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Optimal synthesis of heat exchanger networks for multi-period operations involving single and multiple utilities

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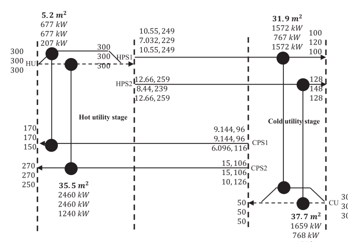
HIGHLIGHTS

- We apply a systematic approach to the synthesis of multi-period heat exchange networks.
- Reduced superstructure gives networks with fewer numbers of units.
- Method is applicable to multi-period HENS problems having multiple utilities.

GRAPHICAL ABSTRACT



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ABSTRACT

The synthesis of heat exchanger networks in chemical plants is vital for energy saving. Most papers presented on this subject have focused on processes having single periods of operation. However, in reality, chemical processes may be multi-period in nature due to changes in environmental conditions, requirements for start-ups and shut-downs, etc. In cases like this, there may be variations in operating parameters such as supply and target temperatures, and flow rates. Further, such processes may involve multiple hot/cold utilities. For processes of this nature, it is imperative to use a mathematical based approach so as to adequately handle the multidimensional nature of the problem. However, solving such models may be difficult except a systematic approach is adopted. In this paper, a modified version of the stage-wise superstructure of Yee and Grossman (1990) is adapted to the synthesis of heat exchanger networks having multiple periods of operations. A new set of solution approaches, which involves solving multi-period MINLP models in a two-step approach is presented. The newly developed method is applied to three examples, out of which two were taken from the literature. In the two examples taken from the literature, the solutions obtained from this study performed better than those presented in the literature.

1. Introduction

In recent times, emphasis is being placed on reduction of the use of fossil based energy sources due to their potential to emit greenhouse gases when burnt, into the atmosphere. A major way by which process plants can reduce the use of these carbon based fuels is through an efficient design of heat exchanger networks that are capable of selecting utilities based on economics and potential environmental impact. A good heat exchanger network synthesis method should be able to handle multiple periods of operations as well as multiple utilities.

Ability to adequately select the best option of utility or combination of utilities is essential due to the fact that utilities have different costs in terms of economics as well as different potential to impact the environment.

Various methods which are both sequential and mathematical in nature have been applied to the synthesis of heat exchanger networks.

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Chief among the sequential methods is pinch technology. The mathematical based approaches have been sequential and simultaneous in nature. Examples of the sequential based mathematical approach are the transhipment and transportation models of Papoulias and Grossmann (1983) and Cerda et al. (1983) respectively. Techniques under the simultaneous mathematical approach include the stage-wise superstructure (SWS) of Yee and Grossman (1990), the flexible multi-period model of Papalexandri and Pistikopoulos (1994) and the interval based mixed integer non-linear superstructure model of Isafiade and Fraser (2008). Heat exchanger network design methods which are able to handle problems involving single period operations and multiple utilities have been presented in the literature. One of these methods is sequential based while other ones are mathematical programming based. The sequential based method was developed by Shenoy et al. (1998), while the mathematical programming based methods were developed by Isafiade and Fraser (2008) and Ponce-Ortega et al. (2010).

In reality, plant operating parameters may deviate from nominal operating conditions due to environmental factors, start-ups, shut-downs, changes in market demand, etc. Such deviations from nominal conditions may in some cases be planned or unplanned deviations. For planned deviations, a heat exchanger network, which is capable of handling multiple periods of operations should be designed. In this context, the degree of deviations is known upfront. For unplanned deviations, uncertainties surround the extent to which process parameters would shift from the nominal values, hence a flexible network should be designed. It is worth stating that most of the methods which were originally developed for single period heat exchanger network synthesis (HENS) problems have been extended to multi-period and flexible heat exchanger network scenarios (Papalexandri and Pistikopoulos, 1994; Aaltola, 2003; Chen and Hung, 2004; Chen and Hung, 2007; Verheyen and Zhang, 2006; Isafiade and Fraser, 2010). Stochastic based optimisation methods have also found applications in the area of multi-period HENS (Ma et al., 2007; Ahmad et al., 2012). In this paper, a new approach for designing HENs involving multiple periods of operations is presented. Hence, previous methods which have been developed for multi-period operations are reviewed in the next section.

2. Synthesis of multi-period HENS

Floudas and Grossmann (1986) presented the multi-period HENS problem statement in the following form:

Given a set H of hot process streams and a set C of cold process streams which have to be cooled and heated respectively. Given also are the supply and target temperatures and the flowrates of these streams at P periods of operation. Hot and cold utilities are also available at each period of operation. The task is to synthesise a heat exchanger network which is optimally operable for the finite set of P periods of operation.

Various methods have been applied to the synthesis of multi-period HENs. These techniques have been sequential and simultaneous in nature. In most cases, both approaches have involved extending the techniques developed for single periods HENs problems to handle multi-period HENs. The sequential methods have chiefly been based on the automated versions of pinch technology, such as the technique developed by Papoulias and Grossmann (1983) for single period HENs. This is based on the transhipment model and it entails establishing the minimum utility and minimum number of heat exchangers required in a network through the use of linear programming (LP) and mixed integer linear programming (MILP), respectively. Floudas and Grossmann (1986) extended this method to multi-period HENs where the minimum utility required for each period of operation, as well as the minimum number of units for the network are targeted. The automatic generation of minimum investment cost networks for the single period transhipment model energy and number of unit targets was developed by Floudas et al. (1986), through the use of a non-linear programming (NLP) model. This automatic network generation step for single period was also extended to handle multiple periods of operations by Floudas and Grossmann (1987). It is worth mentioning that this multi-period LP–MILP–NLP model, which still involves decomposition of the problem into above and below the pinch regions, are fraught with shortcomings similar to those of pinch technology.

Under the simultaneous approach, Aaltola (2003) extended the MINLP SWS model of Yee and Grossman (1990) to handle multi-period HENs problems. Aaltola's method is such that modelling of bypasses is excluded, hence non-linear heat balances and its associated parameters such as binary variables, temperature and flow variables are eliminated. A key feature of this model is the approach used for initialisation in order to obtain optimal solutions. The hot utility required in each period p, is given an upper bound. This upper bound value is determined through the use of the LP transhipment model of Papoulias and Grossmann (1983). Verheyen and Zhang (2006) extended the work of Aaltola (2003) by using a maximum area approach in the multi-period objective function. The aim of this approach is to overcome the shortcomings associated with the average area used in the objective function by Aaltola (2003). The maximum area approach implies that, the heat exchange areas for the same pair of stream matches existing in different periods are compared in the optimisation process, and the largest is chosen as the representative heat exchanger for these pair of stream matches in the final multi-period network. According to Verheyen and Zhang, the maximum area approach is different from the average area method used by Aaltola (2003), in that in the average area approach, the representative heat exchanger is the unit having a size which is the average of all exchangers connecting the same pair of streams in different periods of operations.

Another simultaneous based multi-period HENs synthesis method presented in the literature is that developed by Isafiade and Fraser (2010). In this approach, the authors used the multi-period version of the interval based MINLP superstructure (IBMS) model. The intervals of this superstructure are defined by the supply and target temperatures of either the rich or lean set of streams participating in the problem. This method also used the maximum area approach as presented by Verheyen and Zhang (2006). It is worth mentioning that the objective function of the multi-period IBMS is such that unequal period durations can be adequately handled. This is unlike the approach used by Aaltola (2003) and Verheyen and Zhang (2006) where accurate values are only obtained in the objective function when the duration of periods are equal.

Sadeli and Chang (2012) also adapted the SWS model of Yee and Grossman (1990), to the synthesis of multi-period HENs. The authors extended the work of Verheyen and Zhang (2006) by including some set of time sharing heuristics. Sadeli and Chang (2012) identified a key shortcoming of the previous methods where the maximum area approach was used. According to these authors, there may be cases where there exists a significant difference between the area of the representative heat exchanger (having a maximum area) and actual individual areas for the same pair of streams existing in different periods. This overdesign, according to Sadeli and Chang (2012), may result in inefficient operation by such exchangers. The authors overcame the aforementioned shortcoming by including in each potential heat exchanger for every pair of streams, the F_T correction factors. Further, the authors prescribed four sets of heuristic based rules that can be used to determine an optimal set of representative heat exchangers. The first rule entails dividing the set of matches into two separate groups and identifying time sharing opportunities within