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Synthesis of multi-period heat exchanger networks based on features of sub-period durations

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ABSTRACT

In this work, a representative sub-period method is proposed for synthesis of multi-period heat exchanger networks (HENs). For the multi-period HENs with a large number and significantly different durations of sub-periods, the sub-period with the longest duration is taken as the representative sub-period. The cost-effective HEN structure in this representative sub-period can be obtained by solving the single-period HEN synthesis problems, and the operational parameters are then optimized to meet the requirements of other non-representative sub-periods on the fixed HEN structure achieved by the former step. In particular, for synthesis of multi-period of HENs with similar durations of sub-periods, a simplified model method is also proposed. In this method, the multi-period HENs are finalized by introducing the commonly shared heat exchangers in the multi-period HENs model. Both of the proposed methods avoid directly solving the multi-period HEN model, and hence the computational loads are reduced. An industrial case study for the synthesis of multi-period HENs is carried out to illustrate the procedure of the proposed methods. The effectiveness and advantages of the proposed methods are demonstrated by the comparison with the results obtained by the methods in literature. The effects of period duration on the cost-effectiveness of the multi-period HENs are discussed and highlighted.

1. Introduction

Synthesis of heat exchanger network (HEN) has been one of the most important research fields in process industries because it enables rational utilization of energy and substantially improve the economic and environmental efficiencies of production plants [1]. The methods for systematic synthesis of HEN range from sequential pinch analysis to simultaneous HEN synthesis [2]. In recent, these methods have been extended to the total site heat integration [3], multi-plant heat integration [4] and heat integration for process modification [5].

The synthesis of multi-period HEN becomes extremely challenging due to the fact that the HEN undergoes multiple operations under various conditions [6], which is commonly solved by either sequential methods or simultaneous ones. Floudas and Grossmann [7] pioneered a sequential procedure for synthesis of the flexible HENs, aiming at minimizing the utility costs of each sub-period and the total number of heat transfer units. Papoulias and Grossmann [8] proposed a mixed integer linear programming (MILP) transshipment model to obtain the configuration of multi-period HENs that possesses the fewest heat exchanger units and incurs the minimum utility cost for each sub-period. However, the HEN configurations with larger number of heat transfer units but lower total annual cost (TAC) are neglected. As an extension of this work, a superstructure-based automatic generation of HENs for multi-period operations [9] and a systematic method for the synthesis of HENs with specified variations in uncertain parameters [10] were further developed. Konukman et al. [11] adopted this superstructure to present an optimization model for the synthesis of a flexible HEN aiming at minimum utility demand. However, these methods may lead to sub-optimal solutions as the energy consumption and capital investment are individually optimized [12].

In principle, the shortcomings of the sequential methods can be overcome by the simultaneous methods, and better solutions can be obtained. Aaltola [13] proposed a simultaneous model and corresponding solution strategy for synthesis of the multi-period HENs based on the stage-wise superstructure model [14]. In Aaltola's method, a cost-effective HEN configuration was achieved by

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solving the multi-period simultaneous mixed-integer nonlinear programing (MINLP) model. The NLP formula of the multi-period HENs was then employed to improve the operational parameters by fixing the structure obtained in previous stage. Nevertheless, the assumptions of average areas in the objective function may underestimate the capital investment and the TAC of the multi-period HENs. To solve these problems, Verheyen and Zhang [15] introduced the maximum area of each sub-period in the calculation of area cost and removed the unnecessary variables from the existing NLP model. This model has been further extended by including the multi-stream heat exchangers [16], fluctuations in utility prices [17] and unequal period durations [18]. However, when the problem scale or the number of operational periods increases, this MINLP model will become extremely complicated and difficult to solve [19]. Thus, the problems of the multi-period HENs synthesis are usually solved in a stepwise manner.

Chen and Huang [20] proposed a three-step iterative procedure to solve the problems of the multi-period HEN synthesis. In the first step, a candidate HEN with the lowest cost is achieved by solving the simplified multi-period model that involves few number of operation periods. A flexibility tests step is used to obtain a qualified structure, and an integer cuts step is employed to eliminate the undesired HEN configurations. This procedure was later simplified by using a simulation-based method [21] to realize the flexibility tests instead of the model-based method. To further simplify the synthesis process, Li et al. [22] presented a two-step approach for the synthesis of flexible HENs. The HEN structure is synthesized at the nominal operation point, and it is updated by the improved heat transfer loops disconnection strategy. The area optimization is carried out via an iterative approach. Ma et al. [16] also proposed a two-step strategy to integrate the multi-period HENs. In their method, an over-designed multi-period HEN is obtained by using the temperature-enthalpy (T-H) diagram method, and the over-designed parameters are then improved. This method can effectively reduce the number of decision variables in the multi-period HEN model in the first stage. However, in the second stage, the TAC of HEN in each individual sub-period is obtained by simulations of multi-period HEN, which are certainly time-consuming [16].

To decrease the computational loads and time, Escobar et al. [23] proposed an evolutionary algorithm based on Lagrangean decomposition. The design variables are selected in the first step, and the control variables are adjusted in the second step according to uncertainty parameters. The resulting HEN design ensured that the streams achieved the desired temperatures. However, the optimality of solutions cannot be always guaranteed because the feasible solutions are heuristically constructed. Jiang and Chang [12] proposed an approach for multi-period HEN synthesis with timesharing mechanisms, and a corresponding algorithm was also developed to design the multi-period HEN automatically [24]. In their proposed method, a single-period model is solved to produce the optimal design for each sub-period. A timesharing mechanism is then applied to integrate all single period designs. In this way, the overall capital investment of the HEN is reduced and the utility consumption in each sub-period is kept at its minimum. This procedure also reduces the complexity of the simultaneous optimization models. However, the final HEN structure obtained by this method can only be treated as a preliminary design due to the structure complexity.

To reduce the complexity of the resulting HEN, Isafiade and Fraser [25] modified the multi-period model proposed by Verheyen and Zhang [15] by optimizing a reduced superstructure generated from promising set of matches. The promising matches is identified by selecting the best two or three of networks obtained by solving the multi-period HEN model in different minimum temperature differences and different number of stages. Then, a reduced multi-period MINLP model is established by using the promising matches as the binary variables. The results indicated that the introduction of the promising matches to multi-period HEN model can facilitate the solution generation and obtain a better solution.

Based on the discussion above, it can be seen that the synthesis of multi-period HEN on the basis of the optimization of the single period HENs helps to reduce computational complexity. The promising stream matches can be introduced to simplify the model and facilitate the solution generation. However, the determination of the promising matches lacks of explicit criteria. In addition, although some researchers have mentioned or solved the multi-period HENs problem with unequal period durations, none of them take the characteristics of sub-periods into consideration. The effects of period characteristics on the design of multi-period HENs are also unclear.

In this paper, a representative sub-period method and a simplified model method are developed to facilitate the synthesis of multi-period HEN by considering the characteristics of the sub-periods. In the proposed methods, the single period model of HEN is employed to reduce the computational efforts and the promising matches are introduced to enhance the solution generation. The rest of this paper is organized as follows. The problem statement is present in Section 2, followed by the procedure of the proposed methods for the synthesis of multi-period HENs in Section 3. In Section 4, a case study of multi-period HEN synthesis is carried out to demonstrate the effectiveness of the proposed methods. The effects of sub-periods characteristics on the design of multi-period HENs are analyzed and discussed in Section 5. The conclusions are drawn in Section 6.

2. Problem statement

This work focuses mainly on the synthesis of multi-period HENs on the basis of characteristics of sub-periods. In contrast to the previous studies, the proposed methods address the influences of the number of sub-periods and the period duration variation on the cost-effective design of the multi-period HENs.

The problem of the synthesis of multi-period HENs by considering the characteristics of sub-periods can be stated as follows. Given are (1) operational conditions of each sub-period, including supply and target temperatures, heat capacity flow rates, heat transfer coefficients of hot and cold streams; (2) parameters of utility supplied, such as inlet and outlet temperatures of utilities, and annual costs of utilities in each sub-period; (3) cost coefficients of heat transfer units, including the fixed cost coefficients, area cost coefficients and area cost exponents of heat exchangers, heaters and coolers. The main objective of this work is to obtain a cost-effective design of multi-period HEN by using the proposed methods, which aim to overcome the difficulties associated with obtaining good solutions of multi-period HEN synthesis.

3. Two methods for synthesis of multi-period HENs

In this section, two stepwise methods for the synthesis of the multi-period HENs, i.e., the representative sub-period method and the simplified model method, are proposed and illustrated.

Fig. 1 shows the procedure of a multi-period HEN synthesis by considering the characteristics of sub-periods. As shown in Fig. 1, both of these two methods are based on the optimization of single period HENs [14]. One of them can be used according to the characteristics of sub-periods. Fig. 1 also shows that only the structure information of the HENs in sub-periods is required to simplify the synthesis process. It should be noted that the minimum temperature differences of HENs in each sub-period are simultaneously optimized.