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Irreversibility analysis for optimization design of plate fin heat exchangers using a multi-objective cuckoo search algorithm

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ABSTRACT

This paper introduces and applies an improved multi-objective cuckoo search (IMOCS) algorithm, a novel met-heuristic optimization algorithm based on cuckoo breeding behavior, for the multi-objective optimization design of plate-fin heat exchangers (PFHEs). A modified irreversibility degree of the PFHE is separated into heat transfer and fluid friction irreversibility degrees which are adopted as two initial objective functions to be minimized simultaneously for narrowing the search scope of the design. The maximization efficiency, minimization of pumping power, and total annual cost are considered final objective functions. Results obtained from a two dimensional normalized Pareto-optimal frontier clearly demonstrate the trade-off between heat transfer and fluid friction irreversibility. Moreover, a three dimensional Pareto-optimal frontier reveals a relationship between efficiency, total annual cost, and pumping power in the PFHE design. Three examples presented here further demonstrate that the presented method is able to obtain optimum solutions with higher accuracy, lower irreversibility, and fewer iterations as compared to the previous methods and single-objective design approaches.

1. Introduction

Energy conservation and its effects on climate change is a crucial consideration for social consciousness. The heat exchanger, a piece of heat and cold transfer equipment widely used in various aspects of industry, demands improvement in order to reduce its energy consumption and increase energy efficiency [1]. Among different types of heat exchangers, plate-fin heat exchangers (PFHEs) are regarded for excellent heat exchange capacity and compact size. They are commonly used in air separation, aerospace, cryogenics, chemical and petrochemical processes industries, etc. [2]

Generally, the design of PFHEs is a trial-and-error process under finite constraint conditions (structure and operation parameters), which are selected to satisfy prescribed requirements and create optimal design results. This is essentially a compromise between desirable heat transfer efficiency and low cost. Careful selection of design parameters may improve performance, lower capital and operating costs, and conserve energy and materials [3]. To this effect, many analysis methods exist in order to suggest optimization methods for heat exchangers. These can be separated into three categories. First is the conservation of energy, which is commonly used in various thermodynamic analyses. Second is entropy and exergy, which combine the first and second laws of thermodynamics [4,5]. The number of entropy generation for irreversibility minimization has been used for modeling and optimization by Bejan [6]. The irreversibility of heat exchanger is evaluated by using entropy generation minimization, which is still an active research field [7]. However, a paradox may arise when this method was used as a single objective function [8]. The third includes various new methods, such as thermal economy [9], entransy dissipation theory, and others. Notably, Guo et al. [10] have defined entransy dissipation as the rate and efficiency of heat exchanger designs. Similar to the process of entropy generation, the more entransy dissipates, the higher its degree of irreversibility is. Thus the entransy dissipation becomes a quantitative index for evaluating the performance of heat exchangers, and there is no entropy generation paradox in applications of heat exchanger design [11,12]. In general, there are two types of irreversible energy loss in the heat exchanger—heat transfer and fluid friction irreversibility degrees, which are competing functions. In this study, a modified irreversibility degree was separated into two objective functions, and both entropy generation minimization (EGM) and entransy dissipation minimization (EDM) methods were used for the optimization of heat exchanger for verifying each other.

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Nomenclature

A	heat exchanger surface area (m^2)
A_{flow}	free flow area (m^2)
b	fin height (m^2)
C	heat capacity rate (W/K)
C_r	C_{min}/C_{max}
c_p	specific heat (J/kg K)
C_{inv}	initial cost ($)
C_{ope}	operating cost ($)
D_h	hydraulic diameter (m)
f	Fanning friction factor
$f(x)$	objective function
$g(x)$	constraint
G	entransy dissipation rate (W K)
h	convective heat transfer coefficient (W/m^2 K)
j	Colburn factor
k_{el}	electricity unit price ($/MW h)
L	heat exchanger length (m)
m	mass flow rate (kg/s)
n	fin frequency (fin/m)
n^*	exponent of non-linear
N_p	number of hot side layer
NTU	number of transfer units
N	dimensionless number
Pr	Prandtl number
P	pressure (kPa)
Q	heat duty (kW)
R	specific gas constant (J/kg K)
R_1	penalty parameter
Re	Reynolds number
S	entropy generation rate (W/K)
T	temperature (K)
t_f	fin thickness (m)
x	a decision variable
X	a set of each decision variables

Greek symbols

ε	effectiveness
μ	fluid dynamic viscosity (kg/m s)
η	pumping efficiency
ρ	density (kg/m^3)
ΔT	temperature difference (K)
ΔP	pressure drop (kPa)

Subscripts

c	cold fluid
h	hot fluid
max	maximum
min	minimum
1	inlet
2	outlet
i, j	variable number

Previous optimization methods have failed to obtain functional solutions over a broad range of common problem. The optimization process for heat exchangers is complicated, and under numerous constraints [13]. Considering these many existing shortcomings, evolutionary algorithms (EAs) are often used to address problems, generating solutions by use of a natural evolutionary mechanism [14]. Because EAs do not need any assumptions about the objective functions, the EAs are independent of the mathematical model to be optimized and the initial values. Recently, the application of EAs has received much interest from researchers for the optimal design of heat exchangers. In a review of relevant literature [15,16], different authors used different optimization techniques for single as well as multi-objective optimization of PFHEs.

Previous heat exchangers design effort have utilized traditional mathematical methods, including simulated annealing [17] and artificial neural networks [18]. In 2004, Mishra et al. [19] exploited a Genetic algorithm (GA) to minimize the total cost of optimal design. Xie et al. [20] further added a pressure drop restriction to a compact heat exchanger designed by GA. Mishra et al. [21] minimized the rate of entropy generation, based on the second law of thermodynamics, to optimize cross-flow PFHEs. Sanaye and Hajabdollahi [22] performed the simultaneous minimization of total cost and maximization of efficiency using a design which featured non-dominated sorting GA multi-objective PFHEs. 2010 also saw the rapid development of certain meta-heuristic algorithms. Rao and Patel [23] applied Particle Swarm Optimization (PSO) to minimize entropy generation units and total volume for PFHEs. Peng et al. [24] presented an improved PSO, which had a shorter computational time and more favorable results compared to GA. Imperialist competitive algorithm (ICA) is a social heuristic optimization mechanism based on imperialism and colonial competition which Yousefi et al. [25] first employed to optimize cross-flow PFHEs under a constrained conditions, where the objective functions were EGM units, minimization of cost, and weight. Hadidi et al. [26] proposed to use the ICA to optimize shell-and-tube heat exchangers from economic point of view, which can help the manufacturer and engineers to reduce design time in engineering applications. Babaelahi et al. [27] used multi-objective optimization to make concession between thermal efficiency and pumping cost, achieving lower total cost in compared to the original method. Wang et al. [28] used the dual fitness functions that act on Genetic Algorithm alternatively to obtain a highly efficient automatic layer pattern arrangement. The thermal performance showed good agreement with those of the layer arrangement experiments. In the past two years, several optimization strategies have been created to optimize the design of heat exchangers, including teaching–learning-based optimization (TLBO) [29], the harmony search algorithm [30], the Bees Algorithm [31], and the Cuckoo search Algorithm [32,33]. However, no single algorithm is able to outperform the others for all engineering applications, due to continuous improvements in meta-heuristic algorithms. Any new methods which is introduced to PFHEs design optimization must be submitted for further study. On the other hand, with multiple objectives and constraints taken into consideration, an optimum design problem must then be solved, in which some of the objectives might be opposed or not. So the results are more likely to fall into local optimum than single objective. Multi-objective optimization is a difficult work. The parameters are related and could influence each other. In order to solve this problem, we use a new method called improved multi-objective cuckoo search algorithm, expecting more effective results with good robustness.

This study investigates the irreversibility degree for optimization geometric parameters of PFHEs using an improved multi-objective cuckoo search algorithm (IMOCS). The primary objectives of this work include: (1) Demonstrating the effectiveness of the IMOCS algorithm for optimization of PFHEs. (2) Using heat transfer and fluid friction entropy generation/entransy dissipation model as two separate evaluation function objectives to