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Research Paper

Design of heat exchangers using a novel multiobjective free search differential evolution paradigm

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HIGHLIGHTS

- A novel approach combining differential evolution and free search (MOFSDE) is proposed.
- Simulations showed that MOFSDE produces competitive results to heat exchanger design.
- Results illustrate that MOFSDE efficiently achieves goals of multiobjective optimization.

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ABSTRACT

Free search (FS) is a recently proposed population-based metaheuristic algorithm, inspired from the animals' behavior. FS can be applied to real value numerical optimization problems, as well as evolutionary algorithms and swarm intelligence techniques. In this paper, a novel multiobjective FS approach combined with differential evolution (MOFSDE) to heat exchanger optimization is presented. Two case studies of heat exchanger design are carried out to illustrate the efficiency of the MOFSDE. Simulation results for the two multiobjective case studies using the proposed MOFSDE are compared with those obtained by using the nondominated sorting genetic algorithm, version II (NSGA-II). The results from this comparison indicate that the MOFSDE performs better than the NSGA-II. The results illustrate that MOFSDE efficiently achieves two goals of multiobjective optimization problems: to find the solutions that converge to an approximated Pareto-front which is well spread, having the advantage of no parameter tuning apart from the population size and the number of generations.

1. Introduction

Heat exchanger is a device that is used to transfer thermal energy between two or more fluids, between a solid surface and a fluid at different temperatures in thermal contact [1].

Heat exchangers are significant components in various industrial fields, and the past few decades witnessed the rapid development of heat transfer enhancement technology. There are numerous ways to increase the heat transfer in heat exchangers which include treated surfaces, rough surfaces [2], extended surfaces, coiled tubes, surface or fluid vibration, jet impingement [3], and creating longitudinal vortices in the flow. An efficient heat exchanger in such systems could result in the lesser consumption of the energy resource, which provides both economic and environmental benefits.

A good design, in terms of both economics and efficiency, can be obtained through appropriate selection of design parameters. In this context, the utilization of optimization methods can be useful. Moreover, considerable efforts for various optimization methodologies mainly using mathematical programming [4–6] and optimization metaheuristics [7–17] have been devoted to optimizing heat transfer processes. Onishi et al. [4] proposed a mixed integer non-linear programming model for the design of shell-and-tube heat exchangers. Mizutani et al. [5] presented a mathematical programming model based on generalized disjunctive programming for heat-exchanger network synthesis. Unuvar and Kargici [6] proposed a steepest descent approach for the design of heat exchangers, which takes the minimization of annual total cost as a design objective, and heat balance and rate equation as equality constraint. Caputo et al. [7] presented a genetic algorithm approach to shell and tube

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heat exchanger optimization based on the minimization of the life cycle cost. Gosselin et al. [8] presented a survey of genetic algorithm applications in the field of heat transfer including thermal systems design problems, inverse heat transfer problems, and development of heat transfer correlations. Yousefi et al. [9] presented a learning automata based particle swarm optimization employed to multi-stage thermal–economical optimization of compact heat exchangers. Chauduri et al. [10] presented a strategy based on simulated annealing for the design of heat exchangers. Mishra et al. [11] evaluated a genetic algorithm for crossflow plate-fin heat exchangers minimizing the total annual cost for a specified heat duty under given space and flow restrictions. Selbas et al. [12] proposed a new design approach for shell-and-tube heat exchangers using genetic algorithms from economic point of view. Ozcelik [13] developed a genetic algorithm to estimate the configuration of heat exchangers by minimizing the sum of the annual capital cost and exergetic cost of the shell and tube heat exchangers. Caputo et al. [14] proposed a procedure for optimal design of shell and tube heat exchangers, which utilizes a genetic algorithm to minimize the total cost of the equipment including capital investment and the sum of discounted annual energy expenditures related to pumping. Asadi et al. [15] presented an optimization of shell and tube heat exchangers with respect to the total annual costs by a cuckoo search algorithm. Patel and Rao [16,17] studied a particle swarm optimization approach for design optimization of shell-and-tube heat exchangers from economic viewpoint.

On the other hand, optimal design of heat exchangers is usually achieved by locating the best trade-off between different, often contradicting, performance criteria. Multiobjective optimization involves the simultaneous optimization of several incommensurable and often competing objectives. When several criteria are considered simultaneously there is no unique optimal solution but a set of mathematically equivalent Pareto optimal solutions, a non-dominated set of solutions [18]. A solution is Pareto optimal if no criterion can be improved without impairing some other criterion. Over the last years, some studies related to multiobjective optimization in heat transfer and heat exchanger design in particular can be found from the literature.

Hilbert et al. [19] developed a multi-objective optimization approach based genetic algorithm to find the geometry most favorable to simultaneously maximize heat exchange while obtaining a minimum pressure loss. Yin and Ooka [20] used a genetic algorithm method to single objective optimization and multi-objective optimization to obtain the optimal structural parameters of a water-to-water plate-fin heat exchanger applied to an air-conditioning system. Khosravi et al. [21] investigated the performance of evolutionary algorithms and swarm intelligence approaches, such as genetic algorithm, firefly algorithm, and cuckoo search, for design optimization of shell and tube heat exchangers. Asadi et al. [15] presented an optimization of shell and tube heat exchangers with respect to the total annual costs by a cuckoo search algorithm. Patel and Savsani [22] investigated a multi-objective improved teaching–learning-based optimization algorithm applied for the multi-objective optimization of plate-fin heat exchangers. Agarwal and Gupta [23] proposed an elitist non-dominated sorting genetic algorithm for design of the shell and tube heat exchangers. Sanaye and Hajabdollahi [24] adopted a fast and elitist non-dominated sorting genetic algorithm with continuous and discrete variables for multiobjective design heat exchangers. In Fettaka et al. [25], a multiobjective optimization of the heat transfer area and pumping power of a shell-and-tube heat exchanger is presented to provide the designer with multiple Pareto-optimal solutions which capture the trade-off between the two objectives using genetic algorithms. In Rao and Patel [26], a modified version of the teaching–learning-based optimization was introduced and applied for the multi-objective optimization of heat exchangers. Gomez et al. [27] presented a multiobjective genetic algorithm approach applied to design the heat exchanger of a generating turbomachine. Belanger and Gosselin [28] investigated the design of a thermoelectric generator sandwiched in the wall of a crossflow heat exchanger based genetic algorithm optimizer. Hilbert et al. [19] evaluated a multi-objective design optimization concerning the blade shape of a heat exchanger using genetic algorithms. Wang and Li [29] applied an improved cuckoo search algorithm for the multi-objective optimization design of plate-fin heat exchangers. Hajabdollahi et al. [30] presented a multiobjective optimization based on genetic algorithm applied to plain fin-and-tube heat exchanger. Selleri et al. [31] proposed a mathematical model for a mini-channel heat exchanger. Furthermore, multiobjective optimization using genetic algorithm was performed in the next step in order to obtain a set of geometrical design parameters, leading to minimum pressure drops and maximum overall heat transfer coefficient. Turgut [32] proposed a hybrid approach called chaotic quantum behaved particle swarm optimization algorithm for thermal design of plate fin heat exchangers. Hadidi [33] investigated a robust approach for optimal design of plate fin heat exchangers using biogeography based optimization algorithm. Yousefi et al. [34] proposed an improved harmony search algorithm to optimize plate-fin heat exchangers. Huang et al. [35] proposed a multiobjective design optimization strategy based on genetic algorithms for vertical ground heat exchangers. Bidabadi et al. [36] investigated the spiral heat exchanger optimization using genetic algorithm. Jena et al. [37] evaluates the multiobjective optimization of design parameters of a shell and tube type heat exchanger using genetic algorithm.

Also, in optimization metaheuristics, the differential evolution (DE) algorithm is a powerful, yet simple to implement, robust and versatile population-based metaheuristic method for the global numerical optimization. It has been proposed by Storn and Price in 1995 [38] and has been widely used since then and successfully applied in diverse fields. According to a recent review [39], the characteristics which made the DE algorithm effective are: (i) in comparison to other evolutionary algorithms (EAs), DE is relatively simpler to implement while maintaining competitive results; (ii) the number of control parameters is very low, namely three in the classical DE algorithm; and (iii) the space complexity, with respect to the decision variables, of the DE algorithm is low, making it suitable to handle high dimensional problems. Since its inception in 1995, the DE algorithm remains the focus of attention of many researches, as shown in the following. In [40], the authors employ the concept of coevolution in order to use two populations, one to handle diversity and other convergence, to solve multiobjective problems with DE. A novel self-adaptive scheme is given for DE with surrogate models in [41], which is tested against single objective optimization problems. Another multi-population algorithm for single objective optimization is implemented in [42], to solve large-scale single objective optimization problems, where the population is divided into subgroups with different update mechanisms, with the goal to balance exploration and exploitation. In [43] the authors introduce an auto-enhanced population diversity mechanism in order to deal with the problem of premature convergence.

Based on the above consideration, a motivation of this paper is to improve the DE and, as a result, a new improved method is proposed to multiobjective applications. In this context, a novel multiobjective free search (FS) approach combined with differential evolution (MOFSDE) to heat exchanger optimization is presented and evaluated in this paper. Two case studies are evaluated to demonstrate the effectiveness of the MOFSDE: an application example of plate-fin heat exchanger (PFHE) and an application example of shell-and-tube heat exchanger (STHE).

This paper has two main contributions: Firstly, a novel MOFSDE approach via hybrid of DE and free search to multiobjective problem. Secondly, extensive simulation studies showed that MOFSDE is