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# Synthesis of heat exchanger networks featuring batch streams

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## HIGHLIGHTS

- Heat integration of heat exchanger networks featuring batch streams is firstly considered.
- A new method based on the heat duty–time ($Q$–$t$) diagram is proposed.
- Energy targeting and network design can be obtained easily.
- Both direct and indirect heat integration of batch streams are considered.

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## ABSTRACT

A new method based on the heat duty–time ($Q$–$t$) diagram is proposed for heat integration of heat exchanger networks featuring batch streams. Using the $Q$–$t$ diagram method, the energy targets and the structure of the initial heat exchanger network can be easily obtained. The method can be used both for direct and indirect heat integration of batch streams. For indirect heat integration, the heat degradation of intermediate media is considered. A case study on optimizing the heat exchanger network of a hydrazine hydrate plant is used to illustrate the application of the method. The results show that integration of this heat exchanger network without considering its batch streams can limit the total energy savings.

## 1. Introduction

Chemical processes can be broadly divided into continuous and batch operations. Although not common, there exist some continuous processes featuring batch streams. Notable examples include the hydrazine hydrate production process and the delayed coking process. Because chemical processes consume large amounts of finite energy resources, many heat integration techniques have been developed over the years to improve their energy efficiency. For example, heat exchanger networks in numerous continuous and batch processes in the chemical industry have become highly energy efficient as a result of heat integration. Nevertheless, despite this remarkable success, heat integration analysis has not yet been applied to continuous processes featuring batch streams. Although usually only a limited number of key batch streams are present in such processes, the heat content of these batch streams could be quite substantial. As such, heat integration analysis that treats this type of hybrid processes as strictly continuous by ignoring the small number of batch streams can limit the total energy savings.

Synthesis of heat exchanger networks of continuous processes has been studied extensively, either by pinch technology [1,2] or by mathematical programming techniques [3,4]. Because pinch technology offers the advantages of intuitiveness, simplicity and clarity when compared to the mathematical programming approach, it is widely used in industry. In recent development of heat exchanger networks synthesis of continuous processes, Wang et al. [5] proposed a methodology to consider heat transfer enhancement in the optimization of heat exchanger network. Zhang et al. [6] developed a method for optimizing the operation condition of heat exchanger network and distillation columns simultaneously. This methodology allows the industry to improve its economic and environment performance at the same time. Vaskan et al. [7] developed a multi-objective design method for heat exchanger network by using a MILP based model. Life cycle assessment and environment were involved in this method. Markowski et al. [8] proposed a heat exchanger network synthesis methodology considering fouling. This methodology can monitor long-term changes in the heat exchanger network efficiency.

With suitable adaptations, most of the heat integration methods developed for continuous processes can be used to search for heat integration opportunities in batch processes which are

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characterized by their time-dependent mode of operation. A variety of models have been developed for heat integration of batch processes since the 1980s [9], some of which are described below.

(1) Time average model [10]: This model is also called pseudo-continuous process model. The heat duties of all streams in the batch process are time averaged in the production cycle, and the utility targets are then obtained by pinch technology. Because the time-dependent features of batch streams are not considered, the targets are highly ideal and can only be approached with extensive use of heat storage.
(2) Time segmentation model [11]: In this model, batch streams are re-arranged in a limited manner to recover more waste heat and avoid heat storage. This method is constrained by whether the actual process allows the re-arrangement of batch streams.
(3) Time and temperature cascade analysis [12,13]: The method considers simultaneously time and temperature. Heat integration in the same time interval is considered first, followed by consideration of the time sequence. Although intermediate heat storage is included in the method, the heat degradation of intermediate media is not considered.
(4) Time pinch method [14]: The heat recovery target is obtained by using time as the main constraint and heat transfer driving force as the secondary factor. The method includes direct and indirect heat recovery. The heat degradation of intermediate media is not considered.

In this paper, a new graphical method based on the heat duty–time diagram will be provided for the heat integration of continuous processes featuring batch streams. The proposed method is largely based on the many heat integration concepts and tools arising from the research on continuous and batch processes. The method can be used both for direct and indirect heat integration.

## 2. The heat duty–time diagram

The heat duty–time diagram ($Q$–$t$ diagram) method developed in this work expresses the time and thermal features of batch streams intuitively and provides a practical graphical tool for heat exchanger network synthesis. As will be explained below, the method is based essentially on a combination of the Gantt chart and the temperature–enthalpy diagram ($T$–$H$ diagram) commonly used in traditional pinch analysis to represent continuous streams.

The $Q$–$t$ diagram will now be illustrated by application to a batch process reported by Kemp and Deakin [12]. The stream data are given in Table 1. In this four-stream example, the batch period is 1 h with each stream only existing for a limited time period. Representing the streams graphically will allow a better appreciation of their time-dependent nature. A handy method of visualization is the Gantt chart, which is a type of time event chart. The Gantt chart is useful for visualizing which streams exist in which periods.

As pointed out earlier, the $T$–$H$ diagram is a key tool of energy-based pinch analysis which is used to represent the thermal features of continuous streams. And the proposed $Q$–$t$ diagram is a hybrid of the Gantt chart and the $T$–$H$ diagram which is able to represent the thermal features as well as the time-dependent nature of batch streams on the same plot. Fig. 1 shows a cold stream (Fig. 1a) and a hot stream (Fig. 1b) plotted on $Q$–$t$ diagrams, which use the stream heat load ($Q$) for the vertical axis and time for the horizontal axis. The arrowheads in Fig. 1 indicate the direction of temperature increase for the cold stream and the direction of temperature decrease for the hot stream. The temperature of the cold and hot streams increases and decreases with time, respectively. Therefore, the cold stream line has a positive slope while the hot stream line a negative slope. The vertical axis length defined by the stream boundaries gives the stream heat load while the horizontal axis length defined by the stream boundaries provides the stream time interval. Like $T$–$H$ diagrams, in the $Q$–$t$ diagrams, moving the cold and hot streams upward or downward will not affect their heat loads. They can therefore be plotted anywhere on the vertical axis.

For multiple batch streams, a systematic procedure for constructing the $Q$–$t$ diagram is given below.

(1) Calculate the heat load of each stream.
(2) Rank the streams in ascending order of supply temperature. The top ranked stream is the one with the lowest supply temperature and must thus be a cold stream (If the stream with lowest supply temperature is a hot stream, it should be kept outside the heat recovery project). If two streams have the same supply temperature, rank the one with the lower target temperature first. If two streams have identical supply temperature and target temperature, rank the one with the lower heat duty first.
(3) Plot the top ranked stream on the $Q$–$t$ diagram using its calculated heat duty value and time interval. Begin with the start time. Its $y$-coordinate (initial heat duty value) at the start time is assumed zero. Its $y$-coordinate (final heat duty value) at the end time is the computed heat duty value. The plotted line will have a positive slope.
(4) Plot the next stream on the $Q$–$t$ diagram. If it is a cold stream, begin with the start time. Its $y$-coordinate at the start time is given by the largest $y$-coordinate of the preceding stream. Its $y$-coordinate at the end time is given by the sum of its heat duty and the largest $y$-coordinate of the preceding stream. The plotted line will have a positive slope. If it is hot stream, begin with the end time. Its $y$-coordinate at the end time is given by the largest $y$-coordinate of the preceding stream. Its $y$-coordinate at the start time is given by the sum of its heat duty and the largest $y$-coordinate of the preceding stream. The plotted line will have a negative slope. Plot the remaining streams in the ranking order using the above procedure.

With the four-stream example given in Table 1, let us illustrate how the $Q$–$t$ diagram can be constructed using the procedure described above.

(1) The heat load of each stream is calculated from the following equation:

$$Q_i = CP_i \Delta T_i \Delta t_i \tag{1}$$

where $Q_i$ = heat load of stream $i$ (kW h), $CP_i$ = heat capacity flow rate of stream $i$ (kW °C$^{-1}$), $\Delta T_i$ = difference of target and supply

**Table 1**
Stream data.

| No. | Type | Supply temperature (°C) | Target temperature (°C) | Heat capacity flow rate (kW °C$^{-1}$) | Start time (h) | End time (h) | Heat duty (kW h) |
|---|---|---|---|---|---|---|---|
| 1 | H1 | 170 | 60 | 4 | 0.25 | 1 | 330 |
| 2 | H2 | 150 | 30 | 3 | 0.3 | 0.8 | 180 |
| 3 | C1 | 20 | 135 | 10 | 0.5 | 0.7 | 230 |
| 4 | C2 | 80 | 140 | 8 | 0 | 0.5 | 240 |