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Synthesis of heat exchanger networks using genetic algorithms

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Abstract

This paper presents a methodology for carrying out both the synthesis and the optimization of heat exchanger networks (HEN) based on a genetic algorithm (GA) technique. The proposed methodology allows the topology of the HEN and the heat load distribution that satisfy an energy target to be obtained from a single pass calculation. The technique is characterized by a high reliability in determining the best HEN structure. In addition, it also allows the generation of several HEN configurations to be obtained; thus, a best HEN selection in accordance to a given application can be easily achieved. The proposed approach permits the HEN topology to be obtained only if flow stream divisions are avoided. The simplicity of the proposed procedure makes this technique useful when a fast solution of a problem is looked for. The validation of the algorithm is carried out by solving benchmark tests taken from the open literature. In all the cases studied, the results compare quite well with those given in the open literature.

Keywords: Heat exchanger networks; Optimization; Energy recovery; Genetic algorithms

1. Introduction

The synthesis of a HEN is usually a very complex task that implies a combinatory problem for matching hot and cold flow streams in order to permit a maximum energy recovery to be achieved. In general, the HEN synthesis process can be summarized as follows:

A set of hot flow streams must be cooled to specific temperature values, while another set of cold flow streams must be heated up to determined values. Each flow stream is characterized by its own specific heat capacity and mass flow velocity. Thus, the problem to be solved consists in finding the optimal topology (i.e., heat exchanger structure) of a HEN having the most appropriate heat load distribution in such a way that the maximum thermal power can be transferred between the flow streams. It is obvious that the optimization process also must reduce the number of external utilities (i.e., heat sources and sinks). Therefore, the synthesis of the optimal HEN requires working in two different "solution spaces":

(a) a *topological space* where, according to the nature of the interaction between the flow streams different structures are possible and
(a) a *thermal load space* where different thermal power distributions between heat exchangers are possible.

Thus, the optimization process consists in simultaneously finding the HEN topology and the heat load distribution that permits a maximum energy recovery to be satisfied without violating thermodynamics principles. In most of the works carried out on this subject, the topology and the thermal power distributions are treated separately. The technique proposed in this paper allows the aforementioned two processes to be simultaneously handled by using a genetic algorithm (GA).

The research work in this area have been essentially developed according to three different concepts: the pinch method that is based on thermodynamic principles [1];

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the use of mathematical methods [2–4] and the methods based on the use of artificial intelligence first used among others by Grimes et al. [5]. One of the most important concepts used in the first method cited above consists of constructing heat load composite curves. These curves provide detailed information on the energy recovery, the minimum heating and cooling power required by the whole process as a function of a minimum temperature admissible across the heat exchangers. Consequently, these curves permit the overall thermal power in conjunction with the heat transfer surface required by the process, to be determined. The pinch technology, successfully used in a great number of industrial applications, requires two steps [1]; first it targets the maximum energy recovery, and then it synthesizes the heat exchangers network. This method supposes that the flow streams, the supply temperatures and the flow heat capacities are known. Even though, this technique is based on thermodynamic principles, it also uses several heuristic rules. These heuristic rules constitute the major disadvantage of this method, because they are based on approximations which are sometimes difficult to validate. Moreover, in some cases, the application of the pinch method may be quite lengthy and cumbersome. Even though, the rules used for matching the hot and cool flow streams are simple, finding an initial network design is usually a very difficult task. The decomposition in two pinch sub-systems, limits the evolution of the design because it becomes conditioned by the initial halved design [6]. These limitations have motivated the search of more efficient mathematical techniques for handling HEN optimization problems.

In general, a mathematical modeling technique consists in an ensemble of equality and inequality equations that must satisfy the minimization of an objective function. The resulting system of equations can be written under the following general form:

$$\begin{aligned}&\text{Objective function to be minimized:}\quad f(X,Y),\\&\text{Constrained equations:}\quad g(X,Y)\geqslant 0,\ \ h(X,Y)=0,\end{aligned}\tag{1}$$

where $X \in R^n$ and $Y \in [0,1]^m$. Note that X and Y are vectors of variables while g and h are vectors of functions. For the case where there are no binary variables (i.e., $\dim(Y) = 0$), and the f, g and h are linear functions, the mathematical problem is reduced to the simplest case, that is a "Linear Programming" (LP) system. If the model includes binary variables (i.e., $\dim(Y) \neq 0$) and f, g, and h are linear functions, the problem is of the "Mixed Integer Linear Programming" (MILP) type. For the synthesis and optimization (maximum energy recovery) of a HEN without flow stream division then, the optimization problem is of the MILP type.

However, the applicability of this technique requires two questions to be addressed simultaneously. The first one concerns the solution of an integer problem that results from the discretization of the temperatures and enthalpies. It is important to remark that moderate size networks may require a large number of intervals; thus, resulting in very large linear system of equations to be solved. The second question concerns the parametric optimization itself that usually is handled by another mathematical solver, such as the Simplex technique. Duran and Grossmann [7] have proposed a method that optimizes simultaneously the process as well as the heat exchanger network. In this method, the flow streams, as well as the supply and target temperatures of the flow are not imposed, but they result from the optimization process itself. This method also permits the minimum approach temperature to be determined. A MILP model is then used to synthesize the optimal heat exchanger network for the maximal heat recovery, by using the minimum number of utility units. In order to reduce the size of the system of equations, different approaches have been proposed such as: the use of the stage concept [8] and the use of the block concept [9]. Even thought, the use of the aforementioned techniques can help in reducing the size of the problem to be handled, some industrial applications can still produce quite large optimization schemes that cannot be easily solved.

Recently, new stochastic methods based on GA's have been successfully used in several engineering applications. The strategy of these algorithms is founded on the principle of natural evolution as postulated for the biological spices, where a large number of possible solutions can be handled. This is in contrast to classic mathematical methods that converge through a solution by evaluating the local gradient of the functions. According to the authors' knowledge, only few works have been published where the GA have been used for synthesizing a process including HEN, starting from pre-established known topologies [10]. In some cases the GA were used to find the optimal heat exchange topologies while other methods were used for obtaining the parametric optimization [11]. Similarly, Lewin et al. [12] have proposed a procedure based on the use of GA's for the optimization of the heat exchanger topology from a compact and constant representation of the HEN. This representation is used for both, satisfying the requirements of the GA itself and for carrying out the parametric optimization. Recently, Ravagnani et al. [13] have used GAs for synthesizing HENs based on a previous optimization of the network pinch temperature that permitted the authors to determine the optimal power of the utilities. A design methodology of HEN including flow stream splitting based on the use of a randomized algorithm was developed by Pariyani et al. [14]). In these two works, the authors have used the decomposition technique across the HEN pinch point for carrying out the synthesis of HENs. Thereafter, each sub-network is optimized separately by using evolutionary algorithms. It is important to remark, however, that in both cases the best HEN solution cannot be achieved without some external intervention of the user.

The method presented in this paper, however, assumes that the flow streams are completely defined including supply and target temperatures, minimum approach temperatures and flow heat capacities. We use the table algorithm