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Heat exchanger network synthesis for batch processes by involving heat storages with cost targets

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HIGHLIGHTS

- The problem on matching streams of different time intervals is solved.
- Compared with existing methods, total annual cost (TAC) is considered.
- How to add heat storages between different time intervals is solved.
- Compared with existing methods, much more energy can be recovered.

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ABSTRACT

Based on time slice model (TSM), two methods, in both of which heat storages are employed to realize the indirect heat exchange operation between different time intervals, are proposed for the synthesis of heat exchanger networks (HENs) for batch processes. Firstly in the first method, a non-linear programming (NLP) model aiming at the minimum total annual cost (TAC) of networks is formulated, with which the operating cost for utilities as well as the capital cost for heat exchanger units are minimized simultaneously. Direct and indirect heat exchange operations are both considered, so this method is suitable for the two time intervals in which cold and hot streams coexist. However, when there are time intervals in which only either cold or hot streams involved, the first method is not feasible to fix the problem. So the second method is proposed in which only indirect heat exchange operation is considered. A graphical approach is introduced for the sub-networks synthesis of concerned intervals. The proposed two methods are complementary as they are applicable to different interval cases. Temperatures of heat storages in both methods are all determined through building mathematical models with the target of minimum TAC. Heat storages are added between the different time intervals and more heat can be recovered with the TAC reducing in some extent. The better HEN structure is gotten and the problem on matching streams of different time intervals is solved through the proposed methods. At last, the two methods are combined to solve an example to demonstrate the application and effectiveness of the proposed methods.

1. Introduction

Reducing energy consumption by means of energy integration began from the energy crisis happened in the 1970s. Since then, many systematic methods such as the “pinch technology” have been proposed as the effective tools in synthesizing heat exchanger networks (HENs). The situation now is most of these methods are only for the continuous processes, but not for their batch partners, which are more suitable for the small-scale production [1]. As streams in batch processes are time-dependent, the methods used

Abbreviations: HEN, heat exchanger network; NLP, non-linear programming; PT, pinch temperature; PTHDA, pseudo-T-H diagram approach; TAC, total annual cost; TAM, time average model; TSHI, total site heat integration; TSM, time slice model.

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for synthesizing HENs of continuous processes can not be directly applied to batch processes. Therefore, developing HENs synthesis methods for batch processes has become an urgent issue as considering the extensive application of batch processes in the future.

Considering the time-dependence of streams in a batch process, three kinds of heat exchange modes are usually implemented: 1) direct heat exchange operation; 2) indirect heat exchange operation; 3) direct–indirect mixed operation. Direct heat exchange operation can be used between the process streams which co-exist in operating time. In most cases, however, using merely direct heat exchange operation is not enough for a full heat recovery, the indirect exchange operation involving heat storages is required. Therefore, direct–indirect mixed operation becomes more appropriate, compared with the former two operation modes, there are many difficulties for the third mode, so the related studies are still limited.

The first report about the integration of HENs for batch processes was from Vaselanak and Grossmann [2] in 1986. One year later, the time average model (TAM), in which any two streams were allowed to exchange heat no matter they coexist or not, was proposed by Linnhoff et al. [3,4]. In their work, the total annual cost (TAC) of batch HEN was not considered. Kemp and Deakin [5] presented a method called time slice model (TSM) in 1989. In their work, heat storages were used for sake of more heat recovery, however, the capital cost caused by setting storages was not considered, and how to match streams of different time intervals was also not introduced. In recent reports, the pseudo-T-H diagram method (PTHDA) [6], in which the temperature difference contribution values of streams was taken as variables instead of the overall allowable minimum approach temperature (ΔT_{min}), was used by Liu et al. [7] to synthesize HEN of batch process based on TSM. Common units matching the same pair of streams during different intervals were identified and used in their work to reduce the heat exchanger number in obtained network. To further optimize the HEN structure, three rules were put forward in their later work [8]. However, heat exchange was limited to be direct heat exchange operation and indirect thermal integration between different time intervals was not considered in the above two papers. Andrew et al. [9] have proposed that the increase in the cost of energy has been at a far greater rate than the increase in equipment costs. So more and more scheduling, rescheduling and multipurpose problems in batch process have been investigated to recover more energy. The related studies include: Zhao et al. [10] proposed that HEN of batch process can be synthesized based on cascade analysis after process scheduling. Bozan and Borak [11] developed an interactive computer program to synthesize HEN of batch process by tackling the scheduling problem at first. Chen and Chang [12] considered the production scheduling and heat recovery problems simultaneously. Besides process scheduling, a continuous-time mathematical formulation for heat integration of multipurpose batch plants was presented by Majozi [13]. Using heat storages is a good choice for recovering more heat but without influencing the technological processes. Total site heat integration (TSHI) is a methodology for the integration of heat recovery among multiple processes [14]. Liew et al. [15] proposed that the heat storages could also be used in total site systems. Chew et al. [16] have investigated the main factors that could influence the practical implementation of TSHI in industries. Foo [17] has proposed an automated targeting technique which can be used to determine the minimum resource consumption, aiming at the minimum transferred heat between different time intervals and utility based on TSM. How to match streams between different time intervals was not investigated and the TAC was not considered in their work. Stoltze et al. [18] proposed a kind of heat storage. The heat storages were limited to be constant-temperature and variable-mass. Krummenacher and Favrat [19] used the kind of heat storages proposed by Stoltze et al. [18] to realize indirect heat exchange operation based on TAM. Heat storages' temperature was investigated in the paper reported by Walmsley et al. [20]. But the integration of HEN was not described. Chaturvedi and Bandyopadhyay [21] introduced one method which can account for indirect thermal integration between various different time intervals based on TSM, but the TAC was not calculated.

In conclusion, the current studies about exchanging heat between different time intervals are still very limit. As the cost of energy becomes more and more expensive, more heat in process requires to be recovered. In this study, indirect heat operation was studied based on the method proposed by Liu et al. [7] for the sake of recovering more heat. Different from the previous studies on indirect thermal integration between time intervals based on TSM, TAC is considered here. Moreover, the streams matching problem between different time intervals is particularly investigated.

2. Problem statement

The HEN synthesis problem discussed can be described as: given are the initial and target temperatures, as well as the start and end time of streams in a batch process. In addition to these, the heat capacity flow rate of each stream is also given as a constant. The purpose is to find out how to use the direct and indirect heat exchange operations to get a target HEN. A minimum TAC solution is looked forward by this study.

3. Indirect heat exchange operation

Direct heat exchange operation is feasible when the related streams coexist, however, it is impracticable to the case of streams which are not overlapped of running time. This problem can be settled with indirect heat exchange operation, by setting heat storages to overcome the time gap. Stoltze et al. [18] have proposed an effective synthesis strategy based on this idea. They carried out the heat exchange by introducing medium fluid between the so called constant-temperature and variable-mass heat storages. The basic thought is represented with Fig. 1. In Fig. 1, a hot stream (H) with a higher temperature and a cold stream (C) with a lower temperature locate in two different time intervals. A heat storage couple of variable-mass heat storage A and heat storage B are constructed to implement the heat transmission between the two time intervals. Streams in and between heat storages are medium fluid, so there will not cause any change to the original process. Heat storage A has a higher temperature than heat storage B. Along with the medium fluid moving from heat storage B to heat storage A, a cold medium stream is formed to absorb heat from stream H through a heat exchanger. Conversely, a hot medium stream is generated to release heat to cold stream C when the medium fluid runs from heat storage A to heat storage B. Following this cycle, the heat exchange between streams H and C is carried out.

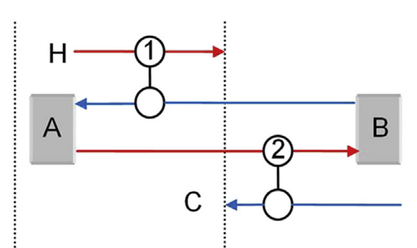

Fig. 1. Model of indirect heat exchange operation.