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Research Paper

Synthesis of batch heat exchanger networks utilizing a match ranking matrix

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HIGHLIGHTS

- The match ranking matrix supports heat exchanger network synthesis for batch processes.
- Streams with large heat exchange potential are preferred for matching.
- Iteration steps during economic optimization of the network are reduced.
- The new development is compared to existing methods employing a literature example.

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ABSTRACT

Direct heat exchanger network synthesis for continuous processes based on pinch methodologies benefits from its intuitiveness and simplicity. The challenge in synthesizing direct heat exchanger networks in batch processes is to handle many small heat streams to form an economic heat exchanger network. In this publication, a new approach for synthesis of direct heat exchanger networks is presented and compared to existing approaches described in literature. Within the new approach a match ranking matrix is utilized to prioritize stream combinations which exhibit the largest potential for cost effective installation instead of matching the streams by their temperature. Thereby, possible loss of heat integration potential is accepted. As a result, the following optimization of the heat exchanger network takes less iteration steps compared to stream matching by temperatures. The approach is applied to an example process to show its applicability.

1. Introduction

Climate change and global warming belong to the major challenges of the 21st century. Since carbon dioxide emissions are made accountable for global warming, their reduction is a desirable objective [1]. Besides switching from fossil fuels to renewable energies, improving resource and energy efficiency is a key goal for future technology development. Investigating new technologies to increase energy efficiency is also a key goal of the “First European Climate Change Programme” of the European Comission [2]. In Germany, the chemical industry has the biggest portion of energy consumption in the industrial sector [3]. Therefore, the chemical industry must contribute to the reduction of emissions. A positive side effect of an increase in energy efficiency is the related reduction of operating costs resulting in increasing competitiveness.

Heat integration represents an effective measure to increase energy efficiency. For continuous processes, pinch technology developed by Linnhoff [4] is a systematic approach for heat integration widely used in chemical industry. Heat integration is also part of methodologies for process synthesis [5]. Streams that have to be cooled (hot streams) are matched with streams that have to be heated (cold streams) in order to reduce external heat and cooling supply if temperature levels within the process allow for internal heat exchange. In contrast to continuous processes, heat integration in batch processes is rarely applied. Batch processes are often characterized by high value creation of their products and therefore saving energy costs has a much lower impact than a reduction of raw material consumption. Inefficient operation is accepted to benefit from the flexibility related to batch processes [6]. As a result of mostly small production capacities in batch processes, internally exchangeable heat amounts are often comparatively small. Additionally, in batch processes energy streams do only exist temporarily so that heat exchangers for internal heat exchange are only poorly utilized. These reasons increase the necessity for an efficient heat exchanger network.

For batch processes, two approaches have been established for heat exchanger network synthesis in general: on the one hand, approaches based on pinch technology initially presented by Kemp and Deakin [7] and on the other hand approaches based on mathematical programming initially presented by Vaselenak et al. [8].

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Mathematical approaches usually aim to find a heat exchanger network with maximum economic benefit. This can be reached by preferring shared use of heat exchangers [9], removing inefficient heat exchangers from the network [10] or even schedule optimizations [11]. Algorithmic targeting procedures even allow a total site evaluation concerning batch heat integration [12]. In the review of Fernández et al. [13] more information about batch heat integration in general can be found. However, approaches based on pinch technology offer the advantage of higher traceability compared to mathematical approaches. Additionally, mathematical approaches are not suitable for application during early design stages as they usually require detailed input date which is not available at stage of process design. Therefore, the pinch-based approach will be followed in this paper and a method to facilitate direct heat exchanger network synthesis will be presented. Like in pinch technology the method presented aims at optimizing the optimal exchange potential for a given process with given operating conditions. Additional heat exchange potential created e.g. by pressure changes in phase change operations are not considered initially. This should be checked in case large energy streams caused by evaporation or condensation remain uncoupled after applying the methodology.

2. State of the art

Heat integration is usually performed in a three step approach: 1. determination of the heat integration potential, 2. synthesis of a heat exchanger network realizing the full heat integration potential and 3. economic optimization of the heat exchanger network [14].

In continuous processes, heat integration potential is determined by dividing the heat streams into temperature intervals. Interval boarders are set by supply and target temperatures of the heat streams. Heat amounts of hot and cold streams in these temperature intervals can be integrated and are therefore assigned to each other. Excess heat will be transferred to lower temperature intervals. Lacking heat is compensated by adding hot utility to the appropriate temperature level and cold utility compensates surplus heat on the appropriate temperature level. The synthesized heat exchanger network realizes the complete heat integration potential. It implies no heating below the pinch temperature, no cooling above the pinch temperature and that no heat is transferred across the pinch point. Violating one or more of these rules would increase the necessary amount of external utilities [15]. Afterwards, the resulting network can be optimized regarding economic aspects. Uneconomic heat exchangers are removed from the network and other heat exchangers in the network partly take over the heat transfer. Thereby, uneconomic heat exchangers creating loops and paths are primarily removed. A loop is a closed connection between heat streams by internal heat exchangers. A connection of external heat sources and sinks by internal heat exchangers is called a path. Uneconomic heat exchangers are removed in an iterative procedure until the heat exchanger network is entirely economic [15].

For the determination of heat integration potential in batch processes, various authors have presented approaches to adapt pinch technology for continuously operated processes in order to make the fundamental ideas applicable to batch processes. Linnhoff et al. [16] developed the Time Average Model (TAM). The temporal behavior of heat streams is thereby ignored and the pinch analysis for continuously operated processes is executed. The resulting energy integration target is therefore overoptimistic. Kemp and Deakin [17] presented the Time Slice Model (TSM). For the application of TSM, the batch process is divided into time intervals in which steady-state behavior is assumed. Therefore, time interval boarders are set when a heat stream begins or ends. For continuous processes containing also batch streams, Wang et al. recommend to use a heat-time-diagram for the heat integration procedure [18].

Heat integration in batch processes can be executed as direct or indirect heat exchange. Within direct heat exchange, heat can be transferred between temporary coexisting heat streams, only. Heat transfer from one stream to latter streams can only be realized utilizing indirect heat exchange. For indirect heat exchange, heat integration potential can be determined by TSM as well or by rigorous algorithms [19]. Recent publications also consider costs when synthesizing a corresponding storage network to implement the determined heat integration potential [18]. In this paper, direct heat exchange is investigated only.

In batch processes, four categories of heat streams can occur [20]. These can be attributed to two types of heat streams due to their temperature progressions: steady-state and dynamic heat streams. Steady-state heat streams are characterized by temporally constant supply and target temperatures. In contrast to this, dynamic heat streams exhibit a temperature profile over time. TSM is only applicable for steady-state heat streams. Dowidat et al. [21] presented a detailed discussion of the two stream types and developed a method to prepare dynamic heat streams for consideration with TSM. Thereby, dynamic heat streams are divided into virtual sub-streams at certain points of time which are relevant for determining the heat integration potential. These sub-streams can be considered as steady-state heat stream without any loss of accuracy.

To achieve a direct heat exchanger network, which is able to realize the maximum internally exchangeable heat, individual heat exchanger networks are synthesized in every time interval. The heat exchanger networks are afterwards combined to form the overall heat exchanger network following the approach presented by Kemp et al. [7]. Thereby, heat exchangers involving the same heat streams are merged to one heat exchanger for the respective time intervals. Increasing numbers of time intervals will also increase the number of heat exchangers required in the overall heat exchanger network. Thus, the resulting energy efficiency improvement is rarely economically beneficial as a result of the high number of heat exchangers exchanging only small amounts of heat. Therefore, economic optimization has to be performed. Anastasovski developed a methodology to reduce the number of heat exchangers required for internal heat exchange by prioritizing heat exchangers used for multiple stream combinations [22]. The strategy of this approach is to use one heat exchanger to serve for example one cold stream with multiple hot streams. The limitation of this approach is that all hot streams in this case have to be compatible to use the same heat exchanger.

Generally, economic optimization procedures aim at reducing the number of heat exchangers transferring only small amounts of heat in order to increase the number of large heat exchangers. Large heat exchangers amortize earlier than small heat exchangers as a result of economies of scale. For cost estimation, the degression exponent of shell and tube heat exchangers is 0.71 [23] while energy savings are increased linearly with heat exchanger size. For an accurate economic optimization of the heat exchanger network, a lot of details of the process and the respective heat exchangers have been known. Only few of this information are available in the early design stages of batch processes. In these stages, a simple methodology to prefer possibly large heat exchangers is required.

For economic optimization procedures, iterative procedures are obligatory which will be demonstrated in the next section. Iteration is necessary because information of other time intervals is not taken into consideration during conventional synthesis of the direct heat exchanger network in the individual time intervals. In the following, the match ranking matrix is introduced which allows to consider information about other time intervals during the synthesis. In that way, the number of iteration steps during the economic optimization procedure can be reduced. Thereby, quantitative evaluation of the matrix's benefit is not possible in general. It cannot be predicted how many iteration steps can be avoided.