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Synthesis of large-scale multi-stream heat exchanger networks using a stepwise optimization method

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ABSTRACT

In this paper, an efficient stepwise approach is presented for synthesizing large-scale multi-stream heat exchanger networks (MSHENs). The proposed approach employs the pseudo-temperature enthalpy diagram method to gain an initial network. In the next stage, several heuristic strategies are raised to conduct the selection and mergence of enthalpy intervals. The sub-networks are re-designed in the merged intervals based on the introduced strategies to disconnect the heat exchanger loops caused by involving too many intervals in the initial networks. A corresponding mathematical model is established with the objective of minimum total annual cost (TAC), and the simulated annealing and genetic algorithm (SA/GA) is adopted for the optimization. Two cases taken from literatures are studied to illustrate the effectiveness of the proposed method on solving MSHEN synthesis problems. The results obtained are better than those of previous paper and have shown an excellent performance of the multi-stream heat exchanger.

1. Introduction

Synthesis of heat exchanger network (HEN) has been widely studied because of the increasing concern about the efficiency of energy utilization and heat recovery technologies. A significant amount of papers on the subject has been published in the last few decades. However, few of them have focused on a large-scale problem. In fact, in most plants, such as refineries, the amount of the streams to be heated up and cooled down could be up to 100 [1], and usually when the number of the streams contained in the HEN is more than 40, it can be categorized as a large-scale problem [2]. So, it is absolutely necessary to develop a method that can handle large-scale HENs efficiently.

The conventional methods for synthesizing HEN always have their respective deficiency while confronting large-scale problems. The pinch analysis method [3–5] is a famous HEN synthesis method, and it is one of the most widely used techniques in process industry because it has good adaptability to real plant situations. It divides a HEN at its pinch point into two sub-networks which are designed separately using the heuristics. Nevertheless, in the pinch analysis method, the optimization is always achieved in the followings sequence: the maximum heat recovery and the minimum number of heat exchanger units, and by this means it realizes the minimum cost of the HEN. However, it cannot offer a real global optimal solution such as the total annual cost (TAC). This defect could be more obvious for large-scale problems.

The mathematical programming method is another well-known kind of HEN synthesis method. Many mathematical models have been proposed, such as the two-stage superstructure by Yee and Grossmann [6] and the transportation model by Papoulias and Grossmann [7]. In the mathematical programming method, the synthesis of heat exchanger network is usually treated as a Mixed-Integer Non-Linear Programming (MINLP) problem [8–11]. This method contains rigorous logic and can obtain the optimal solution theoretically, but the complexity of calculation grows exponentially with the scale of the problem, which makes the solving almost impossible for a large-scale problem. Most of the proposed methods resolve this problem by introducing simplifying assumptions such as the linearization. But these mainly affect the topological features of the candidate solutions and thus artificially limit the boundaries of the search space [12]. As a result, this will make the solution far away from the global optimum one.

The stochastic or meta-heuristic optimization methods such as genetic algorithm (GA), simulated annealing (SA) were used for synthesizing HEN during recent years [13–16]. These methods show some special advantages compared to the traditional ones. They are suitable for complex spaces and since they do not use gradient for solving, the goal function can be nonlinear and non-continuous. As a result, some complex design task [17–19] such as the HEN synthesis with exchanger details can be completed with

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Nomenclature

A	heat transfer area, m^2
a	cost per unit heat transfer area, \$ m^{-2}
C_b	branch coefficient
C_{CU}	cold utility cost per unit duty, \$ kW^{-1} y^{-1}
C_{EX}	cost of heat exchanger, \$ y^{-1}
C_{HU}	hot utility cost per unit duty, \$ kW^{-1} y^{-1}
C_T	total annual cost, \$ y^{-1}
f	fitness value
Fcp	heat capacity flow rate, kW K^{-1}
h	heat transfer film coefficient, kW m^{-2} K^{-1}
HI	enthalpy interval
m_i	element i in merge array
N_{EX}	number of heat exchangers
N_C	number of cold streams
N_H	number of hot streams
Q	heat load of a heat transfer process, kW
Qc	the sum of enthalpy values of cold common streams, kW
Q_{CU}	quantity of cold utility, MW
$Q_{CU,i}$	the cold utility used by hot common stream i, kW
Qh	the sum of enthalpy values of hot common streams, kW
Q_{HU}	quantity of hot utility, MW
$Q_{HU,j}$	the hot utility used by cold common stream j, kW
dQ	absolute value of the difference between the sum of enthalpy values of cold common streams and that of hot common streams, kW
R_b	ratio of the flow rates of the branch to that of the original stream
S	stream
S_s	stream selected to be split
t	annealing temperature
T_{TM}	thermodynamic mean temperature, K
T_i^P	pseudo temperature of stream i, K
ΔT_c^i	temperature difference contribution value of stream i, K
U	heat transfer coefficient, kW m^{-2} K^{-1}
α,β,γ	coefficients in heat exchanger cost function

Subscripts

b	branch of a stream
C	cold stream
CU	cold utility
H	hot stream
HU	hot utility
i	hot/cold stream index
in	inlet
j	hot/cold stream index
k	heat exchanger index
out	outlet

these methods. Besides, there is no need for a suitable initial guess and both of the solution time and the required memory are less than those in mathematical methods.

The HEN synthesis has been proved as an NP-hard problem by Furman and Sahinidis [20]. Therefore, for solving the large-scale problems, the development of non-rigorous approximating algorithms, which should balance the solution optimization and computational time, is necessary. Wang *et al.* [21] developed a new superstructure MINLP model for large-scale HEN synthesis and solved it by genetic algorithm. However, their method still costs too much time and can only deal with the problem without stream splitting which makes solving easier. Björk and Nordman [22] introduced a mathematical optimization procedure which is achieved through a hybrid optimization framework. The genetic algorithm is used for decomposing the original problem into several subproblems, after which a deterministic optimization method (a MINLP solver) optimizes the design and operational conditions within the subproblem. Pettersson [2] studied a 39 streams problem with a sequential match reduction approach which solved four different subproblems in order to result in a close to optimal design. The approach reduced the problem into manageable sized design tasks. Fieg *et al.* [1] proposed a monogenetic algorithm based on the optimization of sub-networks. The functional groups (sub-networks) are found in the first step of optimization with the hybrid genetic algorithm, and then the monogenetic algorithm for evolution of them is carried out to improve the HEN. Xiao *et al.* [23] introduced pseudo-temperature enthalpy diagram method based on pinch analysis. Compared with the pinch analysis method, this one considers the influence of heat transfer coefficient and cost per area of corresponding heat exchanger by treating heat transfer temperature difference contribution values of each stream as optimization variables, which can offer an optimal solution of TAC by integrating the heat recovery with the capital of units. Due to the small amount of optimization variables, this method could synthesize a HEN effectively, but it can rarely obtain the optimum solution because the match rules in this method seriously reduce the diversity of network configuration. Li *et al.* [24] suggested a combined method which divides the initial network obtained by the pseudo-temperature enthalpy diagram method into several sub-networks synthesized with a two-stage superstructure respectively. Brandt *et al.* [25] proposed a method based on a hybrid genetic algorithm. It uses sub-networks in order to improve the resulting network structures and the calculation time. All the above methods seem promising to handle the large-scale HEN problems, however their computational times or the solutions are not so satisfactory.

In addition, multi-stream heat exchangers are more and more commonly used in industrial practice due to its advantages such as higher efficiency, more compact structure and lower cost [26,27]. As a result, this area has attracted researchers recently [28]. The advantages would be more visible in a large-scale network [23,24], so the multi-stream heat exchangers are employed in this study. The multi-stream heat exchanger can be generally divided into two categories based on its structure: multi-channel heat exchanger and plate-fin heat exchanger [29]. The former one can handle one cold stream and two or more hot streams or vice versa, called one vs. more multi-stream heat exchanger, while the latter one can handle both more than two cold streams and hot streams, called more vs. more multi-stream heat exchanger here. Only one vs. more multi-stream heat exchanger is used here according to the industry situation of the case, and a simplified model is presented to make it adaptive to a HEN synthesis. More vs. more multi-stream heat exchanger can be obtained by a further reorganization.

In this study, a novel stepwise method is proposed for solving the large-scale problem using multi-stream heat exchangers. The present method chooses the pseudo-temperature enthalpy diagram method to generate the initial network because of its higher computational efficiency. Then the merge array is introduced to determine the selection and mergence of enthalpy intervals. Each merged interval can be regarded as a sub-network. The streams in each sub-network are divided into common streams and uncommon ones and are matched respectively, where the strategies of generating heat exchangers are retrofitted, compared to the