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Research paper

Efficient simultaneous synthesis for heat exchanger network with simulated annealing algorithm

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HIGHLIGHTS

- A two-level SA algorithm is developed to solve HENS problems.
- A flexible utility placement is presented to substitute infeasible matches.
- Two novel probability models are proposed to generate candidate structures.
- Two most economical networks with no splits are solved by the proposed method.

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ABSTRACT

The simultaneous synthesis of heat exchanger network is primarily regarded as mixed integer nonlinear programming models and its combinatorial nature can easily lead to a suboptimal network design and unmanageable computational effort. Based on simulated annealing algorithm, this paper presents an efficient simultaneous synthesis method that provides the optimal networks in a two-level procedure. Two probability models are proposed to generate candidate structures by random perturbations in the upper level. The minimum total annualized cost of each candidate structure is solved in the lower level and then sent to the upper level where different structures are evaluated by simulated annealing mechanism. This two-level method is applied to solve four benchmark cases of heat exchanger network synthesis and the computational results show that satisfactory heat exchanger network designs can be guaranteed with reasonable cooling schedules and two most economical networks with no splits are solved for case 1 and case 3.

1. Introduction

Heat exchanger network synthesis (HENS) is one of the most studied problems for its significant impact on energy and cost saving in chemical and petrochemical industry. The objective of HENS is to design a heat exchanger network that minimizes total annualized cost (TAC) as the sum of annualized investment cost and annual operating cost with the given sets of hot/cold streams and utilities. In the past 50 years, many algorithms based on sequential or simultaneous synthesis models have been developed to obtain the optimal energy or cost effective network.

The sequential methods usually divide the HENS problem into a series of subproblems to reduce the computational requirements. Generally, these three subproblems of the minimum utilities, the minimum number of matches and the minimum cost network are solved sequentially. Pinch analysis [1,2] is probably the best known sequential method considering the laws of thermodynamics. The maximum heat recovery can be guaranteed by identifying the heat recovery approach temperature (HRAT) and dividing the corresponding temperature intervals. This concept demonstrates excellent efficiency and applicability in many process synthesis problems [3–5]. Based on the mathematical programming theory, Cerda et al. [6,7] and Papoulias et al. [8] solved the minimum utilities and the minimum number of matches problems respectively with Transportation model and Transshipment model. These two subproblems were formulated as a linear programming (LP) and a mixed integer linear programming (MILP) model. Subsequently, Floudas [9] developed a nonlinear programming (NLP)

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model for the minimum cost network subject to the heat load distribution and matches derived form the previous two subproblems. More sequential methods were also proposed by other researchers [10–12]. The limitation of sequential methods is that the three-way trade-off between different costs cannot be accounted for accurately, which can often lead to a suboptimal network design. The HEN simultaneous synthesis is primarily formulated as a mixed integer nonlinear programming (MINLP) problem and also a complex task. To find the optimal networks, several simultaneous synthesis models have also been developed. The hyperstructure model proposed by Floudas and Ciric [13] can simultaneously minimize the costs of heat exchange units and areas by combining the Transshipment model [8] and the network topology 'hyperstructure' presented in their NLP model [9]. However, the HRAT still needs to be specified previously until the minimum utilities subproblem was incorporated into the model in a further modified work [14]. Yee and Grossmann [15,16] proposed a stage-wise superstructure (SWS) model that can accomplish simultaneous synthesis of the selection of matches, utility and area cost. The representation of stage-wise superstructure can include possible stream splits and possible matches among all streams in each stage, and the simplifying assumptions of isothermal mixing, no split stream flowing through more than one exchanger and no stream bypass make the constraint equations defining the feasible region all linear. However, Furman and Sahinidis [17] have proven that the simultaneous synthesis problem of HEN is actually NP-hard in the strong sense and hence it is not known if there exists computationally efficient (polynomial) exact solution algorithm for this problem. Increasing problem size can lead to substantial computational task as well and global optimal network designs are hard to obtain in even small cases. Therefore, more approximation techniques and stochastic algorithms are introduced to tackle such problems.

Due to the nonconvex terms for calculating heat exchanger areas and cost, the common deterministic global optimization methods such as generalized Benders decomposition (GBD), the branch and bound (BB) and outer approximation (OA) for MINLP problems may easily be trapped at local optimal solutions. Zamora and Grossmann [18,19] proposed a hybrid BB/OA algorithm under the simplifying assumptions of linear/nonlinear area cost functions and no stream split. Adjiman et al. [20,21] applied a α-based branch and bound (αBB) for solving HENS problem under the assumptions of linear area cost functions. Björk and Westerlund [22] solved the problem by signomial terms convexification and creating approximate convexified subproblems. Bergamini et al. [23,24] presented a OA algorithm combining piecewise underestimators of nonconvex terms and constraints from physical insights. A recent attempt proposed by Bogataj and Kravanja [25] introduced a concept of a stage-wise superstructure augmented by an aggregated substructure and applied a modified outer approximation/equality relaxation (OA/ER) algorithm to obtain global optimal solutions. However, most of these deterministic methods face significant difficulty in case of large nonconvex MINLP problems [26]. Usually, stochastic algorithms can deal with the large-scale problems more efficiently. This kind of algorithms is not limited by the non-linearity, the nonconvexity and the discontinuity of the models. The randomized algorithms without/with stream splits were developed for design of HENs although they failed to converge to the global optimum [27–29]. It is worth noticing that the synthesis of cost optimal heat exchanger network is basically a combinatorial optimization problem, which objective is to find out a specified structure and heat distribution with optimal TAC. Lewin et al. [30,31] applied genetic algorithm (GA) respectively to determine the structure of HEN and heat loads of units. Another contribution of their work is to introduce the concept of 'HEN level' for structure representation which was then used in a two-level synthesis method of HENs combining harmony search (HS) and sequential quadratic programming (SQP) [32]. Yerramsetty and Murty [33] proposed a differential evolution (DE) algorithm for the synthesis of HENs and also utilized the structure representation similar to 'HEN level'. Silva et al. [34] and Huo et al. [35] respectively presented a particle swarm optimization (PSO) method and a GA/PSO algorithm for finding cost optimal network. Although these methods incorporating stochastic technique are robust and can easily find a suboptimal network within reasonable time, they still have the difficulty in converging to the precise global optimal solution in the feasible region.

Despite of substantial achievements of various methods in HENS, some serious problems may still plague the existing mathematical algorithms. The combinatorial nature of HENS problem can easily lead to a suboptimal solution and unmanageable computational effort. Even for a small-scale network, there exist a large number of possible structures and it is almost impossible to find out its global optimum. Since computational efficiency and precision are often regarded as two fundamental criterions, the motivation of this paper is to explore a novel simultaneous synthesis method of HEN that can find out satisfactory network designs with acceptable computational effort. In this paper, an efficient two-level synthesis strategy of cost-optimal HEN design using simulated annealing (SA) algorithm is presented. Simulated annealing algorithm was firstly introduced to network design by Dolan et al. [36] and Athier et al. [37] developed a hybrid algorithm based on SA to tackle industrial HENS problems. However, for the reason that simulated annealing algorithm is usually regarded as a high computational cost algorithm, more attentions have been paid to another stochastic algorithm GA when evaluating structures of HEN in two-level methods [30–33,38]. Compared with NLP subproblems, it is much more difficult to find out optimal structures especially for large-scale networks with substantial possible matches. Since simulated annealing algorithm has been proven to a powerful technique for large-scale combinatorial optimization [39], its potential to solve the discrete problems of HENS is investigated in this paper. A flexible utility placement which permits to substitute infeasible matches with utilities is proposed and two novel probability models are used to generate candidate structures.

The rest of this paper is organized as follows. In Section 2, the mathematical formulation of HENS is presented. Section 3 describes the proposed two-level synthesis method in detail. Section 4 demonstrates the application of this synthesis method to four HENS cases and finally conclusions are summarized in Section 5.

2. Mathematical formulation

The HENS problem was first rigorously defined by Masso and Rudd [40] and its objective is to design a optimal energy or cost effective heat exchanger network under the following requirements:

a) a set N_H of hot streams to be cooled from the inlet temperatures to the outlet temperatures,
b) a set N_C of cold streams to be heated from the inlet temperatures to the outlet temperatures,
c) the utilities available, heat capacity for each stream and cost data for calculating TAC.

Section 2 presents the mathematical formulation solved by the two-level simultaneous synthesis method in this paper. A modified structure representation based on the stage-wise structure