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MINLP model and two-stage algorithm for the simultaneous synthesis of heat exchanger networks, utility systems and heat recovery cycles

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ABSTRACT

This work proposes a novel approach for the simultaneous synthesis of Heat Exchanger Networks (HEN) and Utility Systems of chemical processes and energy systems. Given a set of hot and cold process streams and a set of available utility systems, the method determines the optimal selection, arrangement and design of utility systems and the heat exchanger network aiming to rigorously consider the trade-off between efficiency and capital costs. The mathematical formulation uses the SYNHEAT superstructure for the HEN, and ad hoc superstructures and nonlinear models to represent the utility systems. The challenging nonconvex MINLP is solved with a two-stage algorithm. A sequential synthesis algorithm is specifically developed to generate a good starting solution. The algorithm is tested on a literature test problem and two industrial problems, the optimization of the Heat Recovery Steam Cycle of a Natural Gas Combined Cycle and the heat recovery system of an Integrated Gasification Combined Cycle.

1. Introduction

The optimal design of energy systems and chemical processes involves the synthesis of the Heat Exchanger Network (HEN) and the utility systems necessary to provide thermal, refrigeration and electric power to the process units. The so-called heat integration problem aims at determining structure and design variables (inlet/outlet temperatures, mass flow rates and heat exchanger areas) of the process HEN, and the selection, structure and design variables of the utility systems. Both tasks involve the optimization of integer (binary) variables. When optimizing the HEN, integer variables are needed to select the heat exchangers among all the possible matches between hot and cold streams (Yee and Grossmann, 1990). When designing the utility systems, integer variables are needed to select the type of utility system (Marechal and Kalitventzeff, 1998) and to define its arrangement (Papoulias and Grossmann, 1983a). As a result, the overall optimization problem (HEN + utility) is a Mixed Integer Non-Linear Problem (MINLP) and its combinatorial nature makes it very difficult to solve. Indeed, the optimization problem of just the HEN (without utility systems) is proven to be "NP-Hard" in the strong sense (Furman and Sahinidis, 2002).

To the best of our knowledge, all the available synthesis techniques tackle the problems of the optimization of the design of the HEN and of the utility systems (e.g., steam cycle) separately. The separate approach limits the set of integration options between the HEN and the set of utility streams. For instance, the well-known sequential approach proposed in the works of Papoulias and Grossmann (1983a, 1983b), and Floudas et al. (1986) are limited by the fact that utility systems are designed after optimizing the HEN, with the objective of providing to the HEN the required hot/cold utility loads. The following limitations are implied:

1. As far as steam cycles/networks are concerned, in Papoulias and Grossmann (1983a) it is assumed that the utility streams available for supplying/removing heat from the process can be only evaporating/condensing steam. For instance, hot process streams cannot economize feedwater or superheat steam. This limitation to the possible integration options between utility and HEN may be suitable only for chemical processes (where saturated steam is typically used) but not for power plants, like Integrated Gasification Combined Cycles (Martelli et al., 2011b);

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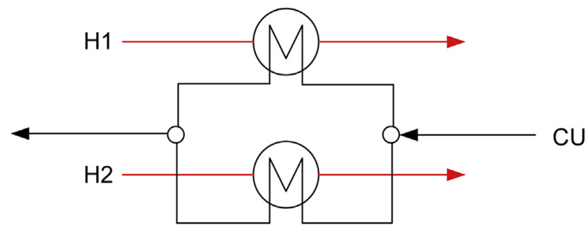

Fig. 1. Parallel branches of utility streams assumed in Floudas et al. (1986).

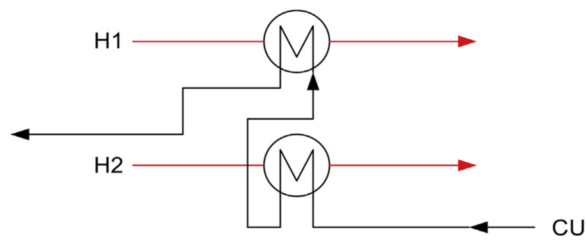

Fig. 2. Utility streams with matches in series.

2. In the NLP superstructure of Floudas et al. (1986), the matches of each utility stream can only be in parallel. Indeed, it is considered one utility sub-stream for each match which involves the given utility: i.e., if a cold utility stream (CU) has two matches, one with stream H1 (H1-CU) and one with H2 (H2-CU), when building the HEN they are considered as two different streams, stream CU1, matched with H1, and stream CU2, matched with H2 (see Fig. 1). This implies that, for the CU stream the series arrangement H1-CU – H2-CU (shown in Fig. 2) is excluded from the HEN;
3. Because of limitation (2) which imposes the parallel arrangement, the outlet temperature of cold utility stream must be lower than the inlet temperature of the matching hot stream. For the same reasons, the outlet temperature of the hot utility stream must be higher than the inlet temperature of the cold streams matched. This constraint does not allow to use cold utility streams with high outlet temperatures (e.g., feedwater of a steam cycle whose target temperature is 200–300 °C) or hot utility streams with low outlet temperatures (e.g., the flue gases of a gas turbine which can be cooled down to 100–60 °C) which are the streams of the most efficient utility systems.

Also simultaneous HEN synthesis techniques, such as (Yee and Grossmann, 1990) and its improved versions (Björk and Westerlund, 2002; Bergamini et al., 2007), have limitations which make them not suitable for designing HENs optimally integrated with utility systems. In detail, the MINLP SYNHEAT superstructure of (Yee and Grossmann, 1990) has the following limitations:

1. Utility superstructures/models are not included for selection and optimization;
2. The optimization of the utility stream mass flow rates is not tackled because it would make the MINLP more difficult to solve (constraints would become nonlinear and nonconvex due to the bilinear terms corresponding to the products between utility mass flow rates and stage temperatures);
3. Utility streams are not included in the HEN superstructure but placed at the hot and cold ends of the superstructure;
4. The matches of each utility stream can only be in parallel since it is considered one utility sub-stream for each possible match with the process stream (i.e., the configuration of Fig. 2 cannot be reproduced).

In utility synthesis techniques, like that proposed by Bruno et al. (1998), the optimization of the HEN is not dealt with. The utility system is optimized to provide thermal, electric and refrigeration power to the process (for fixed process requirements, i.e., assuming that the process HEN has been already determined in a previous step). Among the simultaneous synthesis techniques for HENs with multiple utilities, like those proposed by Isafiade et al. (2015), Na et al. (2014), Ponce-Orega et al. (2010), to the best of our knowledge, only the superstructure proposed by Isafiade and Fraser (2008) allows to place the matches of utility streams in series because it regards utility streams as process streams. All the other above-cited techniques do not envisage the possibility for utility streams to have matches in series (as in Fig. 2) so as to avoid non-convex terms (i.e., bilinear terms due to the products between utility mass flow rates and stage temperatures). On the other hand, the interval-based superstructure of Isafiade and Fraser (2008) is not as flexible as that of Yee and Grossmann (1990) and Isafiade et al. (2015), Na et al. (2014), Ponce-Ortega et al. (2008) because the temperature stages are defined on the basis of the supply and target temperatures of the hot streams. Consequently, (1) the matches of each cold stream with the hot streams are necessarily sequenced according to the order of temperatures of the hot streams, (2) some streams with narrow temperature range can have only one stage with the impossibility of having two or more matches in series. This limitation may significantly penalize the area cost of the solution if hot streams have considerably different heat transfer coefficients (in such a case the optimal order of the matches may not coincide with the order of stream temperatures) or if the series arrangement is economically advantageous (see the test case in Section 6). Another important limitation of all above-cited simultaneous synthesis techniques for HENs with multiple utilities is that the design and synthesis of the utility systems are not tackled.