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Optimal design of plate-fin heat exchanger by combining multi-objective algorithms

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ABSTRACT

In this paper, a multi-objective optimization method is proposed which is a combination of Genetic algorithm, Differential Evolution and Adaptive Simulated Annealing algorithms. This technique is intended to generalize and improve the robustness of the three population based algorithms. In optimization problems, it is essential to keep the balance between local and global search abilities of algorithms. In the current method, DE, GA and ASA algorithms are linked in the variation stage to enrich the searching behavior and enhance the diversity of the population. The performance of the proposed DE-GA-ASA is tested against benchmark problems for multi-objectives and compared with two widely recognized vector optimizers. Next, the proposed technique is successfully implemented to optimize the design of plate-fin heat exchanger. The effectiveness of the present method is illustrated by comparing with various case studies. Some of the earlier case studies violated the constraints and/or only focused on single objective optimization. Results show that DE-GA-ASA method can be used effectively for the optimal design of plate-fin heat exchanger. Moreover, the effect of variation of fin and heat exchanger parameters on the optimal design is also investigated. Hot, cold and no-flow length of the heat exchanger, fin offset length, fin height and fin length are introduced as the optimization variables to obtain maximum heat transfer rate and minimum total annual cost. The investment cost and operating costs are independently optimized to provide a detailed investigation on the effect of fin and heat exchanger geometry parameters on their variation. Furthermore, a multi-criteria decision making method, TOPSIS is introduced for the selection of final optimal solution from the set of non-dominated solutions.

1. Introduction

Heat exchangers are used to transfer thermal energy between two or more media. Various types of heat exchangers are used for different industrial applications and one of the important types is the compact heat exchanger. The advantage of these exchangers is high heat transfer area in volume unit which reduces the space, weight and ultimately the required cost and improve the energy efficiency and design process in comparison with ordinary heat exchangers [1]. The compact heat exchanger can be either plate-fin type or tube-fin type. Cross flow plate-fin heat exchangers are widely used in gas-gas applications such as cryogenics, micro-turbines, automobiles, chemical process plants, naval and aeronautical applications. The design of a PFHE is a complex task based on trial-and-error process in which geometrical and operational parameters are selected to satisfy specified requirements such as outlet temperature, heat duty and pressure drop. To increase the heat transfer area, secondary surface is connected to the primary surface. These extended surface elements are referred to as fins. Some of commonly used fins in these exchangers are plain, wavy, louver, perforated, offset strip and pin fins [2]. A typical plate-fin heat exchanger with rectangular offset strip fins shown in Fig. 1 is used in this study. Since the average boundary-layer thickness decreases significantly when offset-strip fins are used, the convection coefficient increases. Therefore, these fins have higher heat transfer performance than plain flat fins [3]. However the superior thermal performance of the compact heat exchanger is at the expense of higher frictional losses (i.e. pressure drop). Therefore, the optimum design of compact heat exchanger is always required as the optimal trade-off between the increased heat transfer rate and the power consumption due to higher pressure drop within the given set of constraints. Consequently, researchers attempt to optimize thermal equipment and systems using heuristic based optimization algorithms. Moreover, finding a relation between heat transfer increment, total heat transfer area and consumption power due to high pressure drop is necessary.

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Nomenclature

A_f	flow free flow cross-sectional area (m^2)
A_{tot}	total heat transfer area (m^2)
b	fin height (m)
c_p	specific heat (J/kg K)
c	fin pitch (m)
C_{min}	minimum of C_h and C_c (W/K)
C	max maximum of Ch and Cc (W/K)
C^*	heat capacity rate ratio (C_{min}/C_{max})
D_h	hydraulic diameter (m)
f	friction factor (–)
G	mass flux (kg/m^2 s)
h	heat transfer coefficient (W/m^2 K)
j	Colburn number (–)
k_f	fin conductivity (W/m K)
L_c	cold stream flow length (m)
L_h	hot stream flow length (m)
L_n	no-flow length (m)
NTU	number of transfer units (–)
Pr	Prandtl number (–)
Re	Reynolds number (–)
St	Stanton number (–)
t_f	fin thickness (m)
U	overall heat transfer coefficient (W/m^2 K)
V	volumetric flow rate (m^3/s)
x	fin length (m)

Greek abbreviation

ε	heat exchanger effectiveness (–)
h	compressor efficiency (–)
b	heat transfer area per unit volume (m^2/m^3)
m	viscosity (Pa·s)
n	specific volume (m^3/kg)/fin frequency(fins/m)
ΔP	pressure drop (Pa)
s	ratio between A_{flow} and A_{front}

Subscripts

c	cold
h	hot

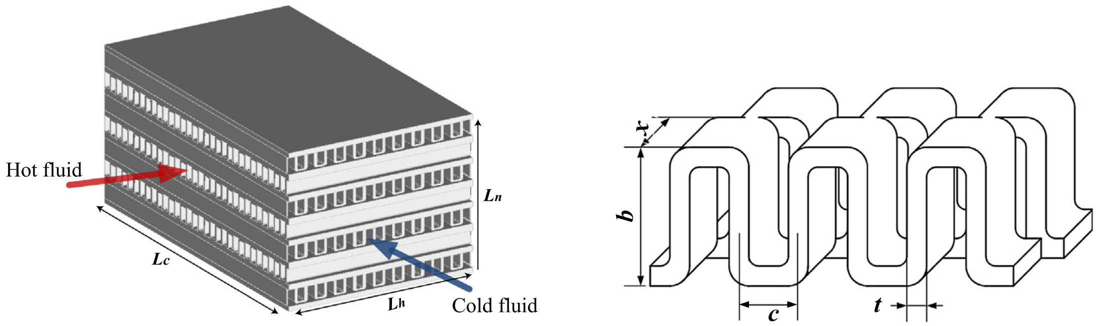

Fig. 1. Schematic diagram of cross flow plate fin heat exchanger with rectangular offset strip fin.

There are a lot of efforts for optimization of different types of heat exchangers with various objectives and decision variables employing various methods. In addition to traditional mathematical techniques [4,5]and artificial neural network [6], many works have been conducted using evolutionary computations in design optimization of compact heat exchangers. Among these Genetic algorithm (GA) has been successfully used for optimization of plate-fin heat exchanger. Sanaye and Hajabdollahi [7] used GA to obtain the maximum effectiveness and the minimum total annual cost as two objective functions in a PFHE with offset strip fins. Xie et al. [8] minimize the total volume and total annual cost of Plate-fin type CHE with and without pressure constraint using Genetic Algorithm.

Similarly, Najafi et al. [9]optimized the total rate of heat transfer and total annual cost of the system by employing multi-objective GA. Wang et al. [10] and Zhao [11] developed a novel GA optimization model in order to effectively obtain the optimal layer pattern of multi-stream plate-fin heat exchanger. They presented few layer pattern criterion models to determine an optimal stacking pattern. They developed mentioned model by employing a genetic algorithm with binary chromosome ring representing alternatively placed hot and cold layer fluid streams. These researchers have concluded that the performance of plate fin heat exchangers in relation to heat transfer and fluid flow was effectively improved by the optimal design of the genetic algorithm layer pattern. Chyi and Hung [12] presented genetic optimization algorithm to solve the formulated multi-objective optimization problem that simultaneously minimizes the entropy generation rate and material cost of the heat sink. Varun and Siddhartha [13] have optimized a flat plate solar air heater using a genetic algorithm. They considered the thermal performance of the exchanger and optimized the exchanger considering the different system and operating parameters to obtain maximum thermal performance. Hang and Ryozo [14] obtained the optimal structural parameters of a water to water plate fin heat exchanger by using CFD and GA. In their work, the convective heat transfer coefficients of plate and fin are defined as independent parameters to obtain more precise results and the corresponding expressions for number of entropy generation units are deduced. In all of the above mentioned works, the Multi objective Genetic Algorithm or its extended version is used.

Apart from Genetic Algorithm, various other evolutionary algorithms in the optimization of plate fin exchangers have been developed and illustrated the need for seeking the new design methods of these equipments [15–18]. In these studies, different fitness functions such as minimization of pressure loss, weight, costs, heat transfer area are considered with various constraints and restrictions. Although many researchers have worked on the development and optimization of compact heat exchanger using new