might have difficulties in linking the network design in one time interval to another. There may be tendencies to regard the streams which exist in one time interval as an independent from the streams in another time interval. As shown in

Figure 2, streams with the same name (for example stream S_1) are in fact the same stream. Streams are seemed to be disconnected due to the existence of the different time intervals.

In order to overcome this potential confusion, we introduce another grid diagram, called the *overall time-grid diagram* (OTGD). The OTGD is a cumulative representation of the MEN during the entire process duration. Each stream is represented in their respective time intervals. Here, the composition is not considered.

Figure 3 shows the OTGD. The rich streams are drawn from right to the left, while lean streams in the opposite direction. Both streams exist in their respective time intervals. A mass exchanger is represented by a pair of linked circles with the amount of mass being transferred shown in a box. Composition is not shown in this diagram, but could be easily calculated based on the mass balance in each time interval. Both the TGD and OTGD will be used to design the batch MEN system for the COG example in the previous section.

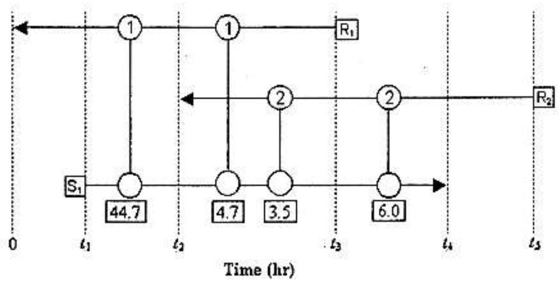

Figure 3 - The OTGD shows the cumulative representation of the entire network throughout the process duration

Batch MEN design for COG case study

In order to design a maximum mass recovery (MMR) network that achieve the utility target set in the first part of this series of paper, the previous mentioned two feasibility criteria for stream matching, i.e. the stream population and operating line versus equilibrium line are followed. These criteria are applicable to the individual time interval of the TGD which have different pinch compositions.

Figure 4 shows the process streams of a single batch COG operation in the TGD, with a one-hour cycle time. R_1 is a process rich stream which exists during the first three time intervals (between 0 – 0.4 hr), while R_2 is another process rich stream which exists in the last three time intervals (between 0.4 – 1.0 hr). The only process lean stream, S_1 exist during the second to fourth time interval between (0.3 to 0.7 hr).

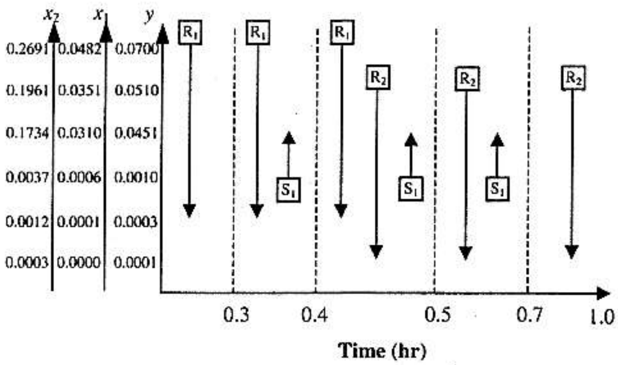

Figure 4 - A TGD showing the process streams of a single batch COG operation

Figure 5 shows the MEN design for the first and final time intervals of the system. Both process rich streams R_1 and R_2 exist below the pinch region in their respective time intervals. Since process MSA is not available in these time intervals, and mass storage system is not employed in this case, external MSA is used to absorb the mass load from the rich streams.

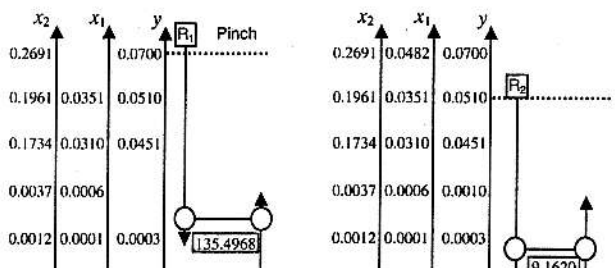

Figure 5 - MEN design for (a) the first and (b) the final time interval

During the second and the fourth time interval, process MSA S_1 is presents in the process in the region above the pinch. Hence, the MEN in this region is designed to match the rich process stream with the process MSA. The external MSA is used in the region below the pinch, since no process MSA is available there (Figure 6).

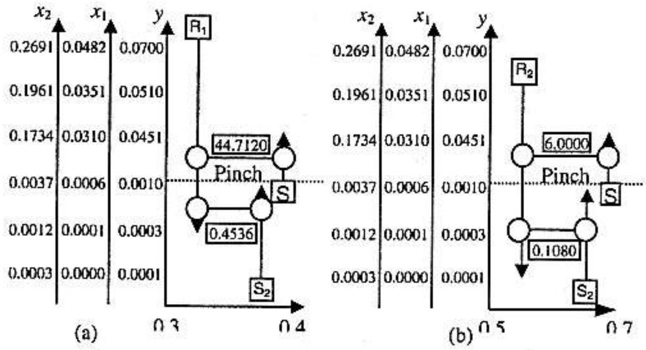

Figure 6 - MEN design for the (a) second and (b) fourth time interval

In the third time interval, two rich process streams exist in the region above the pinch while only one process MSA is found. Thus, in order to have a feasible stream matching criteria, stream splitting is done for the process MSA. Below the pinch, no process MSA is found. Thus, the rich process streams are again matched to the external MSA S_2.

There are two feasible matches as shown in Figure 7. In Figure 7 (a), rich streams exchange mass load with the external MSA in a series configuration. In Figure 7 (b), the external MSA is split to match with the rich streams in a parallel configuration. Note that the minimum composition difference is satisfied in both designs.

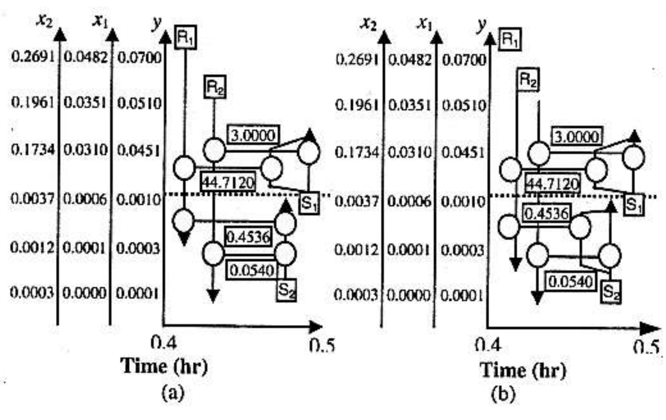

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Figure 7 - Two MEN design for the third time interval: (a) series configuration ; (b) parallel configuration

The network design for the entire process cycle is represented in

Figure 8, taking the series configuration at the lean end of the network in the third interval (Figure 7a). Note that the mass exchangers are numbered after the network designs of individual time interval are combined into a complete network representation (

Figure 8). Four mass exchangers are needed here, as in the case of continuous process (10). An overall representation of the MMR network in the OTGD is shown in Figure 9.

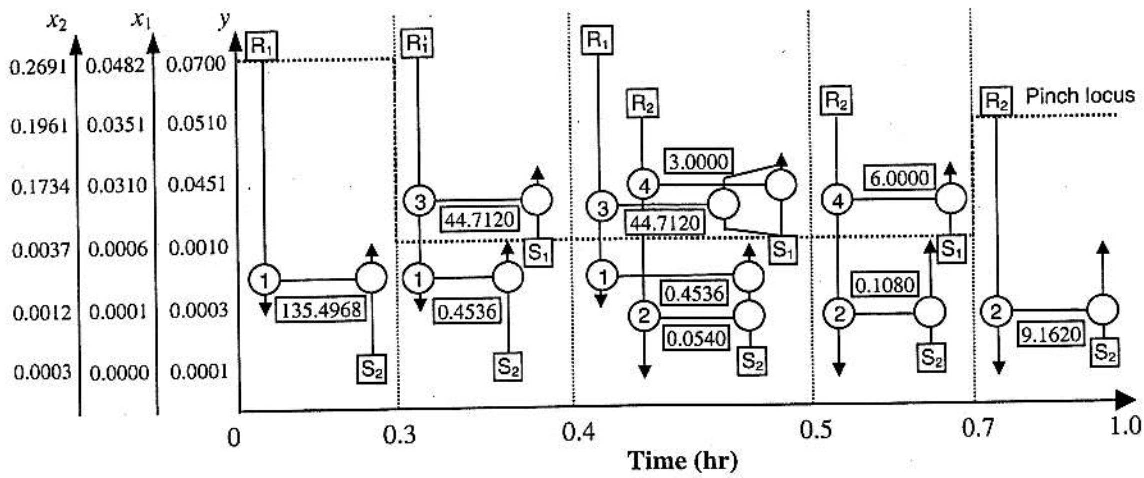

Figure 8 - Network design for COG case study by TGD

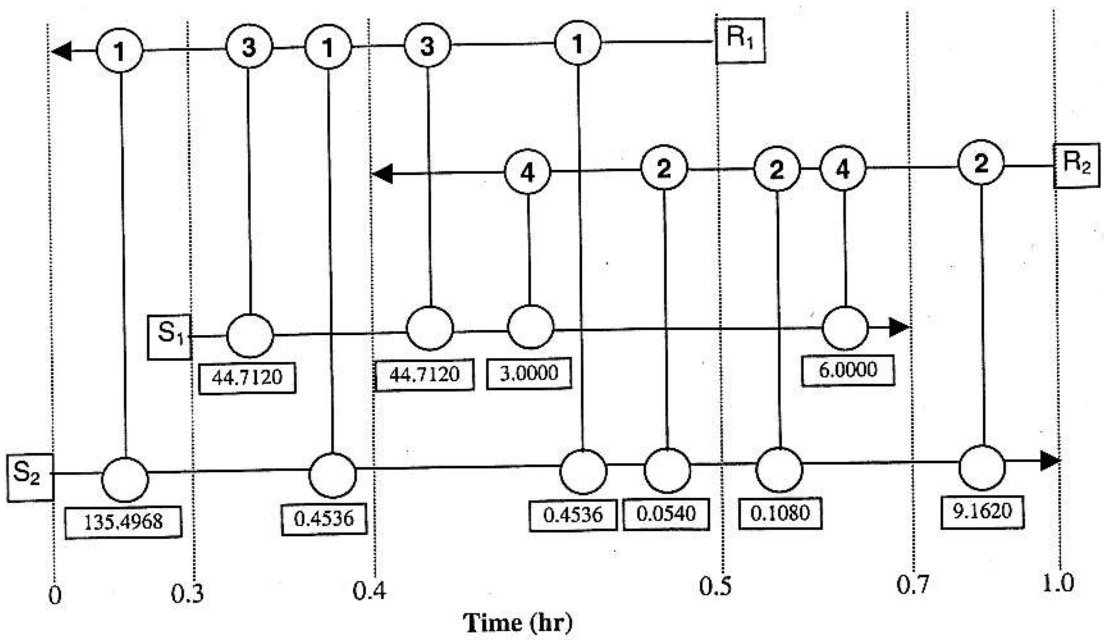

Figure 9 - The OTGD representing the entire network

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Conclusions

A systematic procedure for designing a batch maximum mass recovery (MMR) network has been developed. Two new graphical tools called the time-grid diagram (TGD) and the overall time-grid diagram (OTGD) that incorporat the time and composition axes have been introduced to provide a better representation of the problem during the MEN design for the batch system. These two design tools provide physical insight to the designer in carrying out design for a batch mass exchange network (MEN).

The desired mass transfer in a batch MEN cannot be achieved by mass exchange alone. They are limited by the instantaneous mass flowrate of each stream and by the periods when both streams actually exist. To achieve the minimum utility targets established, network design are conducted independently for each time interval. The design method developed in this paper does not limited to batch MEN alone. It can also be extended in the problem of batch heat exchange network synthesis (HENS) problem.

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