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Heat integration in batch processes including heat streams with time dependent temperature progression

Christian Dowidat, Kirsten Ulonska, Christian Bramsiepe, Gerhard Schembecker*

Laboratory of Plant and Process Design, Department of Biochemical and Chemical Engineering, TU Dortmund University, Germany

HIGHLIGHTS

- Existing models for heat integration of batch processes have been investigated.
- Inaccuracies for the existing models monitored when dynamic heat streams occur.
- Time-Temperature-Interval-Model introduced to overcome these limitations.
- Time-Temperature-Interval-Model applied to literature process.
- Comparison of the models and recommendation for their application.

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ABSTRACT

Time Slice Model (TSM) is an existing model suitable to identify the potential for heat integration in batch processes. However, heat streams occurring during a heating or cooling process in a batch vessel cannot be depicted rigorously due to their time dependent temperature profile. Yet such streams can frequently be found in batch processes. Ignoring the temporal dependence of the temperature can lead to inaccurate heat integration targets. In this publication, necessity for the inclusion of time dependent heat streams is illustrated and drawbacks of existing approaches are demonstrated. A methodology for considering heat streams with temperature profiles in TSM is presented and it is demonstrated that introducing additional time slices allow prediction of integration potential without accuracy loss.

1. Introduction

Prevention of global warming and climate change is one of the major challenges in this century. One opportunity to reduce carbon dioxide emissions, one of the main drivers for global warming, is to increase energy efficiency. Along with other branches of industry, chemical process industry is therefore forced to increase process efficiency. Additionally a reduction of energy consumption results in reduced operating costs. Because of low specific energy consumption and high specific margins, batch processes were only little considered in energy efficiency measures. However, increasing energy costs as well as the introduction of carbon dioxide certificates in Europe will lead to rethinking.

In general, continuous processes are more efficient than the corresponding batch processes. Nevertheless, for every process the operation mode has to be defined carefully [1]. Therefore, both operation modes – batch and continuous mode – have to be optimized first and then compared. Increasing the energy efficiency is one of the most important measures in process optimization for both operation modes. In terms of energy efficiency, heat integration has the greatest potential to reduce the utility consumption. Streams having demand for cooling (hot streams) are matched with streams having demand for heating (cold streams) at a corresponding temperature. Thereby, demand for external heat and cooling supply is reduced. Methods for the increase of energy efficiency such as the Pinch Analysis [2] are well established for continuous processes. Contrary to continuous processes, hot and cold streams in a batch process usually do not exist over the whole process time. When a hot and a cold stream overlap in certain time interval at appropriate temperature levels they can be matched in this overlapping time. This is called direct heat exchange. For matches between streams only existing in temporal offset, indirect heat exchange with heat storage is required.

In the late 1980s, researchers began to adapt established methods for continuous processes for the application on batch

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* Corresponding author. TU Dortmund University, Department of Biochemical and Chemical Engineering, Laboratory for Plant and Process Design, Emil-Figge-Str. 70, D 44227 Dortmund, Germany. Tel.: +49 0231 755 2339; fax: +49 0231 755 2341.
E-mail address: Gerhard.Schembecker@bci.tu-dortmund.de (G. Schembecker).

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processes. The Time Slice Model (TSM) was deviated from the Pinch Analysis for continuous processes [3]. Within this model, the heat streams are subdivided when a change in heat flow occurs. As a result, steady state conditions prevail in every created time interval (slice). Thus, the Pinch Analysis can be applied in these time slices and the results can be combined to receive the minimum amount of external utilities. In more recent publications, researches switched to computational approaches. Liu et al. [4] developed a nonlinear programming model to find the network of direct heat exchangers with the lowest costs. Direct heat exchange can be realized between coexisting streams only. However, the TSM is still applied in current researches. Anastasovski [5] used the TSM to find time intervals for heat exchanger network design.

Realizing direct heat exchange might require rescheduling of the batch processes. Various methodologies for systematic rescheduling are present in literature [6–9]. Besides direct heat exchange, heat integration in batch processes can also be realized via indirect heat exchange with heat storages. Sadr-Kazemi and Polley [10] introduced equations to describe different variants of indirect heat integration. Chen and Ciou [11] presented a methodology for heat storage network design utilizing a superstructure and a mathematical programming to find the optimal solution. Thereby, heat from a hot stream is stored in a heat storage and released to cold streams in a later time period. Also indirect heat integration potential can be calculated with the TSM [3]. A detailed review of research concerning energy recovery in batch processes is given by Fernández et al. [12].

While mathematical approaches usually aspire a cost optimum for heat exchanger networks, the Pinch-based TSM offers information about the maximum possible heat integration potential. Thus, the TSM delivers a benchmark for heat integration potential of a batch process. Heat exchanger networks can be evaluated by these benchmarks. In addition to that, results of rescheduling procedures can be compared on basis of this benchmark. The above mentioned TSM achieves suitable results determining the heat integration potential of a batch process. Nevertheless, heat streams occurring when a medium is heated or cooled in a vessel (dynamic heat streams) cannot be processed by the TSM. These streams have to be converted to have steady-state behavior. In this publication existing proposals for their conversion will be discussed and their limitations will be described. Subsequently, a new approach for an adequate conversion of dynamic heat streams will be presented. Thereby, the focus is set to direct heat integration. Indirect heat exchange requires heat storages and therefore multiple heat exchange (from hot stream to storage and from storage to cold stream). As a result, a higher minimum temperature difference between the heat streams is necessary to realize internal heat exchange. Additionally, the investment for heat storages is commonly higher than for a heat exchanger for direct heat exchange.

2. Determination of the internally exchangeable heat

Kemp and Macdonald [13] introduced the Time Average Model (TAM) to identify potentials for energy integration in batch processes. The procedure is adapted from Pinch analysis for continuous processes [2]. Ignoring the discontinuous behavior, the energy of each stream is averaged over batch cycle time. Hence, the minimum requirements for external heating and cooling as well as the internally exchanged heat can be determined. This approach is usually overoptimistic because it does not consider the temporal existence of the streams and the resulting reduction of exchangeable heat. Thus, the targets of the TAM cannot be fulfilled with direct heat integration alone. Only in case of repeated batches including a storage system with no heat losses, TAM targets can be reached [14].

The TSM considers the schedule of the process and thereby the temporal existence of the streams. The batch cycle is subdivided into time intervals (slices). Boarders for the intervals are set, when the heat flow changes in the process including the starting point or end of a stream. For detailed time analysis a matrix with heat flow for every time and temperature interval is set up. Similar to continuous processes a temperature pinch can be determined for every time slice. In the same manner, heat cascades can be calculated. These heat cascades display the minimum utility consumption for each slice as well as maximum internal heat exchange. Constructing a time energy cascade, the integration targets for a single batch or repeated batches can be determined. Analogue to the grand composite curve for continuous processes a cascade plot for the time temperature cascade can be drawn. Here, a 3-D plot is necessary as time appears as an additional degree of freedom [3].

2.1. Heat streams in batch processes

In continuous processes, streams to be heated or cooled have steady-state supply and target temperatures. This results in a constant temperature difference between process medium and utility. In batch processes these streams also occur when the heating or cooling process is executed during the transfer from one apparatus to another. In the following this kind of heat stream will be called “steady-state heat stream”. Contrary to a continuous process, such steady-state heat streams do not exist during the whole process time. When a stream is heated or cooled in an apparatus a different temperature behavior can be observed. The temperature difference between the medium and the utility is now time dependent. A heat stream showing this behavior will be called “dynamic heat stream” in the following. Both kinds of streams are visualized schematically in Fig. 1.

Kemp [15] divides the streams in batch processes into four types:

- Type A: Stream with steady-state heat flow and fixed inlet and outlet temperatures
- Type B: Stream with non-steady-state heat flow and fixed inlet and outlet temperatures
- Type C: Stream with steady-state flow and changing temperature value
- Type D: Stream with non-steady-state flow and changing temperature value

For examples of the stream types see Kemp [15]. For the determination of the heat integration potential, the consideration of temperature behavior suffices. As long as the temperature of a hot stream is higher than the temperature of a cold streams, internal heat exchange between these streams is possible. Therefore, the streams of type A and C can be considered as steady-state heat streams and streams of type B and D as dynamic heat streams due to their identical temperature behavior. Although dynamic heat streams are probably the most common streams in batch processes, the above mentioned methods for the investigation of heat integration potential have only been examined for streams of type A in literature known to the authors. Therefore, a methodology for treating dynamic heat streams into the TSM will be presented in this paper.

2.2. Correlation of heat stream type and integration potential

To clarify the difference between steady-state and dynamic heat streams a generic process example will be used. Reactants are heated in a continuous heat exchanger (HEX1) to 405 K with steam and are afterwards transferred to a storage vessel (V1). When the