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IFAC-PapersOnLine 49-7 (2016) 067–072

A Novel Algorithm for Design of Mixed Energy-integrated Batch Process Networks ⋆

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Abstract: This paper presents a novel algorithm for calculating minimum utility targets for mixed energy integration which combines direct and indirect strategies. Mixed integration offers enhanced heat recovery compared to direct or indirect strategy at the cost of challenging design. The proposed method is based on time-dependent heat cascade analysis and consists of an iterative application of direct and indirect targeting. The present approach overcomes some of the limitations exhibited by the existing methods. The effectiveness of the proposed algorithm is elucidated for a benchmark energy integration problem wherein the achieved external utility consumption is close to the theoretical minimum value.

Keywords: Heat integration, Utility targeting, Heat storage, Heat exchanger network, Heat cascade.

1. INTRODUCTION

A rapid increase in worldwide energy consumption and the increased fluctuations in the cost of energy have intensified the importance of efficient utilization and management of energy. Improvement in energy utilization can be achieved through heat integration. The objective of heat integration is to establish matches between streams that require cooling and those that require heating in order to find the minimum hot and cold utility targets. Heat integration, thus, reduces the amount of hot and cold utilities consumed and, consequently, lowers the operating costs.

Energy integration in batch processes is relatively an untapped area compared to the continuous processes. In recent decades, several studies have been conducted in order to minimize external energy consumption in batch processes (Clayton, 1986; Linhoff et al., 1988; Kemp and McDonald, 1987; Kemp and Deakin, 1989c; Sadrkazemi and Polley, 1996; Zhao et al., 1998; Krummenacher and Favrat, 2001; Chen and Ciou, 2008; Chaturvedi and Bandyopadhyay, 2014). Due to time-dependent availability of hot and cold streams, energy integration in batch processes is achieved via one of the following three ways.

- Direct energy integration: It involves direct heat exchanges between streams which co-exist at the same time. Direct heat integration is only possible when heat integration is within the same time interval. Some of the existing approaches for direct energy integration include Linhoff et al. (1988); Kemp and Deakin (1989a,b); Ivanov et al. (1995); Zhao et al. (1998).
- Indirect energy integration: When heat integration between two streams available in different time intervals is involved, heat from the hot process stream is first transferred to a heat transfer fluid, which is heated up and stored until heat is finally transferred to the cold process stream when it is available. This is known as indirect energy integration. Some of the existing approaches for indirect energy integration include Stolze et al. (1995); Sadrkazemi and Polley (1996); Krummenacher and Favrat (2001); Chen and Ciou (2008).
- Mixed energy integration: This strategy combines the direct and indirect approaches such that part of the energy integration is achieved directly between co-existing process streams and the rest is achieved indirectly through a heat transfer medium. Some of the existing approaches include Kemp and Deakin (1989a); Wang and Smith (1995); Krummenacher and Favrat (2001); Chaturvedi and Bandyopadhyay (2014).

The mixed energy integration strategy allows for enhanced reduction in energy consumption. Despite economic benefits, this is the least explored strategy for energy integration and the existing contributions are presented as extensions of indirect energy integration approaches. As none of these approaches were specifically developed for mixed energy integration, they present limitations for practical implementation. Kemp and Deakin (1989a) considered the same approach temperature ΔT_{min} while addressing direct and indirect energy integration. This results in infeasible heat transfer during indirect mode. Krummenacher and Favrat (2001) gave only preliminary guidelines for energy targeting in mixed mode. Chaturvedi and Bandyopadhyay (2014) eliminated the limitation of infeasibility in Kemp's approach by using corrected approach temperature for

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⋆ Partial financial support for this work by the Government of India Department of Science and Technology (DST) INSPIRE & SERB-SB/S3/CE/090/2013 grant is gratefully acknowledged.

10.1016/j.ifacol.2016.07.218

indirect integration. However, their approach does not update direct integration calculations after indirect integration and results in infeasible design when some of the temperatures used in direct integration change after indirect integration. Motivated by this, the proposed method overcomes the limitations of previously reported methods by an iterative application of direct and indirect targeting methods while updating stream temperatures after each step.

2. ALGORITHM FOR UTILITY TARGETING FOR MIXED ENERGY INTEGRATION

The targeting method in the proposed approach is based on time-dependent heat cascade analysis originally proposed by Kemp and Deakin (1989a). It involves use of shifted temperatures to ensure that adequate temperature difference is maintained between the hot and cold streams used for integration. If the selected approach temperature for energy integration is ΔT_{min}, the inlet and outlet temperatures of the hot streams are reduced by $\frac{\Delta T_{min}}{2}$ and those of the cold streams are increased by $\frac{\Delta T_{min}}{2}$. The proposed algorithm is depicted in Figure 1.

Before starting the algorithm, the net hot or cold utility required (in the absence of energy integration) is calculated (U_{max}). This will be the maximum utility required for the batch process system and the corresponding heat recovery will be zero ($HR_0 = 0$).

Step 1 - Time intervals: The entire time horizon of the batch process is divided into multiple time intervals, such that the boundaries of time intervals are the time at which one/more stream/s start or end. Let n be the total number of time intervals. This step is common for most of the targeting algorithms for batch process systems. Within each of the intervals, the targeting problem is similar to its continuous counterpart.

The algorithm starts with the first time interval (i = 1). Here we assume that the batch process is operated in cyclic mode i.e. multiple similar batches are conducted one after the other. This provides additional opportunity for energy integration between consecutive batches (inter-batch integration). The iterator m denotes batch number.

Step 2 - Indirect heat integration: Within each time interval, we first check for any possibility of indirect heat integration. We search for any hot streams available in the past time intervals (stored in a repository) and pair them with the cold streams of the current time interval. The matching of these streams is done by considering a minimum temperature difference of $2\Delta T_{min}$ (one ΔT_{min} for heat transfer from the hot stream to the heat transfer medium and the other ΔT_{min} for heat transfer from the heat transfer medium to the cold stream) i.e. hot stream temperatures are reduced by ΔT_{min} and cold stream temperatures are increased by ΔT_{min}. Once such matching is done, the temperature values of the corresponding hot streams (in the past interval) and the cold streams (in the current interval) are updated to reflect heat exchange due to indirect integration.

Step 3 - Direct heat integration: After indirect integration, the hot streams available in the current interval are matched with the updated cold streams by considering a minimum temperature difference of ΔT_{min}.

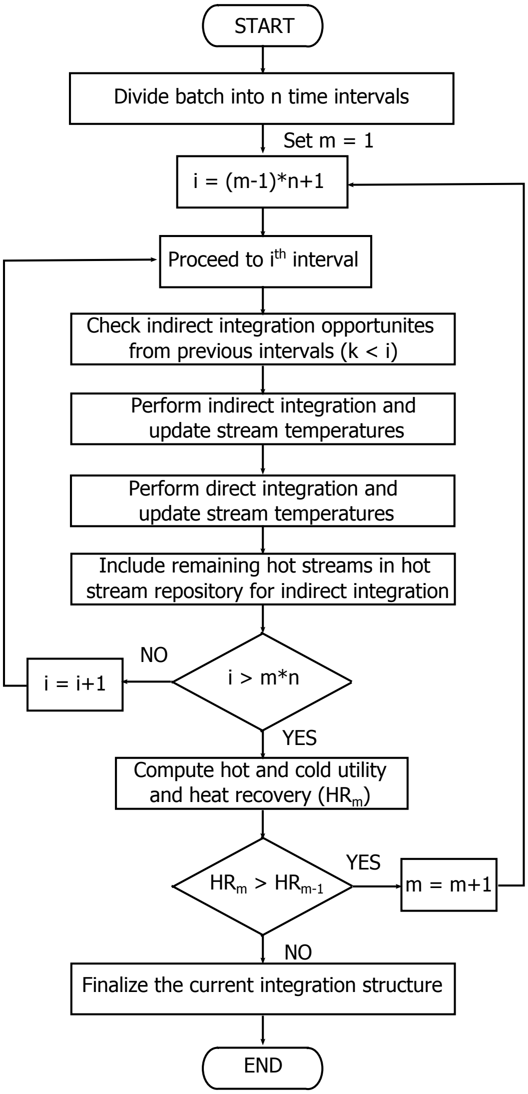

Fig. 1. Algorithm for utility targeting for mixed energy integration

Step 4 - Update the hot stream repository for indirect integration: Once direct and indirect integration is performed for the current interval, any hot streams which have not yet reached the target temperature are added to a repository of available hot streams. Such hot streams can be used for indirect energy integration in any future time intervals (step 2). It is assumed that there is negligible heat loss during storage.

Step 5 - Calculation of targets: When all the time intervals of a batch are analyzed, all the updated hot streams are cooled to their target temperature using cold utility. Similarly, all the updated cold streams are heated to their target temperature using hot utility. The corresponding total utility (U_m) required is computed. Total heat recovery in the batch is computed as $HR_m = U_{max} - U_m$ and compared with the value for the previous iteration (HR_{m-1}). If there is an increase in the heat recovery during the current iteration, the above steps are repeated with the current repository of the hot streams (to exploit