Applied Thermal Engineering 87 (2015) 371–380

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

Heat exchanger optimized design compared with installed industrial solutions

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HIGHLIGHTS

- Exchangers designed with commercial software and a genetic algorithm-optimizer are compared.
- Commercial software tools for design of shell & tube heat exchangers may not provide optimal results.
- Optimization procedures better explore the design space respect computer aided manual design.
- In four case studies significant weight savings are obtained through GA optimized software tool.

ARTICLE INFO

Article history:
Received 27 December 2014
Accepted 8 May 2015
Available online 18 May 2015

Keywords:
Heat exchanger design
Genetic algorithm
Optimization

ABSTRACT

Commercial software tools for computer aided design of shell and tube heat exchangers are widely used in engineering departments of process plant equipment manufacturers. In this paper a comparison is carried out between actual installed heat exchangers, designed resorting to a leading commercial software tool, and the corresponding equipment configurations obtained by a genetic algorithm-based software tool, developed by the authors for optimal heat exchangers design. Reference is made to a set of four case studies representing exchangers built by a firm operating in the process plant construction sector and designed utilizing the commercial software tool. The corresponding design specifications are then used to redesign the heat exchangers resorting to the above mentioned research tool, and the resulting architectures are compared on the basis of equipment weight, assuming that this is the parameter used by manufacturers to estimate cost. Results show that the research tool, although characterized by a simpler user interface and reduced set of features, consistently delivers superior equipment architectures with significant weight reduction respect commercial solutions, allowing at the same time the compliance with thermal duty specifications. This case study analysis against installed benchmark equipment contributes to validate the developed optimization software tool and shows its capabilities of delivering less expensive heat exchanger designs.

1. Introduction

Design of a heat exchanger is an iterative process relying heavily on designer's experience. Usually a reference geometric configuration is chosen at first, and an allowable pressure drop value is fixed. Then heat exchanger structural features, i.e. the design variables, are chosen based on the design specifications and on assumption of several mechanical and thermodynamic parameters, in order to obtain a satisfactory heat exchange coefficient leading to a suitable utilization of the heat transfer surface. The procedure is then iterated until a reasonable design is obtained which meets specifications with a satisfying compromise between pressure drop and thermal exchange performances. A number of textbooks i.e. [20] or reference handbooks [18] are available to guide the designer in this process, while numerical examples are provided for instance by Kakaç et al. [19] for a range of exchanger types, or by Mukherjee [24] for shell and tube equipment.

Although well proven, this kind of approach is time-consuming and may not lead to a cost-effective design as no economic criteria are explicitly accounted for and no guarantee of the solution optimality is given. Considering the functional importance and

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http://dx.doi.org/10.1016/j.applthermaleng.2015.05.010
1359-4311/

widespread utilization of heat exchangers in process plants, their minimum cost design is, instead, an important goal. In particular, the minimization of energy related expenses is critical in the optic of energy savings and resources conservation, as well as in a life-cycle cost perspective. On the other hand, weight or surface area minimization is important when capital investment is to be reduced. In the literature, attempts to automate and optimize the heat exchanger design process have been proposed from a long time, and the problem is still the subject of ongoing research. The suggested approaches mainly vary in the choice of the objective function, in the number and kind of sizing parameters utilized, and in the numerical or analytical optimization method employed. Software packages are also available on the market to assist designers in developing satisfying equipment architectures in reasonable time, while some of them also include optimization features aimed at minimizing cost. Designers of engineering departments frequently turn to these commercial software producing one or more alternative heat exchanger design, and the final configuration is chosen on the basis of designer's experience.

On the other side, academic literature in recent times has shown a renewed interest in developing tools which automate the design process while seeking an optimized design. This corresponds to the availability of new optimization techniques, such as genetic algorithms (GA) and other evolutionary algorithms, able to handle a large number of design parameters including both discrete and continuous variables, without resorting to gradient-based methods, to efficiently explore a large solution space.

Tayal et al. [34] were among the first to suggest using GA in heat exchanger design optimization. However, they did not develop a design tool but rather a methodology based on a command procedure to run the HTRI commercial design program iteratively coupled to a GA or a Simulated Annealing optimization engine. Caputo et al. [6] developed a GA-based design optimization tool which is the basis of the one utilized in this work. Ponce-Ortega et al. [27] use a GA and the Bell–Delaware sizing method to minimize the total annual cost of shell-and-tube heat exchangers. Amini and Bazargan [1] as well as Sanaye and Hajabdollahi [31] adopt the ε-NTU approach for computing heat transfer rates and the Bell–Delaware procedure to size the heat exchanger, choosing design variables values resorting to a GA and exploring the Pareto frontier of efficiency vs total cost. They also perform parametric analysis to assess the role played by relevant design variables. Fettaka et al. [13] frame the GA-based design problem as a multi-objective optimization one, attempting to minimize simultaneously surface area and pumping power. Azad and Amidpour [3] and Yang at al [35]. utilize constructal theory to define an objective function which is then optimized resorting to GA. Guo et al. [14] use GA coupled with an objective function represented by the field synergy number which is defined as the indicator of the synergy between the velocity field and the heat flow. Guo et al. [15] use a GA to minimize an objective function representing the dimensionless entropy generation rate.

Apart from GA, a number of other evolutionary optimization techniques have been suggested to solve the shell-and-tube exchanger design problem. Babu and Munawar [4] use Differential Evolution (DE) algorithm to minimize the heat transfer area of shell-and-tube heat exchangers. Ravagnani et al. [30], Patel and Rao [26] and Lahiri et al. [21] adopt a Particle Swarm Optimization (PSO) method showing that it can be as effective as a GA. Mariani et al. [23] adopt a modified quantum particle swarm optimization (QPSO) method, named Zaslavskii chaotic map sequences (QPSOZ) to shell-and-tube heat exchanger optimization, showing that it could be superior to GA, PSO, and classical QPSO. Asadi et al. [2] approach the design optimization problem resorting to a so called Cuckoo-search-algorithm, which is shown to provide improved results respect a GA and PSO. Şahin et al. [32] instead use the Artificial Bee Colony (ABC) algorithm to minimize the total discounted cost of the equipment. Hadidi and Nazari [17] adopt the biogeography-based (BBO) algorithm which attempts to mimic population migration across diverse habitats and compare it to other evolutionary optimization techniques such as GA, PSO and ABC. Fesanghary et al. [12] use global sensitivity analysis (GSA) and harmony search algorithm (HSA) comparing the effectiveness of their approach to GA. Hadidi et al. [16] develop an economic optimization model based on imperialist competitive algorithm (ICA). Lahiri and Khalfe [22] instead adopt both hybrid DE and Ant Colony Optimization techniques. Rao and Patel [28] suggest using a Teaching-learning-based optimization (TLBO) method, which is an heuristic algorithm based on the natural phenomenon of teaching-learning process. They compare obtained results with those of GA.

Costa and Queiroz [11] develop a design algorithm using an iterative procedure to explore the design space where search is carried out along the tube count table where the established constraints and the investigated design candidates are employed to eliminate nonoptimal alternatives, thus reducing the number of rating runs executed. Surface area minimization was the stated design objective. Serna and Jiménez [33] develop an analytical procedure for heat exchanger optimization based on Bell–Delaware design method and a compact formulation that relates the shell-side pressure drop with the heat exchanger area and the heat transfer coefficient. Ravagnani and Caballero [29] as well as Onishi et al. [25] develop mixed-integer non-linear programming models to optimize shell-and-tube exchangers.

However, some scholars are skeptical about the use of precise optimization methods when applied to heat exchanger design, owing to the inherent fuzziness of the problem given the uncertainty in operating conditions and in the adopted design correlations [5]. Nevertheless, while from this point of view some studies considering heat exchangers operating under variable stochastic conditions have been developed [8] and [10], the utilization in industrial environment of design tools developed in research institutions for academic purposes is still limited.

Therefore, the aim of this paper is to explore in a realistic context the performances of a heat exchanger design optimization tool, developed for research purposes and available in the literature [6], by comparing the architecture of representative heat exchangers designed with this tool with those of corresponding heat exchangers designed by the engineering department of a process plant construction contractor resorting to a state of the art commercial software, and currently operating in process plants. In this manner the research tool can be validated utilizing actual equipment installed in process plants as a benchmark, and its capabilities in providing lower cost design can be assessed. The paper is organized as follows. At first a description of the adopted research tool for optimal design of shell-and-tube heat exchangers is described in brief. Then the design procedure utilized by commercial heat exchangers design packages is reviewed. Afterwards, a methodology for comparing in a consistent manner the results of the two design approaches is stated. Finally, four distinct case studies are examined and their results are discussed.

2. Reference research software tool

The design procedure used in this paper is described extensively in a previous work [6] where a detailed computer model has been developed for optimal design of shell-and-tube heat exchangers operating in stationary conditions and without uncertainties in heat transfer estimation. The tool is built on an optimization procedure based on GA and relies on equipment design procedures based on proven and widely accepted literature methods. The